HANDBOOK OF MRI TECHNIQUE

FOURTH EDITION

Catherine Westbrook

with website

WILEY Blackwell

Handbook of MRI Technique

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Fourth Edition

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WILEY Blackwell

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Preface

The *Handbook of MRI Technique* is now an established text for many MRI practitioners around the world. *MRI in Practice* (also published by Wiley Blackwell) provides radiographers and radiologists with a user-friendly approach to MRI theory and how it may be applied in practice. The book is intended to guide the uninitiated through scanning techniques and protocols and to help more experienced practitioners improve image quality and recognize and rectify common artefacts. In many countries, a lack of educational facilities and funding, as well as the complex nature of the subject, has resulted in practitioners experiencing difficulty in learning MRI techniques. The book has filled this gap and has proven to be a useful clinical text. In this, the fourth edition, it has been my intention to continue with the objectives of previous editions but update the reader on recent advances. Experienced MRI practitioners from the United Kingdom, United States and Europe have made important contributions to reflect these advances and their practice.

The book is split into two parts. Part 1 summarizes the main aspects of theory that relate to scanning and also includes practical tips on equipment use, patient care and safety, and information on contrast media. Part 2 includes a step-by-step guide to examining each anatomical area. It covers most of the techniques commonly used in MRI. Under each examination area, categories such as indications, patient positioning, equipment, suggested protocols, common artefacts and tips on optimizing image quality are included. Guidance on technique and contrast usage is also provided. Each section also includes key facts, and the basic anatomy section has been improved with the inclusion of sophisticated computer-generated diagrams. The accompanying web site consists of multiple-choice questions and image flash cards to enable readers to test their knowledge.

The book provides a guide to the operation of MR systems to enhance the education of MR users. It is not intended to be a clinical book as there are plenty of clinical specialist books on the market. Therefore diagrams and images focus intentionally on scan planes, slice prescriptions and sequencing to reflect the technical thrust of the book. This edition should continue to be especially beneficial to those technologists studying for

board certification or postgraduate and MSc courses, as well as to assistant practitioners, radiographers and radiologists who wish to further their knowledge of MRI techniques. The contributing authors and I hope that it continues to achieve these goals.

Catherine Westbrook

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Contributors

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Catherine is a senior lecturer and postgraduate course leader at the Faculty of Health & Social Care and Education at Anglia Ruskin University, Cambridge, where she runs a postgraduate Masters degree course in MRI.

Catherine is also an independent teaching consultant providing teaching and assessment in MRI to clients all over the world.

Catherine has worked in MRI since 1990 and was one of the first people in the world to gain a Master of Science degree in MRI. She also has a postgraduate certificate in Learning and Teaching and a Fellowship in Advanced MRI. She is currently studying for a Doctorate in Education with a focus on MRI. Catherine is a Fellow of the Higher Education Academy and a qualified clinical teacher.

Catherine founded what is now called the "MRI in Practice" course in 1992 and has taught on the course ever since. She also teaches and examines on many other national and international courses, including undergraduate and postgraduate programmes. In particular, Catherine was involved in the development of the first reporting course for MRI radiographers and the first undergraduate course for assistant practitioners in MRI.

Catherine is the author of several books including *MRI in Practice*, *Handbook of MRI Technique*, *MRI at a Glance* and many other chapters and articles.

Catherine has been President of the British Association of MR Radiographers, Chairman of the Consortium for the Accreditation of Clinical MR Education and Honorary Secretary of the British Institute of Radiology.

John Talbot, MSc, DCRR, PgC (LT), FHEA
John is a senior lecturer in medical imaging at Anglia Ruskin University, Cambridge. He was formerly education and research radiographer at Oxford MRI/Oxford University. He developed an early interest in MRI as a school-leaver in 1977 and was one of the first radiographers in the world to gain an MSc in the field of medical imaging (MRI) in 1997.

He now lectures extensively around the world as copresenter of MRI in Practice | The Course, teaching up to 800 delegates per year on what has become the world's favourite MRI course.

Academically, John is a contributor to undergraduate and postgraduate MRI courses at Anglia Ruskin University. He is a senior lecturer in postgraduate MRI, supervising Masters students dissertations on this pathway. He is also a tutor in research methodology and (as a registered Apple developer) is undertaking research in the field of touch-screen mobile devices as educational tools.

John is the coauthor and illustrator of the fourth edition of *MRI in Practice* (Wiley Blackwell), the fourth edition of *Handbook of MRI Technique* (Wiley Blackwell) and coauthor of *Medical Imaging—Techniques, Reflection & Evaluation* (Elsevier).

John's main interest is exploiting the parallelism between technology and learning, and he is currently working on new pedagogical concepts in virtual learning environments. His previous contributions to the field include the construction of a 'virtual reality' MRI scanner for learning and teaching and other web-based interactive learning materials. More recently, John has been creating computer-generated high-definition movies and anaglyph 3D diagrams of MRI concepts for the all-new update of MRI in Practice | The Course. Some of these computer generated images (CGI) resources are included in the web content for the latest edition of the book *MRI in Practice* and as a range of MRI educational apps for Apple devices.

William Faulkner, BS, RT(R)(MR)(CT), FSMRT
Bill Faulkner is currently working as an independent consultant with his own company, William Faulkner & Associates, providing MRI and CT education as well as MRI operations consulting. His clients have included health care facilities, major equipment vendors, manufacturers and companies such as GE, Philips, Siemens, Toshiba, Invivo, Medtronic, Bracco Diagnostics Inc. and others in the medical imaging field. He has been teaching MRI programmes in Chattanooga, TN, for over 20 years and has been holding MRI certification exam review programmes for more than 15 years. He has been recognized for his contributions to MRI technologist education through several awards including the Crues–Kressel Award from the Section for Magnetic Resonance Technologists (SMRT) and being named 'Most Effective Radiologic Technologist Educator' by AuntMinnie.com. Bill is an active member and Fellow of the SMRT serving as its first president.

Joseph Castillo, MSc (Health Service Management), MSc (MRI)
Joseph is manager for Medical Imaging Services for the National Health Service in Malta. Joseph is also a visiting lecturer at the University of Malta providing teaching and assessment for the Masters degree in MRI. Joseph has worked in MRI since 1995 and has an MSc in MRI, in addition to MSc in Health Service Management. He is currently reading for a PhD with a focus on MRI education and service management. In 2005, Joseph has founded the Malta Magnetic Resonance Radiographers Group which is a community of practice fully dedicated towards MRI education. The group has organised several MRI symposia and workshops.

Erik Van Landuyt, EVL, MC
Erik is the manager for CT and MRI ASZ Campus Aalst, Belgium. As is common in Belgium, Erik first trained as nurse and specialized in CT in 1987. He has a postgraduate certificate in radiography from UZA/VUB, Belgium, and has been an applications specialist for Siemens and GE Healthcare for many years. He currently works on Siemens 1.5T and GE 3.0T systems. Erik's clinical interests include musculoskeletal, neurological and MRA imaging. Erik has several educational responsibilities including acting as a mentor for radiographers and nurses at colleges in Brussels and Aalst. He is also the Belgium organizer of the "MRI in Practice" course.

About the companion website

This book is accompanied by a companion website:

www.wiley.com/go/westbrook/mritechnique

The website includes:

- Interactive MCQs for self-assessment
- Interactive flashcards of book images

1 How to use this book

Introduction

This book has been written with the intention of providing a step-by-step explanation of the most common examinations currently carried out using magnetic resonance imaging (MRI). It is divided into two parts.

Part 1 contains reviews or summaries of those theoretical and practical concepts that are frequently discussed in Part 2. These are:

- parameters and trade-offs
- pulse sequences
- flow phenomena and artefacts
- gating and respiratory compensation (RC) techniques
- patient care and safety
- contrast agents.

These summaries are not intended to be comprehensive but contain only a brief description of definitions and uses. For a more detailed discussion of these and other concepts, the reader is referred to the several MRI physics books now available. *MRI in Practice* by C. Westbrook, C. Kaut Roth and John Talbot (Wiley Blackwell, 2011, fourth edition) describes them in more depth.

Part 2 is divided into the following examination areas:

- head and neck
- spine
- chest
- abdomen
- pelvis
- upper limb
- lower limb.

Each anatomical region is subdivided into separate examinations. For example, the section entitled *Head and Neck* includes explanations on

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imaging the brain, temporal lobes, pituitary fossa, etc. Under each examination, the following categories are described:

- basic anatomy
- common indications
- equipment
- patient positioning
- suggested protocol
- image optimization
- patient considerations
- contrast usage.

Basic anatomy

Simple anatomical diagrams are provided for most examination areas to assist the reader.

Common indications

These are the most usual reasons for scanning each area, although occasionally some rarer indications are included.

Equipment

This contains a list of the equipment required for each examination and includes coil type, gating leads, bellows and immobilization devices. The correct use of gating and RC is discussed in Part 1 (see *Gating and respiratory compensation techniques*). The coil types described are the most common currently available. These are as follows.

- **Volume coils** that both transmit and receive radio-frequency (RF) pulses and are specifically called transceivers. Most of these coils are quadrature coils, which means that they use two pairs of coils to transmit and receive signal, so improving the signal to noise ratio (SNR). They have the advantages of encompassing large areas of anatomy and yielding a uniform signal across the whole field of view (FOV). The body coil is an example of this type of coil.
- **Linear phased array coils** consist of multiple coils and receivers. The signal from the receiver of each coil is combined to form one image. This image has the advantages of both a small coil (improved SNR) and those of the larger volume coils (increased coverage). Therefore linear phased array coils can be used either to examine large areas, such as the entire length of the spinal cord, or to improve signal uniformity and intensity in small areas such as the breast. Linear phased array coils are commonly used in spinal imaging.

- **Volume phased array (parallel imaging)** uses the data from multiple coils or channels arranged around the area under examination to either decrease scan time or increase resolution. Additional software and hardware are required. The hardware includes several coils perpendicular to each other or one coil with several channels. The number of coils/channels varies but commonly ranges from 2 to 32. During acquisition, each coil fills its own lines of k-space (e.g. if two coils are used together, one coil fills the even lines of k-space and the other the odd lines. k-space is therefore filled either twice as quickly or with twice the phase resolution in the same scan time). The number of coils/channels used is called the reduction factor and is similar in principle to the turbo factor/echo training length (ETL) in fast spin echo (FSE) (see section on *Pulse sequences* in Part 1). Every coil produces a separate image that often displays aliasing artefact (see section on *Artefacts* in Part 1). Software removes aliasing and combines the images from each coil to produce a single image. Most manufacturers offer this technology, which can be used in any examination area and with any sequence.
- **Surface/local coils** are traditionally used to improve the SNR when imaging structures near to the skin surface. They are often specially designed to fit a certain area and, in general, they only receive signal. RF is usually transmitted by the body coil when using this type of coil. Surface coils increase SNR compared with volume coils. This is because they are placed close to the region under examination, thereby increasing the signal amplitude generated in the coil, and noise is only received in the vicinity of the coil. However, surface coils only receive signal up to the edges of the coil and to a depth equal to the radius of the coil. To visualize structures deep within the patient, either a volume, linear or volume phased array coil or a local coil inserted into an orifice must be utilized (e.g. a rectal coil).

The choice of coil for any examination is one of the most important factors that determine the resultant SNR of the image. When using any type of coil remember to:

- Check that the cables are intact and undamaged.
- Check that the coil is plugged in properly and that the correct connector box is used.
- Ensure that the receiving side of the coil faces the patient. This is usually labelled on the coil itself. Note: Both sides of the coil receive signal, but coils are designed so that one side receives optimum signal. This is especially true of shaped coils that fit a certain anatomical area. If the wrong side of the coil faces the patient, signal is lost and image quality suffers.
- Place the coil as close as possible to the area under examination. The coil should not directly touch the patient's skin as it may become warm during the examination and cause discomfort.

A small foam pad or tissue paper placed between the skin surface and the coil is usually sufficient insulation.
- Ensure that the coil does not move when placed on the patient. A moving coil during acquisition means a moving image!
- Always ensure that the receiving surface of the coil is parallel to the Z (long) axis of the magnet. This guarantees that the transverse component of magnetization is perpendicular to the coil and that maximum signal is induced. Placing the coil at an angle to this axis, or parallel to the X or Y axis, results in a loss of signal (Figure 1.1).

Patient positioning

This contains a description of the correct patient position, placement of the patient within the coil and proper immobilization techniques. Centring and land-marking are described relative to the laser light system as follows (Figure 1.2):

- The **longitudinal alignment light** refers to the light running **parallel** to the bore of the magnet in the **Z axis**.
- The **horizontal alignment light** refers to the light that runs from **left to right** of the bore of the magnet in the **X axis**.
- The **vertical alignment light** refers to the light than runs from the **top to the bottom** of the magnet in the **Y axis**.

It is assumed in Part 2 that the following areas are examined with the patient placed head first in the magnet:

- head and neck (all areas)
- cervical, thoracic and whole spine
- chest (all areas)
- abdomen (for areas superior to the iliac crests)
- shoulders and upper limb (except where specified).

The remaining anatomical regions are examined with the patient placed feet first in the magnet. These are:

- pelvis
- hips
- lower limbs.

Suggested protocol

This is intended as a guideline only. Almost every centre uses different protocols depending on the type of system and radiological preference. However, this section can be helpful for those practitioners scanning without a radiologist, or where the examination is so rare that perhaps

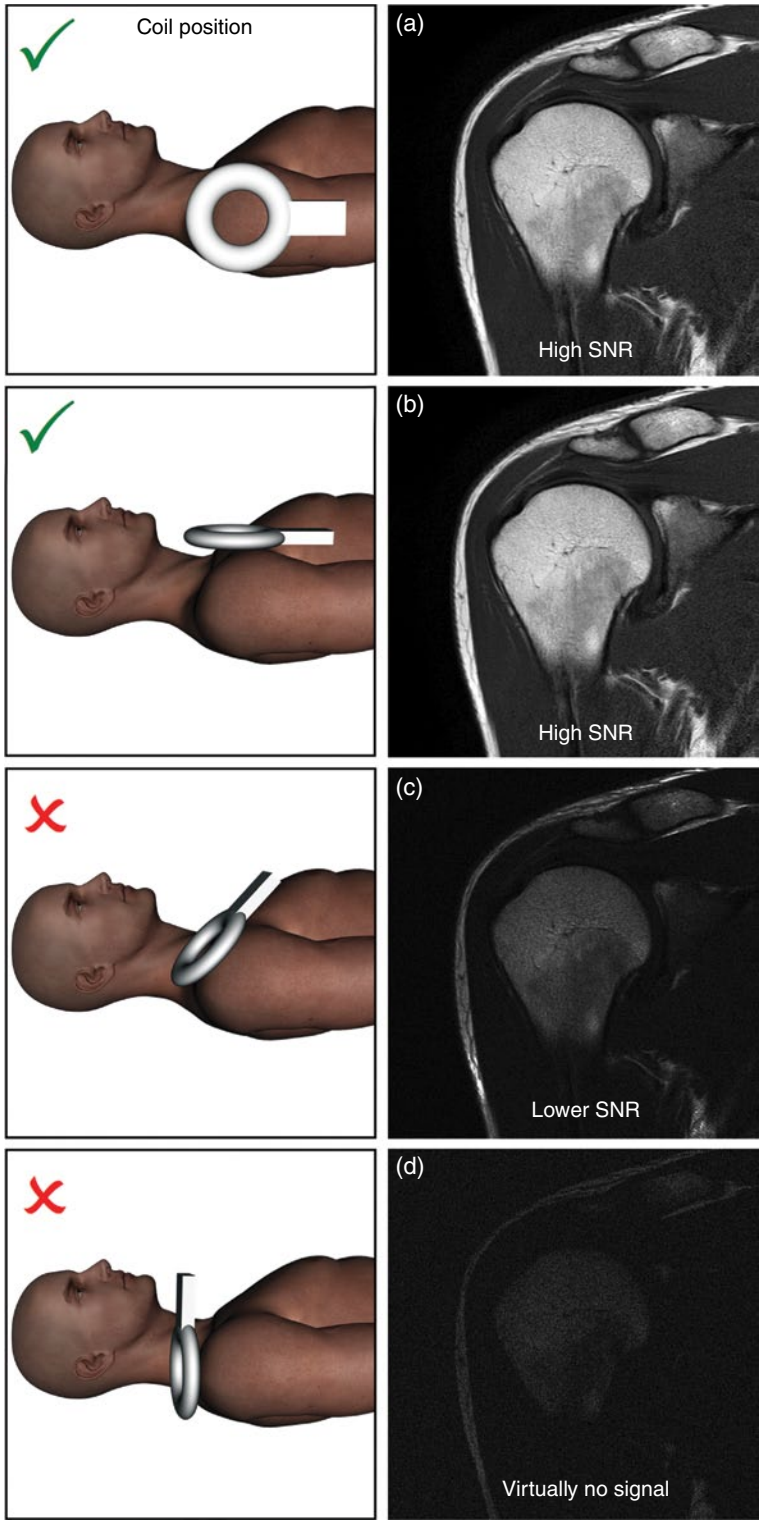

Figure 1.1 Correct placement of a flat surface coil in the bore of the magnet. The surface of the coil (shaded) area must be parallel to the Z axis to receive signal. The coil is therefore positioned so that transverse magnetization created in the X and Y axes is perpendicular to the coil.

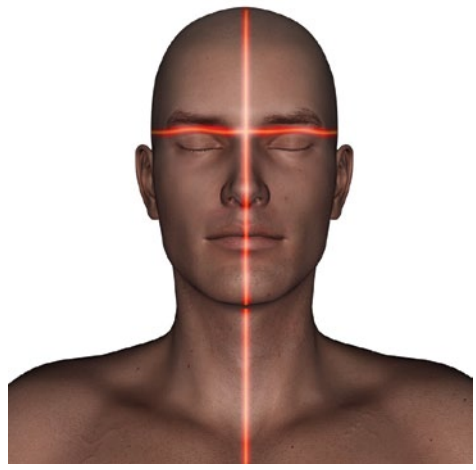

Figure 1.2 Positioning of the alignment lights.

neither the radiologist nor the practitioner knows how to proceed. The protocols given are mainly limited to scan plane, weighting, suggested pulse sequence choices and slice positioning.

It must be stressed that all the protocols listed are only a reflection of the authors' practice and research, and are in no way to be considered the law!

If all your established protocols are satisfactory, this section is included for interest only. If, however, you are unfamiliar with a certain examination, the suggested protocol should be useful.

Occasionally in this section coordinates for slice prescription are given in bold type in millimetres (mm) where explicit prescription can be utilized (mainly for localizers). Graphic prescription coordinates cannot be given as they depend on the exact position of the patient within the magnet and the region of interest (ROI). The explicit coordinates are always given as follows:

- Left to Right **L** to **R**
- Inferior to Superior **I** to **S**
- Posterior to Anterior **P** to **A**.

In the suggested protocols, a certain format is adopted when some parameters remain constant and others change. For example, in the protocol for a coronal spin echo (SE), proton density (PD)/T2 sequence of the brain the text reads.

Coronal SE/FSE PD/T2

As for axial PD/T2, **except** prescribe slices from the cerebellum to the frontal lobe.

This indicates that the pulse sequence, timing parameters, slice thickness and matrix are the same as the axial except the slices are prescribed through a different area. This format is intended to avoid repetition. In most examinations, there is a section reserved for additional sequences. These are extra sequences that we do not regard as routine but may be included in the examination. Of course, some practitioners may regard what we call 'additional' as 'routine', and vice versa.

Image optimization

This section is subdivided into:

- Technical issues
- Artefact problems

Technical issues: This includes a discussion of the relationship of SNR, spatial resolution and scan time pertaining to each examination. Suggestions on how to optimize these factors are described (see *Parameters and trade-offs* in Part 1). The correct use of pulse sequences and various imaging options are also discussed (see also *Pulse sequences* in Part 1).

Artefact problems: This contains a description of the common artefacts encountered and ways in which they can be eliminated or reduced (see also *Flow phenomena and artefacts* in Part 1).

Patient considerations

This encompasses the condition of the patient, including symptoms and claustrophobia. Suggestions to overcome these are given (see also *Patient care and safety* in Part 1).

Contrast usage

The reasons for administering contrast in each particular area are discussed. Again, contrast usage varies widely according to radiological preferences. This section is a guideline only (see also *Contrast agents* in Part 1).

Follow this 10-point plan for good radiographic practice:

1. Review all cases carefully and select appropriate protocols.
2. Have flexible protocols that can reflect the needs of each individual clinical case.
3. Regularly review your procedures and benchmark them against current best practice.
4. Have clear diagnostic goals including the minimum accepted sequences necessary to obtain a useful diagnostic/clinical outcome.
5. Regularly review your protocols and procedures.

6. Understand the capabilities of your system.
7. Recognize your limitations and if necessary refer to another site rather than risking an incomplete or diagnostically unacceptable procedure.
8. Educate all levels of staff to new procedures and/or system capabilities.
9. Be safety paranoid to ensure your unit does not fall victim to the dreaded MRI incident.
10. Most importantly, enjoy your patients and give them the highest standard of care possible.

Terms and abbreviations used in Part 2

Wherever possible, generic terms have been used to describe pulse sequences and imaging options. Explanations of these can be found in the various sections of Part 1. To avoid ambiguity, the specific following terms have been used:

- **Tissue suppression**: includes all suppression techniques such as fat saturation (FAT SAT), spectrally selective inversion recovery (SPIR) and Dixon methods
- **Gradient moment nulling (GMN)**: gradient moment rephasing (GMR) and flow compensation (FC)
- **Oversampling**: no phase wrap, antialiasing and anti-foldover
- **Rectangular/Asymmetric FOV**: rectangular FOV
- **Respiratory compensation (RC)**: phase reordering and respiratory triggering techniques

Abbreviations are used throughout the book for simplification purposes. A summary of these can be found in the following section, *Abbreviations*. In addition, a comparison of acronyms used by certain manufacturers to describe pulse sequences and imaging options is given in Table 3.1 under *Pulse sequences* in Part 1.

Conclusion

To use this book:

- Find the anatomical region required and then locate the specific examination.
- Study the categories under each section. It is possible that all the categories are relevant if the examination is being performed for the first time. However, there may be occasions when only one item is appropriate. For example, there could be a specific artefact that is regularly observed in chest examinations, or image quality is not up to standard on lumbar spines. Under these circumstances, read the subsection entitled *Image optimization*.
- If the terms used, or concepts discussed, in Part 2 are unfamiliar, then turn to Part 1 and read the summaries described there.

Abbreviations

A summary of common abbreviations used in the field of MRI and throughout this book is given below.

A	Anterior
AC	Number of acquisitions
ADC	Apparent diffusion coefficient
ADEM	Acute disseminating encephalomyelitis
ASIS	Anterior superior iliac spine
AVM	Arteriovenous malformation
AVN	Avascular necrosis
BFFE	Balanced fast field echo
BGRE	Balanced gradient echo
BOLD	Blood oxygenation level dependent
CE-MRA	Contrast-enhanced MRA
CNR	Contrast to noise ratio
CNS	Central nervous system
CSE	Conventional spin echo
CSF	Cerebrospinal fluid
CT	Computer tomography
CVA	Cerebral vascular accident
DE prep	Driven equilibrium magnetization preparation
DTI	Diffusion tensor imaging
DWI	Diffusion weighted imaging
ECG	Echocardiogram
EPI	Echo planar imaging
ETL	Echo train length
FA	Fractional anisotropy
FAT SAT	Fat saturation
FC	Flow compensation
FDA	Food and Drugs Administration
FFE	Fast field echo
FID	Free induction decay signal
FIESTA	Free induction echo stimulated acquisition
FISP	Fast imaging with steady precession
FLAIR	Fluid-attenuated inversion recovery
FLASH	Fast low angled shot
fMRI	Functional MRI
FOV	Field of view
FSE	Fast spin echo
GFE	Gradient field echo
GMN	Gradient moment nulling
GMR	Gradient moment rephasing
GRASS	Gradient recalled acquisition in the steady state
GRE	Gradient echo
GRE-EPI	Gradient echo EPI
HASTE	Half acquisition single-shot turbo spin echo

I	Inferior
IAM	Internal auditory meatus
IM	Intramuscular
IR	Inversion recovery
IR-FSE	Inversion recovery FSE
IR prep	Inversion recovery magnetization preparation
IV	Intravenous
IVC	Inferior vena cava
L	Left
MP RAGE	Magnetization prepared rapid gradient echo
MR	Magnetic resonance
MRA	Magnetic resonance angiography
MRCP	Magnetic resonance cholangiopancreatography
MRI	Magnetic resonance imaging
MS	Multiple sclerosis
MT	Magnetization transfer
NEX	Number of excitations
NSA	Number of signal averages
P	Posterior
PC	Phase contrast
PC-MRA	Phase contrast MRA
PD	Proton density
Pe	Peripheral
PEAR	Phase encoding artefact reduction
PSIF	Reverse FISP
R	Right
RC	Respiratory compensation
REST	Regional saturation technique
RF	Radio frequency
ROI	Region of interest
RR	R to R interval
S	Superior
SAR	Specific absorption rate
SAT	Saturation
SE	Spin echo
SE-EPI	Spin echo EPI
SNR	Signal to noise ratio
SPAMM	Spatial modulation of magnetization
SPGR	Spoiled GRASS
SPIR	Spectrally selective inversion recovery
SS	Single shot
SS-EPI	Single-shot EPI
SSFP	Steady-state free precession
SS-FSE	Single-shot FSE
STIR	Short TAU inversion recovery
SW	Susceptibility weighted
TE	Echo time
TFE	Turbo field echo

TI	Inversion time
TIA	Transient ischaemic attack
TLE	Temporal lobe epilepsy
TMJ	Temporomandibular joint
TOF	Time of flight
TOF-MRA	Time of flight MRA
TR	Repetition time
True FISP	Siemens version of BGE
TSE	Turbo spin echo
VENC	Velocity encoding

Part 1 Theoretical and practical concepts

2

Parameters and trade-offs

Introduction

This section refers mainly to the *Technical issues* subheading discussed under the *Image optimization* heading considered for each examination in Part 2. Only a brief overview is provided here. For a more detailed explanation, please refer to Chapter 4 of *MRI in Practice* or an equivalent text.

The main considerations of image quality are:

- SNR
- contrast to noise ratio (CNR)
- spatial resolution
- scan time

Each factor is controlled by certain parameters, and each 'trades off' against the other (see later in Table 2.2). This section summarizes the parameters available and the trade-offs involved. Suggested parameters are outlined in Table 2.1, which can be found here and at the beginning of each anatomical region in Part 2. The parameters given should be universally acceptable on most systems. However, weighting parameters in particular are field strength dependent, and therefore, some modification may be required if you are operating at extremely low or high field strengths.

Signal to noise ratio

SNR is defined as the ratio of the amplitude of signal received by the coil to the amplitude of the noise. The signal is the voltage induced in the receiver coil, and the noise is a constant value depending on the area under examination and the background electrical noise of the system. SNR may be increased by using:

- SE and FSE pulse sequences
- a long repetition time (TR) and a short echo time (TE)
- a flip angle of 90°

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Table 2.1 Summary of parameters

1.5T		3T	
SE		**SE**	
Short TE	Min–30 ms	Short TE	Min–15 ms
Long TE	70 ms+	Long TE	70 ms+
Short TR	600–800 ms	Short TR	600–900 ms
Long TR	2000 ms+	Long TR	2000 ms+
FSE		**FSE**	
Short TE	Min–20 ms	Short TE	Min–15 ms
Long TE	90 ms+	Long TE	90 ms+
Short TR	400–600 ms	Short TR	600–900 ms
Long TR	4000 ms+	Long TR	4000 ms+
Short TEL	2–6	Short TEL	2–6
Long ETL	16+	Long ETL	16+
IR T1		**IR T1**	
Short TE	Min–20 ms	Short TE	Min–20 ms
Long TR	3000 ms+	Long TR	300 ms+
TI	200–600 ms	TI	Short or null time of tissue
Short ETL	2–6	Short ETL	2–6
STIR		**STIR**	
Long TE	60 ms+	Long TE	60 ms+
Long TR	3000 ms+	Long TR	3000 ms+
Short TI	100–175 ms	Short TI	210 ms
Long ETL	16+	Long ETL	16+
FLAIR		**FLAIR**	
Long TE	80 ms+	Long TE	80 ms+
Long TR	9000 ms+	Long TR	9000 ms + (TR at least 4 × TI)
Long TI	1700–2500 ms (depending on TR)	Long TI	1700–2500 ms (depending on TR)
Long ETL	16+	Long ETL	16+
Coherent GRE		**Coherent GRE**	
Long TE	15 ms+	Long TE	15 ms+
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Incoherent GRE		**Incoherent GRE**	
Short TE	Minimum	Short TE	Minimum
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Balanced GRE		**Balanced GRE**	
TE	Minimum	TE	Minimum
TR	Minimum	TR	Minimum
Flip angle	>40°	Flip angle	>40°
SSFP		**SSFP**	
TE	10–15 ms	TE	10–15 ms
TR	<50 ms	TR	<50 ms
Flip angle	20–40°	Flip angle	20–40°

(*Continued*)

Table 2.1 (*Contd.*)

1.5T and 3T			
Slice thickness 2D		**Slice thickness 3D**	
Thin	2–4 mm	Thin	<1 mm
Medium	5–6 mm	Thick	>3 mm
Thick	8 mm		
FOV		**Matrix**	
Small	<18 cm	Coarse	256×128 / 256×192
Medium	18–30 cm	Medium	256×256 / 512×256
Large	>30 cm	Fine	512×512
		Very fine	>1024×1024
NEX/NSA		**Slice number 3D**	
Short	1	Small	<32
Medium	2–3	Medium	64
Multiple	>4	Large	>128
PC-MRA 2D and 3D		**TOF-MRA 2D**	
TE	Minimum	TE	Minimum
TR	25–33 ms	TR	28–45 ms
Flip angle	30°	Flip angle	40–60°
VENC venous	20–40 cm/s	**TOF-MRA 3D**	
VENC arterial	60 cm/s	TE	Minimum
		TR	25–50 ms
		Flip angle	20–30°

The figures given are for 1.5T and 3T systems. Parameters are dependent on field strength and may need adjustment for very low or very high field systems.

- a well-tuned and correctly sized coil
- a coarse matrix
- a large FOV
- thick slices
- a narrow receive bandwidth
- high-order signal averages (number of excitations (NEX)/number of signal averages (NSA)).

In Part 2, the following terms and approximate parameters are suggested when discussing the number of signal averages (NEX/NSA) (see also Table 2.1):

- short NEX/NSA is 1 or less (partial averaging)
- medium NEX/NSA is 2/3
- long or multiple NEX/NSA is 4 or more.

Contrast to noise ratio

The CNR is defined as the difference in the SNR between two adjacent areas. It is controlled by the same factors that affect the SNR. All examinations should include images that demonstrate a good CNR between pathology and surrounding normal anatomy. In this way, pathology is

well visualized. The CNR between pathology and other structures can be increased by the following:

- Administration of contrast agents.
- Utilization of T2-weighted sequences.
- Suppression of normal tissues via tissue suppression or sequences that null signal from certain tissues: short TI inversion recovery (STIR), fluid alternated inversion recovery (FLAIR) and magnetization-prepared sequences.
- Use of sequences that enhance flow, for example, time of flight (TOF).

A note on tissue suppression techniques

The CNR can be improved by suppressing signal from tissues that are not important, thereby increasing the visualization of tissues that are. In addition to pulse sequences such as STIR and FLAIR (see *Pulse sequences*), there are several techniques that achieve this.

Chemical pre-saturation: a 90° saturation pulse is delivered at the specific precessional frequency of either fat or water into the FOV before the excitation pulse, thereby producing saturation. Therefore, no signal is received when the echo is read.

Spectral pre-saturation: uses a saturation pulse of a greater magnitude than 90° and inverts the magnetization in the tissue as in inversion recovery (IR) pulse sequences (see *Pulse sequences*).

Dixon technique (either 2-point or 3-point): a reconstructed image is obtained from only the water protons. This 'water-only' image has no contribution from the fat protons. These images look similar to the pre-saturation techniques described above but rely on the chemical shift between fat and water (the difference in their precessional frequencies). Images are acquired depending on whether the magnetic moments of fat and water are in or out of phase with each other. Unlike saturation techniques, this technique can be used after gadolinium and at any field strength and is a very robust tissue suppression method. Some manufacturers use this technique to produce four images in one sequence (water, fat, in and out of phase).

Tissue suppression is most commonly used to distinguish between fat and enhancing pathology in T1-weighted sequences and in FSE T2-weighted sequences where fat and pathology are often isointense. In Part 2, all of the techniques described above are referred to as ***tissue suppression***.

Spatial resolution

The spatial resolution is the ability to distinguish between two points as separate and distinct. It is controlled by the voxel size. Spatial resolution may be increased by selecting:

- thin slices
- fine matrices
- a small FOV.

The above criteria assume a square FOV so that if an uneven matrix is used, the pixels are rectangular, and therefore, resolution is lost. Some systems utilize square pixels so that the phase matrix determines the size of the FOV along the phase encoding axis. In this way, resolution is maintained because the pixels are always square. The disadvantage of this system is that the size of the FOV may be inadequate to cover the required anatomy in the phase direction, and SNR is often reduced due to the use of smaller, square pixels. Therefore, these systems usually have the option to utilize a square FOV in circumstances where either coverage is required or the SNR is low. In the interests of simplicity, a square FOV is assumed in Part 2, whereby the phase matrix size determines the resolution of the image, not the size of the FOV.

In Part 2, the following terms and approximate parameters are suggested when discussing spatial resolution. The first number quoted is the frequency matrix; the second is the phase matrix (see also Table 2.1):

- A coarse matrix is 256 × 128 or 256 × 192.
- A medium matrix is 256 × 256 or 512 × 256.
- A fine matrix is 512 × 512.
- A very fine matrix is any matrix 1024 × 1024 or above.
- A small FOV is usually less than 18 cm.
- A large FOV is more than 30 cm.
- On the whole, the FOV should fit the ROI.
- A thin slice/gap is 1 mm/1 mm to 4 mm/1.5 mm or less.
- A medium slice/gap is 5 mm/2.5 mm to 6 mm/2.5 mm.
- A large slice/gap is 8 mm/2 mm or more.

Scan time

The scan time is the time required to complete the acquisition of data. The scan time can be decreased by using:

- a short TR
- a coarse phase matrix
- the lowest NEX/NSA possible.

In addition to the SNR, CNR, spatial resolution and scan time, the following imaging options are also described under the *Technical issues* subheading mentioned before.

- **Rectangular/asymmetric FOV**: The use of rectangular/asymmetric FOV is often discussed in Part 2. It enables the acquisition of fine matrices but in scan times associated with coarse matrices. It is most useful when anatomy fits into the shape of a rectangle, for example, sagittal spine. The long axis of the rectangle usually corresponds to the frequency encoding axis and the shorter axis to phase encoding. This is important as certain phase artefacts, such as ghosting and aliasing, occur along the short axis of the rectangle. The dimension of the phase axis is usually expressed as a proportion or percentage of

the frequency axis, for example, 75%. On some systems, rectangular/asymmetric FOV and oversampling are not compatible. If this is so, signal-producing anatomy existing beyond the FOV along the shorter phase axis is wrapped into the image. This is reduced by increasing the FOV, using spatial pre-saturation bands to nullify unwanted signal or, if this function is available, by expanding the short axis dimension to incorporate all signal-producing anatomy (see *Flow phenomena and artefacts*).

- **Volume imaging**: Volume imaging or 3D acquisition collects data from an imaging volume or slab and then applies an extra phase encoding along the slice select axis. In this way, very thin slices with no gap are obtained, and the data set may be viewed in any plane. However, the scan time in volume imaging not only depends on the TR, the phase matrix and the NSA but also on the number of slice locations in the volume. Therefore, scan times are considerably longer than in 2D imaging. For this reason, fast sequences such as steady-state sequences and FSE are commonly used (see *Pulse sequences*). To maintain resolution in all viewing planes, the voxels should be isotropic, that is, they have the same dimensions in all three planes. This is achieved by selecting an even matrix and a slice thickness equal to, or less than, the pixel size. For example, if a matrix size of 256 × 256 is chosen and the FOV is 25 cm, a slice thickness of 1 mm achieves the required resolution. With a larger FOV, a slightly thicker slice can be used. The penalty of isotropic voxels, however, is a reduction in SNR due to the use of smaller, square voxels. In addition, more slices may be required to cover the imaging volume resulting in long scan times. This is compensated for to some degree by the fact that as there are no gaps, a greater volume of tissue is excited and therefore overall signal return is greater. Nevertheless, when volume imaging is employed, the need for resolution in all planes must be weighed against some loss of SNR and longer scan times. As the slices are not individually excited as in conventional acquisitions, but are located by an extra phase encoding gradient, aliasing along the slice select axis occurs. This originates from anatomy that lies within the coil (and therefore produces signal), and exists outside the volume along the slice encoding axis. It manifests itself by the first and last few slices of the imaging volume wrapping into each other and potentially obscuring important anatomy. To avoid this, always overprescribe the volume slab so that the ROI, and some anatomy on either side of it, are included. In this way, any slice wrap does not interfere with the ROI (see *Flow phenomena and artefacts*). Volume imaging is commonly used in the brain and to examine joint anatomy, especially when very thin slices are required. In Part 2, the following terms and approximate parameters are suggested when discussing volume imaging (see also Table 2.1):

  - A thin slice is 1 mm or less.
  - A thick slice is more than 3 mm.

- A small number of slice locations is approximately 32.
- A medium number of slice locations is approximately 64.
- A large number of slice locations is approximately 128 or more.

The following combination of parameters usually yields the optimum SNR and scan time in volume imaging, although this depends on the coil type, the proton density of the area under examination, the slice thickness and the field strength:

- 32 locations use 2 or more NEX/NSA.
- 64 locations use 1 NEX/NSA.
- 128 locations use less than 1 NEX/NSA (partial averaging).

Decision strategies

To optimize image quality, the data should have a high SNR and good resolution and be acquired in a short scan time. This is usually impossible. However, as the factors that must be increased to improve SNR may have to be decreased to gain spatial resolution. An example of this is matrix selection. A coarse matrix is required to obtain large voxels and therefore a high SNR. However, a fine matrix with small voxels and low SNR is not only necessary to maintain good spatial resolution, but also increases the scan time as more phase encodings are performed. The operator must decide which factor (either SNR, phase resolution or scan time) is the most important and optimize this. One or both of the other two may have to be sacrificed accordingly.

When discussing these issues in Part 2, the importance of good SNR over the other factors is emphasized, as in our view there is little point in having an image with good resolution if the SNR is poor. The selection of an appropriately sized and tuned coil is also important, together with the proton density of the area under examination. For example, when examining the chest, which has a low SNR, the parameters selected must optimize the SNR as much as possible, and resolution and scan time are sacrificed. The importance of limiting the scan time for patient toleration is also discussed in Part 2. If the scan time is lengthy, all patients will eventually become uncomfortable and move. The resultant motion artefact degrades any image regardless of its SNR or resolution characteristics. Therefore, it is important to minimize scan times to acceptable levels. If patients are in pain or uncooperative, this strategy is even more important.

Conclusion

The variety of parameters used in MRI is often bewildering, but their importance is undisputed, especially in determining image quality. A good working knowledge of these parameters and how they interrelate is necessary to ensure an optimum examination. Table 2.2 summarizes these trade-offs. The choice of pulse sequence is also important in determining image contrast, and these are outlined in the next section.

Table 2.2 Parameters and their trade-offs

Parameter	Advantages	Disadvantages
TR increased (up to 2000 ms in SE)	Increased SNR Increased number of slices per acquisition	Increased scan time Decreased T1 weighting
TR decreased (below 2000 ms in SE)	Decreased scan time Increased T1 weighting	Decreased SNR Decreased number of slices per acquisition
TE increased	Increased T2 weighting	Decreased SNR
TE decreased	Increased SNR	Decreased T2 weighting
NEX increased	Increased SNR of all tissues Reduced motion artefact due to signal averaging	Direct proportional increase in scan time
NEX decreased	Direct proportional decrease in scan time	Decreased SNR in all tissues Increased motion artefact due to less signal averaging
Slice thickness increased	Increased SNR in all tissues Increased coverage of anatomy	Decreased spatial resolution and partial voluming in slice select direction
Slice thickness decreased	Increased spatial resolution and reduced partial voluming in slice select direction	Decreased SNR in all tissues Decreased coverage of anatomy
FOV increased	Increased SNR Increased coverage of anatomy	Decreased spatial resolution Decreased likelihood of aliasing
FOV decreased	Decreased SNR in all tissues Decreased coverage of anatomy	Increased spatial resolution Increased likelihood of aliasing
Matrix increased	Increased spatial resolution	Decreased SNR if pixel size decreases. If pixel size remains the same, SNR will increase because more phase encodings are performed Increased scan time
Matrix decreased	Increased SNR in all tissues if pixel size increases. If pixel size remains the same, SNR decreases as fewer phase encodings are performed Decreased scan time	Decreased spatial resolution
Receive bandwidth increased	Decrease of minimum TE Decrease in chemical shift	Decreased SNR
Receive bandwidth decreased	Increased SNR	Increase in minimum TE Increase in chemical shift

3

Pulse sequences

Introduction

This section refers mainly to the *Suggested protocol* heading considered for each examination in Part 2, although pulse sequences are sometimes mentioned under the *Technical issues* subheading of *Image optimization*. A summary of the mechanisms and uses of the most commonly used pulse sequences are described. All pulse sequences are described using their generic name. Table 3.1 provides a comparison of the acronyms used by the main manufacturers to describe their pulse sequences and imaging options. The parameters given in Table 2.1 should be universally acceptable on most systems with field strengths of 1.5 T and 3 T. However, weighting parameters in particular are field strength dependent, and therefore, some modification may be required if you are operating at extremely low or high field strengths. Only a brief overview is provided here. For a more detailed explanation, please refer to Chapters 2 and 5 of *MRI in Practice* or an equivalent text.

Spin echo

An SE pulse sequence (also known as conventional spin echo (CSE)) usually uses a 90° excitation pulse followed by a 180° rephasing pulse to produce an SE. Some SE sequences use a variable flip angle, but traditionally the excitation pulse has a magnitude of 90°. This amplitude of the flip angle is consistently assumed in the protocols. SE sequences can be used to generate one or several SE. One echo is usually used for T1 weighting while two echoes are used for proton density (PD) and T2 weighting. SE pulse sequences are the most commonly implemented sequences as they produce optimum SNR and CNR.

Handbook of MRI Technique, Fourth Edition. Catherine Westbrook.

Companion website: www.wiley.com/go/westbrook/mritechnique

Table 3.1 Comparison of manufacturer acronyms (see *How to use this book* for abbreviations)

Pulse sequence/imaging option	General Electric	Philips	Siemens
SE	SE	SE	SE
FSE	FSE	TSE	TSE
Coherent GRE	GRASS	FFE	FISP
BGRE	FIESTA	BFFE	True FISP
Incoherent GRE	SPGR	T1 FFE	FLASH
Steady-state free precession (SSFP)	SSFP	T2 FFE	PSIF
IR	IR	IR	IR
STIR	STIR	STIR	STIR
Fluid-attenuated inversion recovery (FLAIR)	FLAIR	FLAIR	FLAIR
Pre-saturation	SAT	REST	SAT
Gradient moment nulling	FC	FC	GMR
RC	RC	PEAR	RC
Signal averaging	NEX	NSA	AC
Partial averaging	Fractional NEX	Half scan	Half Fourier
Oversampling	No phase wrap	Fold over suppression	Oversampling
Rectangular/asymmetric FOV	Rectangular FOV	Rectangular FOV	Under-sampling FOV

Fast spin echo or turbo spin echo

Fast spin echo (FSE) uses a 90° flip angle followed by several 180° rephasing pulses to produce several SE in a given TR. Each echo is phase encoded with a different amplitude of gradient slope, so that data from each echo are collected and stored in a different line of k-space. In this way, more than one line of k-space is filled per TR, and the scan time is reduced accordingly. The echo train length (ETL) (also known as the turbo factor) refers to the number of 180° rephasing pulses and therefore echoes that correspond to the number of lines of k-space filled per TR. The longer the ETL, the shorter the scan time as more lines of k-space are filled per TR.

FSE can be used to produce either one or two echoes as in SE. The echo train may be split so that data are collected from the first half of the echo train to acquire the first echo, and from the latter half to acquire the second echo. This strategy is commonly used to produce PD and T2 images that demonstrate similar weighting to SE. However, T2 images can be acquired without a PD image. A T2 image alone, rather than a dual echo, is often acquired in Part 2. It is of course perfectly justified to use a dual echo sequence if this is required. For more information, see *Technical Issues* in *Brain* in Part 2.

FSE sequences have been further modified to include 3D acquisitions and single-shot techniques. Single-shot FSE (SS-FSE), which is also termed

HASTE (half acquisition single-shot turbo spin echo), combines long ETLs that fill all of k-space in one shot with half-Fourier acquisition techniques that acquire only half of k-space and then transpose data into the other half. This technique allows very rapid acquisitions, which enables multiple-slice breath-hold and real-time imaging.

Some contrast characteristics of FSE differ from conventional SE. Fat remains bright on T2-weighted images, and fat suppression techniques may be needed to compensate for this. The multiple 180° RF pulses used in FSE sequences cause lengthening of the T2 decay time of fat so that the signal intensity of fat on T2-weighted FSE images is higher than in SE. This sometimes makes the detection of marrow abnormalities difficult. Therefore, when imaging the vertebral bodies for metastatic disease, a short tau inversion recovery (STIR) sequence should be utilized. Muscle can appear darker than usual especially on the T2-weighted images. This is again due to the multiple 180° pulses causing a MT effect.

In addition, certain artefacts may be prominent in FSE sequences. Image blurring is often a problem in long ETL sequences. This occurs because each line of k-space contains data from echoes with a different TE. In long ETL sequences, the very late echoes have a low signal amplitude and, as the outer lines of k-space are filled with data from these echoes, there are insufficient data to provide adequate resolution. Image blurring is most commonly seen at the edges of tissues with different T2 decay times. It may be reduced by decreasing the size of the FOV in the phase direction (depending on how the manufacturer implements a rapid FSE sequence) or by selecting a broad receive bandwidth. However, while the latter does improve overall image quality by reducing blurring, it also reduces the SNR. Lastly, FSE is not always compatible with options such as phase-reordered RC, and therefore, conventional SE or breath-hold sequences are often the sequence of choice when respiratory artefact is likely to be troublesome.

Inversion recovery (IR/IR-FSE)

IR pulse sequences begin with a 180° pulse that inverts the net magnetization vector into full saturation. When the inverting pulse is removed, the magnetization begins to recover and return towards B_0. After a specific time TI (inversion time), a 90° excitation pulse is applied which transfers the proportion of magnetization that has recovered to B_0 into the transverse plane. This transverse magnetization is then rephased by a 180° rephasing pulse to produce an echo. In IR-FSE, several 180° rephasing pulses are applied as in FSE, so that more than one line of k-space can be filled per TR, so reducing the scan times.

Conventional IR is most commonly used to produce heavily T1-weighted images. However, it and IR-FSE may also be implemented to eliminate the signal from certain tissues by applying the 90° excitation pulse when the magnetization in that tissue has recovered into the transverse plane and therefore has no longitudinal component. In this way, signal from tissue is

nulled by the excitation pulse. There are two main uses of this technique. STIR uses a short TI that corresponds to the null point of fat so that the excitation pulse specifically nulls the signal from fat. In Part 2, STIR is used as a fat suppression technique in conjunction with an FSE sequence to produce T2 weighting by using long TEs and ETLs. FLAIR utilizes a long TI corresponding to the null point of cerebrospinal fluid (CSF) so that the excitation pulse specifically nulls the signal from CSF. Again, long TEs and ETLs that enhance T2 weighting are commonly used to enhance the signal from pathology especially periventricular lesions.

In all IR sequences, the TI is field strength dependent. In FLAIR sequences combined with long ETL FSE, if the TR is not long enough to allow full recovery of z magnetization after the last echo in the train has been collected, a shorter TI than usual may be required to null the CSF signal adequately. This is because if only partial z magnetization has recovered at the end of the TR period, this is converted into only partial –z magnetization after inversion, and therefore, the magnetization in CSF does not take long to reach its null point.

Coherent gradient echo (T2*)

Coherent gradient echo (GRE) pulse sequences use a variable flip angle followed by gradient rephasing to produce a GRE. This sequence utilizes the steady state so that the transverse component of magnetization is allowed to build up over successive repetition times. This is achieved by a reversal of the phase encoding gradient prior to each repetition that rephases this transverse magnetization. In this way, the coherence of the transverse magnetization is maintained, so that mainly signal from tissues with high water content and a long T2 is present in the image. They are often said to demonstrate an angiographic, myelographic or arthrographic effect as the blood, CSF and joint fluid are bright. As the TR is short, these sequences are mainly used for breath-holding or in a volume acquisition. The TR can be lengthened, however, to achieve multi-slice acquisitions demonstrating excellent contrast. This strategy is common in spinal and joint imaging.

Faster versions of this sequence are available enabling multiple-slice breath-hold, dynamic and real-time imaging. Scan times are reduced by a combination of partial RF pulses, partial Fourier acquisitions and centric k-space filling. Owing to the inherent lack of contrast in this sequence, magnetization preparation pulses are sometimes used that either null the signal from certain tissues, thereby increasing the CNR between them and the surrounding structures, or increase overall T2 contrast.

Balanced gradient echo (T2*)

Balanced GRE (BGRE) is a steady-state sequence that uses a very short TR for rapid acquisition times and large flip angles to increase SNR. This combination would normally result in saturation or T1 weighting.

Therefore, the phase of each excitation pulse is alternated so that transverse magnetization is not additive, thereby allowing for large flip angle/short TR combinations without saturation. The short TR values reduce the time for flow effects, and balanced gradients that use zero time-integrated areas in all three axes are also used to reduce flow artefact. This is a 'pure' steady-state sequence as signal is obtained from both the longitudinal and transverse steady states. These characteristics, along with ultrashort TR and TE, result in images that are weighted for the ratio of T2/T1. Spins with a high T2/T1 ratio (similar values) are bright; those with a low T2/T1 ratio (dissimilar values) are dark. The most common substances with a high T2/T1 ratio are blood, CSF and fat and muscle has a low T2/T1 ratio.

Incoherent (spoiled) gradient echo (T1/PD)

Incoherent (spoiled) GRE sequences also use a variable flip angle and gradient rephasing resulting in a GRE. They are commonly used in the steady state so that residual magnetization builds up in the transverse plane. However, these sequences spoil this magnetization with phase shifted RF pulses that do not allow the residual transverse magnetization to be received. T2* weighting does not, therefore, dominate image contrast to as great an extent as coherent GRE pulse sequences, and the images are mainly T1/PD weighted. Owing to the short TR, these sequences can be used for breath-holding, dynamic imaging, and in cine and volume acquisitions. As they are mainly T1/PD weighted, they are very effective in conjunction with contrast enhancement and to demonstrate anatomy.

As with coherent GRE, there is a faster version of this sequence enabling multiple-slice breath-hold, dynamic imaging after contrast and real-time imaging. Scan times are reduced by a combination of partial RF pulses, partial Fourier acquisitions and centric k-space filling. Owing to the inherent lack of contrast in this sequence, magnetization preparation pulses are sometimes used that either null the signal from certain tissues, thereby increasing the CNR between them and surrounding structures, or increase the overall T1 contrast.

Steady-state free precession (T2)

This is a steady-state sequence that uses medium flip angles and a short TR to maintain the steady state so that residual magnetization builds up in the transverse plane. These sequences generate contrast by sampling this transverse magnetization, which is mainly T2 weighted. The T2-weighted echo is repositioned by a gradient so that the TE is longer than the TR. Hence, true T2 weighting can be achieved in conjunction with a short TR. The actual TE selected at the console is two times the TR minus the time between the echo and the next RF pulse (usually called, very confusingly, the TE). Therefore, the shorter the TE selected at the console, the longer the actual TE and hence the greater the T2 weighting of the image.

Echo planar imaging

Echo planar imaging (EPI) sequences fill all of k-space in one repetition (called single shot) or multiple repetitions (called multi-shot) by using very long echo trains. Echoes are produced by alternating the frequency encoding gradient, and therefore, the echoes that fill k-space are GRE (if the echoes are SE resulting from repeated application of a 180° rephasing pulse, the sequence is called FSE). EPI sequences are given terms depending on what precedes the EPI filling of k-space. If the sequence begins with a 90°/180° combination, this is called spin echo EPI (SE-EPI). If the sequence begins with a 180°/90°/180° combination this is called IR-EPI. If the sequence begins with a single RF excitation pulse of any flip angle (i.e. there is no 180° RF rephasing pulse), it is called a GE-EPI.

If all of k-space is filled in one go, this is termed single-shot EPI (SS-EPI). SS-EPI produces images much more rapidly than SS-FSE as it uses a train of GRE rather than SE and can therefore fill k-space in a fraction of a second. However, SS-EPI sequences are very prone to artefacts such as chemical shift, distortion and blurring. These artefacts increase relative to the echo spacing and therefore the time of the echo train. For this reason, EPI sequences are often used in multi-shot mode where a quarter or a half of k-space is filled per TR period, thereby reducing the time of the echo train. This can also be minimized by implementing any, or all, of the following:

- increasing the FOV
- increasing the receive bandwidth
- reducing the frequency encoding matrix
- reducing the phase FOV.

EPI, BGRE and the fast versions of both coherent and incoherent (spoiled) GRE sequences currently represent the fastest acquisition modes in MRI. Real-time, dynamic and functional studies are possible using this technique. Some of these are discussed in Part 2 and are therefore summarized here.

- **Real-time imaging**: Very fast sequences, such as EPI, permit real-time imaging of moving structures. This is proving to be very useful in interventional procedures where a biopsy needle, laser probe or other instrument can be visualized in real time. Biopsies, thermal ablations of tumours, angioplasties, endoscopies and limited-field surgical operations are the most promising applications of this technique (see also *Dynamic imaging* below).
- **Dynamic imaging**: Dynamic imaging refers to the rapid acquisition of images either after contrast enhancement, or to observe movement. It may be utilized to visualize the motion of a joint (e.g. a knee), or a structure such as the cervical spine or pelvic floor. Single images may be obtained using GRE or EPI sequences in various degrees of motion. Alternatively, multiple slices can be acquired

either to cover more anatomy or to visualize the structure in many positions during data acquisition. When used with EPI, acquisitions in the order of 20 images per second are possible, and therefore, these techniques are termed real time. If used in conjunction with GRE sequences, however, data acquisition is much slower, and therefore, these techniques are termed quasi real time. Depending on the temporal resolution of the structure under examination, quasi-real-time techniques may not always provide an accurate representation of motion. Used in conjunction with contrast enhancement, dynamic imaging visualizes the speed of uptake of contrast, which may be necessary to determine the nature of a lesion. This technique can be used in many areas including the brain, pancreas, liver and prostate. One of the most important applications of dynamic imaging is in the breast where contrast enhancement is useful to characterize a lesion. Benign lesions take longer to enhance than malignant lesions, and scar tissue may not enhance at all. As gadolinium is given, a T1 sequence is required and, due to the dynamic nature of the series, the acquisition times must be as short as possible. Incoherent (spoiled) GRE or FSE sequences are therefore ideal for this type of examination. The entire breast, rather than only a few slices through a lesion, can be demonstrated (some systems now have ultra-fast volume acquisition available). This method is obviously important if multifocal disease is suspected. Tissue characterization by measuring uptake of contrast is also a useful technique in the prostate.

- **Functional imaging (fMRI)**: fMRI is a rapid technique that acquires images of the brain during activity or stimulus and at rest. The two sets of images are then subtracted demonstrating functional brain activity as a result of increased blood flow to the activated cortex. The mechanism responsible for contrast in fMRI is termed blood oxygenation level dependent (BOLD), which exploits the differences in magnetic susceptibility between oxy- and deoxyhaemoglobin. This results in increased signal intensity in activated areas of the cortex that have lower levels of deoxyhaemoglobin than inactivated areas. The high signal is then overlaid on to anatomical images. Functional MRI is useful to evaluate brain activity in a whole range of disorders including epilepsy, stroke and behavioural problems.
- **Diffusion-weighted imaging (DWI)**: DWI demonstrates areas with restricted diffusion of extracellular water such as infarcted tissue. In normal tissue, extracellular water diffuses randomly whereas in ischaemic tissue, cells swell and absorb water thereby reducing average diffusion. In DWI, the sequence can be sensitized to diffusion by applying equal gradients on each side of a 180° RF pulse. Hence, diffusion-weighted images are most effectively acquired using SE-type sequences such as SE or SE-EPI. These gradient pulses are designed to cancel out the phase shift of stationary spins whilst moving spins experience a phase shift. Therefore, signal

attenuation occurs in normal tissue with random motion, and high signal appears in tissues with restricted diffusion. The amount of attenuation depends on the amplitude of the gradients which is altered by selection of a b-value (expressed as s/mm^2). Gradient pulses can be applied along the X, Y and Z axes to determine the axis of restricted diffusion. The term isotropic diffusion is used to describe diffusion gradients applied in all three axes. DWI is mainly useful in the brain to differentiate salvageable and non-salvageable tissue after stroke. It is also useful in the liver, prostate, spine and bone marrow.

- **Perfusion imaging**: Perfusion imaging refers to the microscopic changes in perfusion when gadolinium first passes through the capillary bed. Mainly used in the brain to assess perfusion kinetics, the MR sequence is sensitized to the very transient changes in T2* as a bolus of contrast first passes through the capillary bed of the area under investigation. Therefore, GRE sequences are always used and typically, SS-GE-EPI is common. Images are acquired very rapidly before, during and after an injection of a small bolus of contrast in the ante-cubital fossa. Images are then post-processed, and perfusion graph and haemodynamic images are produced.

Magnetic resonance angiography

The principle of magnetic resonance angiography (MRA) is to acquire images where the signal returned from flowing nuclei is high, and the signal from stationary nuclei is low. In this way, contrast between vessels and background tissue is achieved. There are several techniques available to obtain this contrast. Black-blood imaging combines SE or FSE sequences with spatial pre-saturation pulses to produce images in which flowing vessels appear black. High signal seen in this type of sequence may indicate stenosis or occlusion of the vessel (see *Flow phenomena and artefacts*). Bright-blood imaging combines GRE sequences with GMN to produce images where flowing vessels are bright. A signal void seen in this type of sequence may indicate either a stenosis or occlusion of the vessel (see *Flow phenomena and artefacts*).

There are additional techniques designed especially for angiography. Both allow for data acquisition in either sequential (2D) or volume (3D) mode. Each has its own advantages and disadvantages, and therefore, each is used for different purposes. The two types of MRA are summarized below. These are TOF and phase contrast (PC).

- **Time of flight**: This usually uses an incoherent (spoiled) GRE sequence in conjunction with TR and flip angle combinations that saturate background tissue, but allow moving spins to enter the slice/volume fresh and therefore return a high signal. Spatial pre-saturation pulses placed between the origin of flow and the

FOV saturate moving spins entering the FOV, thereby improving visualization of either arterial or venous circulation. These pulses are often concatenated in 2D acquisitions so that the spatial pre-saturation pulse is applied around each slice in the stack, as opposed to the whole set of slices. This strategy improves the efficiency of pre-saturation. Unwanted signal is sometimes generated by tissues that have very short T1 recovery times (such as fat), as they recover some of their longitudinal magnetization between each RF pulse and therefore produce signal. Spectral/chemical pre-saturation pulses, imaging with a TE that collects the echo when fat and water are out of phase with each other, and utilizing magnetization transfer (MT) contrast, commonly reduce this problem. In volume imaging, flowing spins often become saturated by the RF pulses, thereby reducing their signal. This problem can be minimized by the implementation of ramped flip angles, which initially use small flip angles, and then gradually increase them incrementally during data acquisition. In this way, the saturation of flowing nuclei is delayed, therefore maintaining vessel signal. In 2D acquisitions, however, TOF-MRA provides good vessel contrast as nuclei are not usually present in the slice long enough to become saturated. Common applications are to demonstrate venous and arterial flow in the head, neck and peripheral vessels.

- **Phase contrast**: This usually uses a coherent GRE sequence acquired both with, and without, a bipolar gradient pulse. The phase acquired by flowing spins as a result of the application of the bipolar gradient is used to produce images based on subtraction. Sensitivity to flow velocity is controlled by a parameter called velocity encoding or VENC, which can be applied in one or all three orthogonal planes. PC-MRA provides excellent background suppression and avoids intra-slice/slab flow saturation. However, the scan times associated with PC-MRA are often very long as the scan time is dependent not only on the TR, matrix size and NEX/NSA, but also on the number of flow encoded axes. Common applications are to demonstrate arterial flow in the head and major vessels.
- **Contrast-enhanced MRA (CE-MRA)**: This is a technique that involves injecting a small amount of gadolinium or a similar agent into the ante-cubital fossa and scanning an area of the patient to visualize the contrast-enhanced vessels. Usually, the timing is such that the arterial supply is seen, but scans may be delayed slightly to visualize venous structures. In arterial imaging, the sequences used must be rapid ones to enable accurate visualization in the arterial phase. Typically, T1-weighted GRE sequences are used as they provide the optimum combination of speed, image quality and contrast. If the ROI is in the chest and abdomen, the patient is usually required to hold his or her breath during acquisition. CE-MRA has an advantage over conventional MRA techniques in that vessel visualization is not as susceptible to flow and directional effects and is thought to be more accu-

rate. However, it does involve an injection of contrast media. Renal, carotid and peripheral arteries are commonly examined with this technique.

- **MT contrast:** MT is a technique that is commonly used to suppress background tissue, thereby enhancing the conspicuity of vessels and certain disease processes. Its function is based on the relaxation differences between water protons in different environments. Water protons broadly fall into two categories: those that are free and those that are bound to surrounding immobile macromolecules. MT involves the exchange of magnetization between the free and bound water protons. Pre-saturation off-resonant pulses applied just before the RF excitation pulse saturate the bound protons and promote an exchange of some of this saturated magnetization on to the free protons. This pulse is designed to excite hydrogen protons in macromolecules such as proteins. These relatively large molecules have a very short T2 and usually do not contribute to the MR image. With the MT pulse, however, some of these spins transfer their magnetization to the more mobile water spins. This

Table 3.2 Summary of the contrast characteristics of pathology and normal anatomy

	T1	T2
High signal	Fat Haemangioma Intra-osseous lipoma Radiation change Degenerative fatty deposition Methaemoglobin Cysts with proteinaceous fluid Paramagnetic contrast agents Slow-flowing blood	CSF Synovial fluid Haemangioma Infection Inflammation Oedema Some tumours Haemorrhage Slow-flowing blood Cysts
Low signal	Cortical bone AVN Infarction Infection Tumours Sclerosis Cysts Calcification	Cortical bone Bone islands Deoxyhaemoglobin Haemosiderin Calcification T2 paramagnetic agents
	T1 and T2	
No signal	Air Fast-flowing blood Ligaments Tendons Cortical bone Scar tissue Calcification	

results in a reduced signal return from the free protons. For example, grey and white matter loses 30–40% of its signal when an MT pulse sequence is utilized. The common uses of MT are to increase the conspicuity of certain disease processes such as multiple sclerosis, haemorrhage and AIDS, and to improve vessel contrast in TOF-MRA images by suppressing background tissue.

Conclusion

The choice of pulse sequence is usually the first decision made by either the radiologist or practitioner as it determines the weighting and contrast characteristics of the image. Table 3.2 summarizes the contrast characteristics of pathology and normal anatomy. Careful consideration of the image quality and the required scan time parameters is also necessary to achieve the optimum examination. The flow and artefact phenomena common to the area under examination must also be taken into account, as some compensation techniques may compromise the pulse sequence chosen. These phenomena are discussed in Chapter 4.

4

Flow phenomena and artefacts

Flow phenomena

Introduction

This section refers mainly to the *Artefact problems* subheading discussed under the *Image optimization* heading considered for each examination in Part 2. The most common flow phenomena are summarized in Table 4.1. Only a brief overview is provided here. For a more detailed explanation, please refer to Chapter 6 of *MRI in Practice* or an equivalent text.

The most common types of flow phenomena are:

- TOF (not to be confused with TOF-MRA)
- entry slice phenomenon
- intra-voxel dephasing.

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Table 4.1 Artefacts and their remedies

Artefact	Remedy	Penalty of remedy
Truncation	Increase phase encodings	Increases scan time
	Use more than one NEX/NSA	Increases scan time
Phase mismapping	Respiratory compensation	May lose slices
	Gating	TR variable
	Pre-saturation	May lose slices
	GMN	Increases minimum TE
	Immobilize patient	None
	Use antispasmodic agent	Costly, invasive
	Sedation	Invasive, requires monitoring
Chemical shift	Increase bandwidth	Decreases TE
	Reduce FOV	Reduces SNR
	Use chemical saturation	Reduces SNR
Chemical misregistration	Set TE at multiple of periodicity	None
Aliasing	Oversampling (frequency)	None
	Oversampling (phase)	None or increase in scan time depending on system
	Enlarge FOV	Reduces resolution
Zipper	Call engineer	Irate engineer!
Magnetic susceptibility	Use SE	Not flow sensitive
	Remove metal where possible	None
Shading	Load coil properly	None
Crosstalk	None	None
Cross excitation	Interleaving of slice acquisition	Doubles the scan time
	Squaring off of RF pulses	Reduces SNR

Time of flight

TOF phenomenon occurs because nuclei that move through the slice may receive only one of the RF pulses applied. In GRE sequences, the gradient rephasing is not slice selective, so nuclei produce signal as long as they have been excited at some point and are rephased by the gradient. In a SE sequence, a nucleus may receive the excitation pulse but then exit the slice before the 180° rephasing pulse can be applied. Conversely, it may not be present in the slice when the excitation pulse is applied, and then enter the slice to receive only the 180° pulse. Under these circumstances, the nucleus does not produce a signal. In SE sequences, TOF effects cause either a signal loss or signal enhancement from flowing nuclei, and they are compensated for by using pre-saturation pulses placed between the origin of the flow and the FOV.

Entry slice phenomenon

This phenomenon depends on the excitation history of nuclei flowing within a vessel, and is largely controlled by the direction of flow relative to slice excitation. Nuclei that flow in the same direction as slice excitation receive several RF excitation pulses and quickly become saturated. Nuclei that flow in the opposite direction to the slice excitation do not experience repeated RF excitation pulses, as they are always entering the selected slice 'fresh'. They are, therefore, not saturated as quickly as nuclei flowing in the same direction as slice excitation. These phenomena result in a difference in signal between arteries and veins where flow is perpendicular to the slice plane, and is most prominent in the first and last slices of the imaging stack. Entry slice phenomenon is compensated for by using pre-saturation pulses placed between the origin of the flow and the FOV.

Intra-voxel dephasing

This is caused by the presence of gradients that either accelerate or decelerate flowing nuclei as they move from areas of differing field strength along the gradient. As a result of this acceleration or deceleration, the flowing nuclei either gain or lose phase relative to their stationary counterparts. This phase difference between stationary and flowing nuclei in the same voxel causes dephasing and a signal loss. Intra-voxel dephasing is compensated for by using GMN.

Flow artefact remedies

The two main remedies of flow-related artefacts are:

- spatial pre-saturation pulses
- GMN

Spatial pre-saturation: nullifies signal from nuclei that produce unwanted signal or artefact by applying a 90° RF pulse to selected tissue before the pulse sequence begins. Therefore, the magnetic moments of these nuclei are inverted to 180° by the excitation pulse and return no signal.

Spatial pre-saturation:

- produces low signal from flowing nuclei;
- reduces motion and aliasing if bands are placed over signal-producing anatomy;
- increases the specific absorption rate (SAR) and may reduce the slice number available per TR;
- mainly reduces TOF and entry slice phenomena.

Gradient moment nulling: utilizes extra gradients to rephase the magnetic moments of flowing nuclei so that they have a similar phase to their stationary counterparts.

GMN:

- produces high signal from flowing nuclei;
- increases the minimum TE and may reduce the slice number available;
- mainly reduces intra-voxel dephasing.

Both GMN and spatial pre-saturation decrease flow artefact seen on an image but are also valuable in reducing phase mismapping and motion artefact.

Artefacts

Introduction

This section also refers mainly to the *Artefact problems* subheading discussed under the *Image optimization* heading considered for each examination in Part 2. The most common artefacts are summarized in Table 4.1. Only a brief overview is provided here. For a more detailed explanation, please refer to Chapter 7 of *MRI in Practice* or an equivalent text.

The most common types of artefact seen in MR images are:

- phase mismapping (motion)
- aliasing (wrap)
- chemical shift
- chemical misregistration
- truncation
- magnetic susceptibility

Phase mismapping

Phase mismapping or ghosting is caused by anatomy moving between each application of the phase encoding gradient and by motion along the phase encoding gradient during the acquisition of data. Pulsatile motion of vessels, movement of the chest wall during respiration and cardiac motion are the most common sources of this artefact. Involuntary movement such as cardiac motion also causes phase mismapping. Tips to reduce voluntary motion are discussed under *Patient care and safety*.

Phase mismapping is reduced by one or more of the following:

- swapping the phase axis so that the artefact does not interfere with the area under examination (only moves the artefact);
- placement of spatial pre-saturation pulses between the origin of the artefact and the FOV;
- using RC (see *Gating and respiratory compensation techniques*);
- using echocardiogram (ECG) gating or peripheral (Pe) gating (see *Gating and respiratory compensation techniques*);
- selecting GMN.

Aliasing

Aliasing occurs when anatomy that lies within the boundaries of the receiver coil (and therefore produces signal) exists outside the FOV. If the data from the signal received are under-sampled by the system, there is a

duplication of frequency and phase values so that anatomy that exists outside the FOV is allocated a pixel position within the FOV. This anatomy is therefore 'wrapped' into the image.

Aliasing can occur along both the frequency encoding axis (frequency wrap) and the phase encoding axis (phase wrap). Frequency wrap is largely eliminated with the use of digital filters that filter out signal originating outside the FOV. Phase wrap is reduced by:

- increasing the FOV to the boundaries of the coil;
- oversampling in the phase direction;
- placing spatial pre-saturation pulses over signal-producing anatomy.

Chemical shift

Chemical shift artefact is caused by the dissimilar chemical environments of fat and water. This results in a precessional frequency difference between the magnetic moments of fat and water and is called chemical shift. Its magnitude significantly increases at higher field strengths. Chemical shift artefact causes a displacement of signal between fat and water along the frequency axis. It is reduced by:

- scanning with a low field-strength magnet;
- removing either the fat or water signal by the use of tissue suppression techniques (see Chapter 2);
- broadening the receive bandwidth;
- reducing the size of the FOV.

Chemical misregistration

Chemical misregistration is also caused by the difference in precessional frequency between fat and water. However, this occurs because as fat and water are precessing at different frequencies, they are in phase with each other at certain times and out of phase at others. When the signals from both fat and water are out of phase, they cancel each other out so that signal loss results. This artefact mainly occurs along the phase axis and causes a dark ring around structures that contain both fat and water. It is most prevalent in GRE sequences, and it can be used positively to reduce the signal from fat (Dixon technique – see Tissue Suppression, Chapter 2). To reduce chemical misregistration:

- Use SE or FSE pulse sequences.
- Use a TE that matches the periodicity of fat and water so that the echo is generated when fat and water are in phase. The periodicity depends on the field strength (approximately 4.2 ms at 1.5 T and 7 ms at 0.5 T).

Truncation

This is caused by under-sampling of data at the interface of high and low signal. It occurs along the phase axis and produces a dark band running through a high signal area. It is most commonly seen in the cervical cord, where it is specifically known as Gibbs artefact. Truncation is mainly reduced by increasing the number of phase encoding steps.

Magnetic susceptibility

Magnetic susceptibility artefact occurs because all tissues magnetize to a different degree depending on their magnetic characteristics. This produces a difference in their individual precessional frequencies and phase. The phase discrepancy causes dephasing at the boundaries of structures with a very different magnetic susceptibility, and signal loss results. It is commonly seen on GRE sequences when the patient has a metal prosthesis in situ but is also visualized at the interface of the petrous bone and the brain on coronal incoherent (spoiled) GRE images. Magnetic susceptibility can be used advantageously when investigating haemorrhage or blood products, as the presence of this artefact suggests that bleeding has recently occurred. Magnetic susceptibility is reduced by:

- using SE or FSE pulse sequences;
- removing all metal items from the patient before the examination.

Conclusion

The main artefacts encountered in MRI are described here. In addition, phase artefact caused by pulsation of great vessels, CSF flow and cardiac and respiratory motion are compensated for by using appropriate software and these are discussed in the next section. Table 4.1 summarizes artefacts and how they may be remedied.

5

Gating and respiratory compensation techniques

Introduction

This section refers to the mechanisms and correct placement of gating leads and respiratory bellows. The basic concepts of these techniques are summarized in the following. Only a brief overview is provided here. For a more detailed explanation, please refer to Chapter 8 of *MRI in Practice* or an equivalent text.

Cardiac gating (ECG gating)

Cardiac gating uses the electrical signal detected by leads placed on to the patient's chest to trigger each RF excitation pulse. In this way, each image is always acquired at the same phase of the cardiac cycle, so that phase mismapping from cardiac motion is reduced. There are several factors to take into account when using cardiac gating.

Lead placement

There are usually four leads that are colour-coded for easy use. Some systems may only use three leads. In addition, not all systems use the same colour coding, but the principle of their placement is the same. Leads can be placed either anteriorly on the chest or posteriorly on the patient's back. Anterior placement is usually simpler as the landmarks are easier to find. In addition, if the leads are placed posteriorly, the patient lies on them during the examination, which may be uncomfortable. The anterior lead placement is described here, but if the trace on the ECG monitor is poor, the leads can be placed posteriorly in a mirror image to the anterior leads. This may improve the trace. Lay the patient supine on the examination couch. The patient wears a front opening gown for easy

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access. The lead stickers are then firmly attached to the patient's skin. The leads are usually colour-coded thus:

- black (ground or earth)
- white
- red (live)
- green (ground or earth).

The white and the red leads are placed across the heart, as the voltage difference between the two produces the ECG trace. The green and black leads (that act as grounds) are positioned as close as possible to each other, but not touching, in the centre of the chest. Some systems may not have colour coding, but directions on lead placement are usually given by the manufacturer. Leads can be placed in a variety of ways as long as the above criteria are met. Described below is the simplest method of lead attachment (Figure 5.1):

- **Black lead** centre of chest
- **White lead** in the midline on the superior aspect of the sternum
- **Red lead** one intercostal space directly inferior to the left nipple
- **Green lead** above black lead but not touching it

The black lead may be omitted if it is not available on the system. Once the leads are attached and plugged into the system, check that the ECG trace is satisfactory. Traces vary according to rate, rhythm and cardiac output. These in turn depend on the activity of the heart, which is often altered by certain disease processes. Arrhythmias and poor cardiac output (which may be why the patient is being examined) are common problems. The signs of a good trace are:

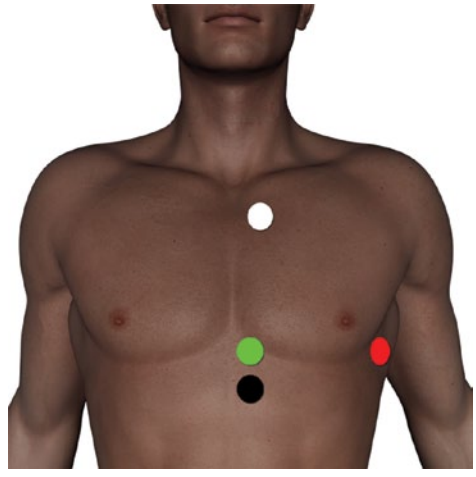

Figure 5.1 The correct placement of gating leads.

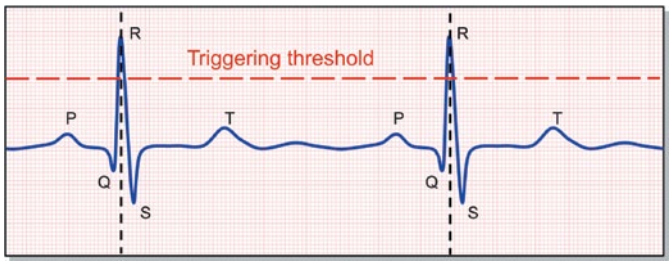

Figure 5.2 A normal ECG Trace and the correct placement of the triggering threshold relative to the R wave.

- a regular rate – the PQRST complexes are spaced evenly apart;
- the R wave is significantly larger than the T wave;
- the PQRST complex has good amplitude (Figure 5.2).

If the trace is satisfactory, the patient is placed within the magnet bore. This action frequently alters the trace, and often does so to such an extent that the trace is no longer acceptable. The commonest problem is an elevation of the T wave so that the system cannot distinguish it from the R wave. If this occurs, or if the original trace is unsatisfactory, several measures can be taken.

How to improve the trace

- Always ensure that the electrodes are firmly attached to the chest wall. In male patients, shave any chest hair in the region of the electrodes and clean the skin with alcohol. This removes grease that may prevent proper attachment. After the skin is dry, the electrodes are attached.
- Make sure that the leads are firmly attached to the stickers in the correct order.
- The leads may be swapped around or placed posteriorly to improve the trace. Initially, swap the black and the white leads or the red and the green leads. If this fails to improve the trace, try any other variation of lead placement.
- Place the patient inside the magnet feet first. Patients are usually positioned head first into the magnet for examinations of the chest; however, placing them feet first is often beneficial, especially if the problem is an elevated T wave.
- Movement of the cable leads causes irregularities of the trace. Ensure that they are immobilized (see *Cable safety*) and that the patient does not touch them during the examination. In addition, coughing or sneezing can interrupt the trace, so ask the patient to try not to move during the acquisition of data.
- Change to peripheral gating or pseudo-gating (dispensing with gating and setting a TR that is equal to the RR interval).

If after all these measures are taken the trace is still poor, the problem could be a faulty monitor or software problem. Gating is often unreliable and there are occasions when the operator has to make do with the trace displayed. In our experience, awful traces can lead to excellent images and vice versa.

Vector cardiac triggering methods have demonstrated potential for depicting the cardiac cycle more accurately than current methods. In this type of gating, a trigger is produced that depends on heart motion, and thus, many of the deficiencies associated with the traditional ECG gating are now overcome even in problematic patient suffering from cardiac arrhythmias.

Cable safety

The cables that connect the leads to the system are conductors and are therefore capable of carrying considerable current. During the examination, the majority of the cables lie within the RF field, and therefore, high currents are induced within them. This current potentially results in the cables storing and transmitting heat to the patient. Although every cable is heavily insulated, a build-up of heat is possible, and this can cause minor burns if the cables are in direct contact with the skin. In addition, if the insulation is damaged, high currents could be transmitted to the patient. To avoid this:

- Check the cable insulation for damage at regular intervals, not just when gating is required. If they are frayed or split, do not, under any circumstances, use them.
- When positioning the cables, avoid looping and crossover as their point of contact induces additional heat.
- Ensure that the cables do not touch the bore when the patient is inside the magnet. Run the cables down the middle of the patient. Looping them over the patient's foot prevents them from slipping to the side during the examination.
- Place foam pads between the cables and the patient's chest, and ensure that there is a layer of gown or blanket between the cables and the patient's skin.
- Tape the cables and pads to the side of the table. This ensures that they cannot slip out of place during the examination. In addition, this prevents movement of the cables that can interfere with the trace.

Peripheral gating (Pe gating)

Peripheral gating uses a photo sensor attached to either a finger or toe to detect the increase in volume in the capillary bed during systole. This affects the amount of light returned to the sensor and a waveform is produced. The waveform does not have the characteristics of the ECG trace, but the

peaks of the waves approximately correspond to the R wave (about 250 ms after the R wave). This waveform is displayed on the monitor. A good trace has:

- equally spaced peaks
- significant amplitude.

If the trace is unsatisfactory:

- Ensure that the photo sensor is firmly attached with the light source adjacent to the skin.
- Ensure the finger or toe is warm and well perfused. Placing it in warm water or rubbing it is often beneficial.
- Swap the sensor to the left hand as the left arm receives arterial blood directly from the aorta (rather than through the innominate artery) and sometimes has a larger pulse.

Gating parameters

For **T1 weighting** and ECG/Pe gating	use 1 R to R interval.
For **PD/T2 weighting** and ECG/Pe gating	use 2 or 3 R to R intervals.

Note: Other parameters used for gating depend on the system. However, the following usually suffice:

Trigger window	15% of the R to R interval.
Delay after trigger	minimum permissible to allow maximum slice number.

Slices are usually acquired evenly across the available imaging time, although cardiac motion is sometimes reduced if slice acquisition is delayed until diastole.

Cine imaging

Cine, balanced GRE and coherent GRE are beneficial to visualize heart function, blood flow and heart wall motion. For example, the restriction of flow through a coarctation or poorly functioning valve in the heart can be clearly visualized using cine. Good contrast between flowing blood and surrounding lung or cardiac tissue is important. Therefore, the implementation of a steady-state sequence that enhances the signal intensity of blood is necessary. In addition, the application of GMN in coherent GRE and the balanced gradients in balanced GRE not only reduces flow artefact, but also increases the signal from flowing blood thereby improving CNR.

The efficiency of cine is mainly governed by the correct selection of the number of cardiac phases acquired for each slice during the TR. Data acquisition (data points) should coincide as closely as possible to these phases. If the system cannot match each phase with a data point, cine imaging is less efficient.

Unfortunately, cine images are often plagued with artefact. If compatible, RC effectively reduces respiratory ghosting. Alternatively, breath-holding single-slice coherent GRE images eliminate respiratory motion. Susceptibility and misregistration artefacts are common due to gradient rephasing in GRE sequences. Reducing the TE decreases susceptibility problems, and selecting a TE when fat and water are in phase minimizes misregistration.

Respiratory compensation (RC)

There are many forms of RC including:

- Breath-holding (patient holds their breath during the acquisition)
- Navigators (a ROI is placed over the diaphragm and the system throws out data that coincide to maximum chest wall motion)
- Respiratory triggering (acquisition of data is limited to minimum chest wall motion)
- RC (phase encodings and therefore k-space lines filled are reordered during the acquisition to minimize artefact)

The latter two techniques are achieved by placing expandable air-filled bellows around the patient's chest (Figure 5.3). The movement of air back and forth along the bellows during inspiration and expiration is converted to a waveform by a transducer. In RC, the system then orders the phase encoding gradients so that the steep slopes occur when maximum movement of the chest wall occurs and reserves the shallow gradient

Figure 5.3 Correct positioning of the respiratory bellows to 'catch' both thoracic and abdominal respiration.

slopes for minimum chest wall motion. In this way, most of the signal is acquired when the chest wall is relatively still, and therefore, phase ghosting is reduced. Respiratory triggering is sometimes not as efficient as RC at reducing artefact but does have the advantage of being compatible with phase reordering sequences such as FSE. The success of respiratory bellows depends on the following:

- Ensure that there is no vacuum within the bellows as this inhibits the back and forth movement of air during respiration. This may entail disconnecting the bellows in between examinations and ensuring that they are kept on the ground until they are reattached. This guarantees that no air pockets collect in the bellows or connecting tubing. Some systems, however, require that you do not disconnect the bellows. Please refer to the manufacturer's specifications.
- Place the bellows so that the corrugating portion lies over the anterior chest wall.
- Place the bellows diagonally across the chest and upper abdomen. This ensures that the bellows 'catch' both thoracic and abdominal movements during respiration (Figure 5.2).
- Attach the bellows firmly. The bellows must be tight enough so that movement of the corrugated portion can be seen clearly during quiet respiration. However, if the bellows are too tight, the patient may become uncomfortable.
- Ensure that the bellows are firmly plugged into the transducer.

If the images show large amounts of respiratory mismapping or the system informs you that compensation is not working adequately:

- Check that the bellows have not become loose or unattached.
- Ask the patient to breathe quietly. Uneven breaths can confuse the system.
- If the patient is small or a child, the bellows may not fit snugly, and therefore, their action can be compromised. Foam pads placed between the bellows and the patient are usually beneficial.

Conclusion

Gating and RC are commonly utilized to examine the chest and abdomen, although gating also has uses in imaging the brain and spinal cord and in cine. The correct use of these techniques can have a profound influence on image quality. If you are unfamiliar with the use of gating, it is often worth practising its implementation on volunteers so that all staff are prepared for its use on sick patients.

6

Patient care and safety

Introduction

This section refers to the *Patient considerations* heading considered for each examination in Part 2. Only a brief overview is provided here. For a more detailed explanation, please refer to Chapter 10 of *MRI in Practice* or an equivalent text.

Any patient motion, whether it is due to fear or discomfort, is likely to degrade the image whatever its SNR and resolution characteristics. When a patient steps into an MRI facility, he or she becomes the responsibility of the unit personnel. This responsibility extends from the patient's magnetic safety and medical condition, to providing a relaxing environment and a smoothly running facility. It is essential for legal and ethical reasons to ensure that all staff, including radiologists, radiographers, technologists, nurses and clerical and ancillary personnel, are competent and are aware of their role in providing optimum patient care.

Patient safety

The main aspect of patient safety in any MRI facility is magnetic safety. It is essential that all patients, relatives and other medical or non-medical personnel are prevented from entering the magnetic field until they have been properly screened. Physical barriers, such as doors and large warning signs, are common ways of achieving this. Clerical personnel (who are usually situated at the entrance to the unit) should be aware of who is present in the facility and whether they have been checked for magnetic safety. Thorough screening of each patient and anyone who is to enter the field is extremely important. Failure to do so may result in injury or even death. All centres should have a proper screening policy which includes checking for:

- pacemakers
- aneurysm clips

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- intra-ocular foreign bodies
- metal devices or prostheses
- cochlear implants
- spinal implants and stimulators
- possibility of early pregnancy
- removal of all jewellery, credit cards, money, watches, etc.

Most facilities provide a screening form that patients, relatives and other persons fill in before entering the magnetic field. This ensures that all important questions have been addressed, and provides a record that screening has taken place. This may be very important if an accident subsequently occurs. Any additional items, such as unremovable jewellery and splints, are thoroughly checked for safety before the patient and their relatives enter the magnetic field. It may be necessary to insulate the item by placing bandages between it and the patient's skin. If the patient or relative has any unusual prosthesis or implant such as a heart valve, its magnetic safety must be established **before** they are taken into the magnetic field.

The safety of intra-cranial aneurysm clips has been the subject of debate for some years. Ferromagnetic clips must not be scanned. Patients having ferromagnetic clips must not cross the 5 gauss threshold as the clips may be subjected to torque effects and may cause damage to the associated blood vessel. Non-ferrous metals are not deflected by the magnetic field of the scanner; however, utmost caution must be observed when scanning any patients with non-ferrous aneurysm clips as there can be fatal consequences if the type of clip is incorrectly identified.

Cardiac pacemakers have long been considered a contraindication for MRI procedures although some manufacturers are now producing devices that may be safe to scan under certain strictly enforced conditions. Non-compatible pacemakers have been responsible for a number of MRI fatalities over the years due to the magnetic field of the scanner compromising the function of the device. Research has also shown torque effects and heating effects in non-compatible devices. For safety's sake, it is prudent to assume that a pacemaker is non-compatible until proven otherwise, and even if shown to be a conditionally compatible model, advice should always be sought from the manufacturer before attempting any MRI scanning procedure to ensure that the correct conditions are met for a safe outcome.

It is usually advisable to ask the patient to change into a gown for their MRI procedure, as this avoids the problem of ferromagnetic items inadvertently entering the magnetic field inside pockets. Ferromagnetic items are strongly attracted to the external magnetic field of the scanner, and there have been many reported injuries and at least one fatality caused by projectiles. Clerical, nursing or radiographic staff usually perform the magnetic screening procedure. However, it is important to remember that whoever screens the patient, ultimate responsibility for projectile safety falls on the person who takes the patient over the 5 gauss threshold. From a historical viewpoint, it is interesting to note that in some unshielded units, the magnetic field sometimes extended beyond the confines of the examination room.

There are many other aspects to patient safety within the unit. Care must be taken when transferring patients either on to trolleys or into the examination room. This is especially important if the patient is physically disabled, traumatized or in pain. Non-slip flooring and trolleys with an adjustable height and lockable brakes not only ensure that patients are transported in safety but also prevent injury to unit personnel. In addition, any equipment that comes into contact with the patient during the examination must be carefully checked on a regular basis. This includes gating cables (see *Gating and respiratory compensation techniques*), monitoring equipment and other devices such as coil holders.

The safety of coils and cables is also important (for more information on different types of coils see *Equipment* in the section *How to Use this Book*), as cables have occasionally been known to heat up during the MRI procedure. Ensure that there is adequate insulation between the coils and their cables and the patient's skin. Small foam pads or the patient's gown usually suffice. In addition, if patients have metallic implanted devices in situ, they should be instructed to operate the call button should they experience any sensations of warmth or discomfort during the examination. Another potential safety concern is the loud acoustic noise generated by the gradient coils during the scan procedure. Noise levels have been measured to be in excess of 120 dB during some procedures. Earplug or headphone protection is mandatory at this level of noise to reduce the risk of permanent hearing damage to the patient.

Lastly, when rapidly switched gradient magnetic fields are used in a pulse sequence, some patients have reported mild cutaneous sensations described as a tingling feeling, especially in areas where there is bone close to the skin surface. Some researchers have also identified the generation of *magnetophosphenes* – a perceived visual disturbance resembling the 'flashing light' effect experienced by migraine sufferers. It is thought that both of these effects are due to electromagnetically induced current flow in the tissues (or retina) of the patient. Patients also experience similar effects, including nausea, vertigo and metallic taste sensations when moving in relation to the static field, particularly at flux densities of 3 T or above. Reducing these effects is not usually practicable, but it is important to note that they are transitory and unlikely to cause permanent harm. Of more concern, electromagnetically induced currents have also been described as being responsible for tissue burns where the anatomy forms a closed loop. Patients should therefore be instructed to place their arms by their sides and to not cross their ankles during the scan procedure to prevent the anatomy forming a loop shape. It is advisable to warn the patient that any of the above sensations may occur, especially if rapid sequences are utilized. It is also necessary to provide the patient with a call button during the examination to alert the scan operator in the event that they should experience any ill effects.

For further information about patient safety in MRI, there is a very useful online resource from Dr. Frank Shellock at http://www.mrisafety.com. In this free web portal, Dr. Shellock presents his own research and also summarizes the research of others in a very user-friendly way.

Patient counselling

The emotional well-being of a patient is just as important as their physical condition. Many patients are not only anxious about the examination, but are also aware that the outcome of the study may affect their subsequent treatment and/or prognosis. Ensuring that the patient is calm and relaxed during the procedure is the responsibility of all unit personnel. The clerical staff are usually the first people to come into contact with the patient, and it is therefore important that they are welcoming and understanding of the patient's emotional needs. A pleasant reception environment further enhances a patient's well-being. In addition, a smooth-running department, where patients are scanned at their designated appointment time, nearly always reassures the patient. If the schedule is running late, or an emergency is fitted in, ensure that the patients are aware of the circumstances and given an approximate time for their examination.

Properly informed patients are usually more comfortable with the examination than those who are fearful of the unknown. An information leaflet sent with the appointment time is a very effective way of preparing a patient for their visit to the unit. Once they have arrived, a careful explanation of the procedure including positioning, gradient noise, contrast injections and the approximate length of the examination is necessary. If equipment such as gating leads or respiratory bellows is required, the explanation is expanded to include the reasons for the use of such accessories, and how they may affect the patient. Any special requirements of the patient, such as breath-holding, opening the mouth or fixing the eyes, must be thoroughly explained before the examination. If the patient does not understand these requirements, the whole examination may be void. It is probably preferable for the radiographer/technologist to provide this explanation, as it not only establishes a relationship with the patient, but also alerts the radiographer to specific anxieties.

When the patient is transferred into the examination room, the sight of the magnet bore and unfamiliar surroundings commonly increase their anxiety. The technologist should be prepared to repeat the explanation of the procedure if necessary, and address any concerns that the patient might have.

Claustrophobia is a common problem in MRI examinations. The enclosing nature of the bore, and equipment such as the head coil, invariably exaggerates any claustrophobic or nervous tendencies. Listed below are a few tips on avoiding claustrophobia:

- If the coil has a mirror, use it and make sure that it is adjusted so that the patient can see out of the magnet.
- If possible, examine the patient prone, as this often means that the patient can see out of the magnet. This strategy is mainly beneficial when imaging the pelvis, abdomen, chest and areas of the upper and lower limbs, such as the femora and wrists.

- Remove the pillow under the patient's head as this increases the distance from the patient's face to the roof of the bore of the magnet.
- Tell the patient to close their eyes or place a piece of tissue paper over their face. Some patients dislike this, but others are comforted by the knowledge that if they open their eyes by accident, they will be unable to see the bore of the magnet.
- Use the bore light and fan as they increase the brightness and air circulation.
- Explain that the bore is open at both ends. These few words are often all that is needed to reassure a patient.
- Tell the patient that they can come out of the magnet at any time and that they may refuse the examination without disruption to the facility. This makes the patient feel that they are in control.
- Encourage a friend or relative to accompany the patient during the examination.
- Keep the patient informed over the system intercom of the length of the sequences and the progress of the examination.
- Remember to provide the patient with an alarm bell that he or she can press to alert the radiographer/technologist during the study.
- If these measures fail, a successful examination is usually possible after sedation.

Using the system intercom, the radiographer/technologist updates the patient during the study on the length of each sequence and the necessity of keeping still. It is extremely reassuring for the patient to hear a familiar voice and to be kept informed on how the examination is progressing. This is also an opportunity to check on the well-being of the patient. There are several medical conditions that may affect how the patient is handled in the unit. Examples of these are blindness, deafness, epilepsy, breathlessness and physical or mental disability. The imaging technique may have to be adapted accordingly. These, and other specific conditions, are described in more detail in Part 2. Some coils are fitted with mirrors to enable the patient to see out of the magnet bore, and it is worth remembering that they may also be able to see out of the examination room window and observe the technical staff at work. Therefore, all unit personnel should be aware that the patient may be watching their every move and facial expression!

Patient immobilization

Careful immobilization of the patient is always necessary to ensure an optimum study. Immobilization is especially important during lengthy examinations and when the area under investigation is very small and optimum spatial resolution is required. The key to good immobilization is correct positioning, and making the patient as comfortable as possible. Most positions assumed by the patient during an MRI study are in natural

relaxed poses, that is, supine with the arms at the side. However, examinations of the upper limb and breast often involve placing the patient prone with their arms above their head. In addition, some medical conditions may preclude the use of standard positioning. Severe pain and breathlessness are common reasons for modifying the patient's position. It is important to remember, however, that even the most comfortable positions usually become uncomfortable if the patient has to maintain them for long periods of time.

Once the patient is placed correctly on to the examination couch and the coils have been positioned, immobilization is then required. All manufacturers provide foam pads of various shapes and sizes that are used to maintain a certain position. Many are moulded for use with a certain coil. Once immobilized, it is important to ensure that the patient is relaxed as, if effort is required to maintain the position, the likelihood of patient motion is increased. Unless the patient is in pain, it is almost impossible to over-immobilize. It is obviously necessary, however, to ensure that the patient is comfortable with the amount of immobilization used. Other accessories such as sticky tape are beneficial for immobilization purposes of both the patient and coils. Compression bands placed across the abdomen and pelvis are very effective at reducing bowel motion.

Other pads are useful to increase patient comfort, for example, a small pad elevating the patient's knees during the examination reduces back pain.

Patient after care

Once the examination is over, remove all immobilization devices, coils, straps and foam pads and carefully transfer the patient back into the waiting area. Patients are often very disorientated after an MRI study. Providing patients with a drink before they leave the unit often calms them and allows the unit staff to assess their medical and emotional condition. If the patient has received sedation, it is essential that they have fully recovered before they leave the unit. Lastly, patients are usually grateful if they are informed when to see their doctor about the results of the examination.

Conclusion

Unless the patient is very relaxed, almost any MRI examination is an ordeal. Therefore, the importance of patient safety and care cannot be overemphasized. Ensuring optimum safety and counselling standards is as important as correct parameter selection. It is often difficult for medical staff to appreciate patient anxieties. The magnetic environment is second nature to unit personnel, but it is a totally new experience for most patients. Always put yourself in the patient's shoes, and volunteer to be scanned as often as possible, as this gives the best insight into the patient's experience.

7

Contrast agents

Introduction

Contrast enhancement is extremely valuable in many disease processes including tumours, inflammation and infection. Although these pathologies contain a high water content and are often visualized in T2-weighted images, sometimes, there is insufficient contrast between the lesion and surrounding tissue. In addition, T1-weighted images demonstrate a higher SNR and are therefore advantageous, but water and pathology are commonly isointense in these sequences. Therefore, it is sometimes necessary to selectively enhance pathology by administering a contrast agent. As in other diagnostic modalities, MRI contrast media can be classified as either positive or negative agents depending on whether they are required to increase or decrease the amount of signal returned by the tissue in question. Positive agents tend to contain rare earth metal gadolinium as their active ingredient; negative agents have historically contained iron oxide. Only a brief overview is provided here. For a more detailed explanation, please refer to Chapter 11 of *MRI in Practice* or an equivalent text.

Positive contrast agents

At the time of writing, there are nine positive MRI contrast agents commercially available. The active ingredient in these agents is gadolinium. In its native state, gadolinium is a silver-coloured rare earth metal refined from naturally occurring mineral ores. Below 20°C, metallic gadolinium is ferromagnetic due to the presence of seven unpaired electrons; at body temperature, it is strongly paramagnetic. At a molecular level, the net effect of these negatively charged unpaired electrons is a fluctuating magnetic field with a similar frequency to the Larmor frequency of the nearby hydrogen nuclei. This leads to a shortening of T1 time by increasing the ability of the hydrogen nuclei to dissipate energy but also a shortening of T2 time due to the dephasing effect of the microscopic fluctuations in the local magnetic field.

Handbook of MRI Technique, Fourth Edition. Catherine Westbrook.

Companion website: www.wiley.com/go/westbrook/mritechnique

At the recommended dose of 0.1–0.2 mmol/kg, the predominant effect is on T1 shortening, and for this reason, gadolinium-based media are known as T1 enhancement agents. The only exception to this rule is when a bolus of gadolinium agent is used in conjunction with GRE in perfusion imaging, causing a momentary decrease in T2* signal intensity throughout the capillary bed (see Chapter 3 on *Pulse sequences*).

In vivo, free gadolinium ions tend to bind to proteins in the various body tissues. This is undesirable from a toxicology viewpoint, and therefore, gadolinium is combined with a molecule known as a *ligand*. The ligands used can be either cyclic or linear in shape. A cyclic ligand surrounds the gadolinium ion, the linear ligand latches onto the gadolinium ion, and in each case, the resulting compound is known as a *chelate*. The chelate largely prevents the gadolinium ions from binding with the endogenous tissues in the patient's body. Another function of the ligand is to facilitate rapid elimination from the body via the kidneys. A dose of gadolinium is largely excreted in less than one hour. There has been recent concern about the use of gadolinium contrast media in patients with poor renal function, particularly due to its implication in the disease known as nephrogenic systemic fibrosis (NSF). Although the exact cause of this rare disease is still a subject of debate, it is thought that gadolinium ions are freed from the ligand by a process called transmetallation. This process involves the replacement of the gadolinium ion by a naturally occurring body cation such as zinc. The disease causes characteristic hardening and tightening of the skin and joint pain.

Gadolinium is usually given intravenously (IV) but can also be injected directly into a joint or administered orally. Oral gadolinium provides positive contrast of the gastrointestinal tract to label the bowel thereby increasing the visualization of abdominal organs such as the pancreas. Oral gadolinium has a neutral taste and is easily mixed with water prior to ingestion. Problems may arise from the bowel 'whiting out', although this can be minimized by careful adjustment of the dose, and optimum timing of the scan sequence post-ingestion. A dilute solution of gadolinium chelate may also be injected directly into a cavity such as a joint. Magnetic resonance arthrography is an important technique, especially in the hip, shoulder and ankle.

Negative contrast agents

Historically, iron oxide was used as a negative contrast agent in MRI. The super-paramagnetic nature of iron oxide creates microscopic changes in magnetic field homogeneity in the vicinity of any particles injected into the bloodstream or taken up by tissues such as the liver parenchyma. This in turn causes dephasing of the magnetic moments, shortening of T2 decay time and a marked reduction in signal intensity. Like gadolinium, iron in its native state can be toxic and must be rendered safe before it is administered. Most of the original negative agents used nanoparticles of iron oxide coated with a polymer to prevent the iron from becoming free in the

bloodstream. Iron oxide particulates have fallen out of favour in recent years, but many centres still use fruit juices such as pineapple or blueberry to achieve negative contrast in the bowel. The contrast mechanism is due to the high concentration of paramagnetic manganese ions which, like iron oxide, cause magnetic field inhomogeneity and dephasing.

Conclusion

The development of contrast agents has rapidly advanced, and their use will increase the diagnostic capabilities of MRI in the future. It is therefore important that MR users keep abreast of these developments so that their optimum and safe use is assured.

Part 2 Examination areas

8

Head and neck

Handbook of MRI Technique, Fourth Edition. Catherine Westbrook.

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Table 8.1 Summary of parameters

1.5T		3T	
SE		**SE**	
Short TE	Min–30 ms	Short TE	Min–15 ms
Long TE	70 ms+	Long TE	70 ms+
Short TR	600–800 ms	Short TR	600–900 ms
Long TR	2000 ms+	Long TR	2000 ms+
FSE		**FSE**	
Short TE	Min–20 ms	Short TE	Min–15 ms
Long TE	90 ms+	Long TE	90 ms+
Short TR	400–600 ms	Short TR	600–900 ms
Long TR	4000 ms+	Long TR	4000 ms+
Short TEL	2–6	Short TEL	2–6
Long ETL	16+	Long ETL	16+
IR T1		**IR T1**	
Short TE	Min–20 ms	Short TE	Min–20 ms
Long TR	3000 ms+	Long TR	300 ms+
TI	200–600 ms	TI	Short or null time of tissue
Short ETL	2–6	Short ETL	2–6
STIR		**STIR**	
Long TE	60 ms+	Long TE	60 ms+
Long TR	3000 ms+	Long TR	3000 ms+
Short TI	100–175 ms	Short TI	210 ms
Long ETL	16+	Long ETL	16+
FLAIR		**FLAIR**	
Long TE	80 ms+	Long TE	80 ms+
Long TR	9000 ms+	Long TR	9000 ms + (TR at least 4 × TI)
Long TI	1700–2500 ms (depending on TR)	Long TI	1700–2500 ms (depending on TR)
Long ETL	16+	Long ETL	16+
Coherent GRE		**Coherent GRE**	
Long TE	15 ms+	Long TE	15 ms+
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Incoherent GRE		**Incoherent GRE**	
Short TE	Minimum	Short TE	Minimum
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Balanced GRE		**Balanced GRE**	
TE	Minimum	TE	Minimum
TR	Minimum	TR	Minimum
Flip angle	>40°	Flip angle	>40°
SSFP		**SSFP**	
TE	10–15 ms	TE	10–15 ms
TR	<50 ms	TR	<50 ms
Flip angle	20–40°	Flip angle	20–40°

(*Continued*)

Table 8.1 (*Contd.*)

1.5T and 3T			
Slice thickness 2D		**Slice thickness 3D**	
Thin	2–4 mm	Thin	<1 mm
Medium	5–6 mm	Thick	>3 mm
Thick	8 mm		
FOV		**Matrix**	
Small	<18 cm	Coarse	256 × 128/256 × 192
Medium	18–30 cm	Medium	256 × 256/512 × 256
Large	>30 cm	Fine	512 × 512
		Very fine	>1024 × 1024
NEX/NSA		**Slice number 3D**	
Short	1	Small	<32
Medium	2–3	Medium	64
Multiple	>4	Large	>128
PC-MRA 2D and 3D		**TOF-MRA 2D**	
TE	Minimum	TE	Minimum
TR	25–33 ms	TR	28–45 ms
Flip angle	30°	Flip angle	40–60°
VENC venous	20–40 cm/s	**TOF-MRA 3D**	
VENC arterial	60 cm/s	TE	Minimum
		TR	25–50 ms
		Flip angle	20–30°

The figures given are for 1.5T and 3T systems. Parameters are dependent on field strength and may need adjustment for very low or very high field systems.

Brain

Basic anatomy (Figures 8.1 and 8.2)

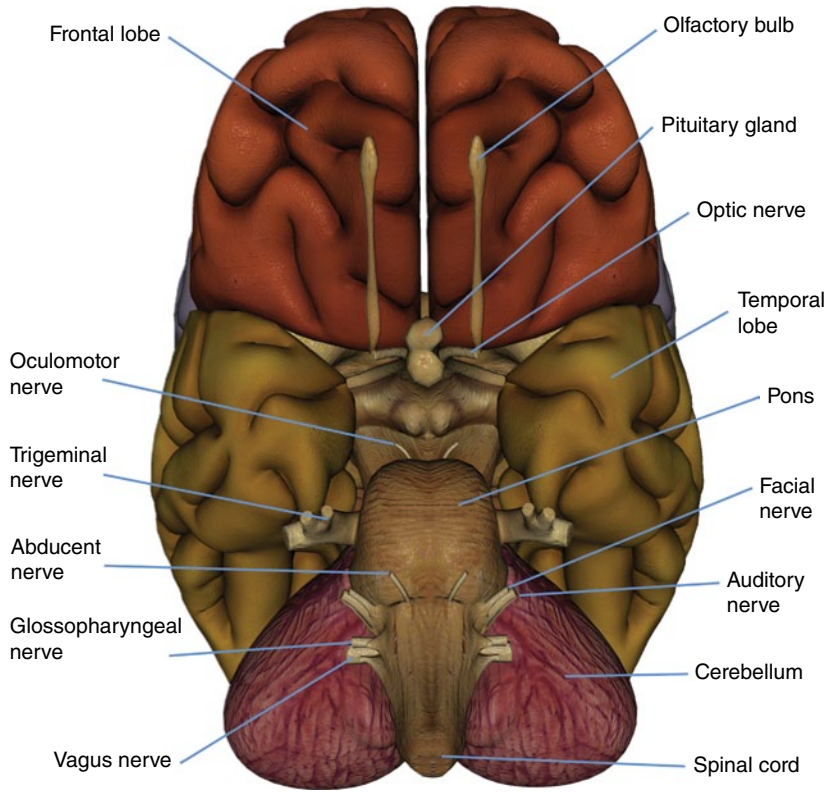

Figure 8.1 Transverse aspect of the brain showing inferior structures.

Common indications

- MS
- Primary tumour assessment and/or metastatic disease
- AIDS (toxoplasmosis)
- Infarction (cerebral vascular accident (CVA) versus transient ischaemic attack (TIA))
- Haemorrhage
- Hearing loss
- Visual disturbances
- Infection
- Trauma
- Unexplained neurological symptoms or deficit
- Preoperative planning

- Radiation treatment planning
- Follow-up (surgical or treatment)

Equipment

- Head coil (quadrature or multi-coil array)
- Immobilization pads and straps
- Earplugs/headphones
- High-performance gradients for EPI, diffusion and perfusion imaging

Patient positioning

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the inter-pupillary line is parallel to the couch and the head is straight. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the nasion. Straps and foam pads are used for immobilization.

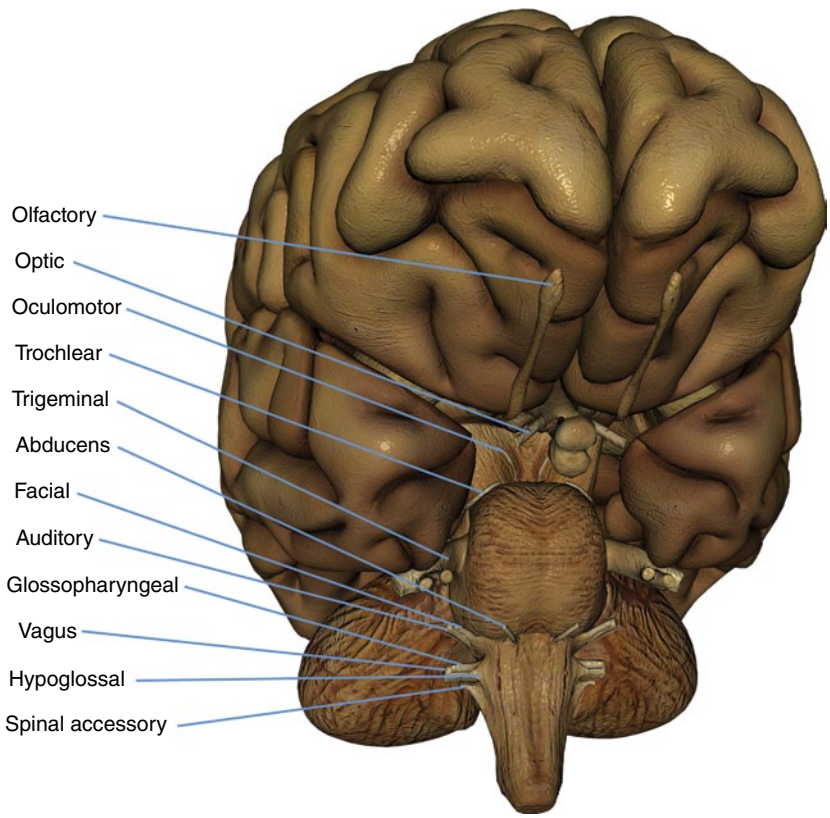

Figure 8.2 Oblique aspect of the brain showing inferior structures.

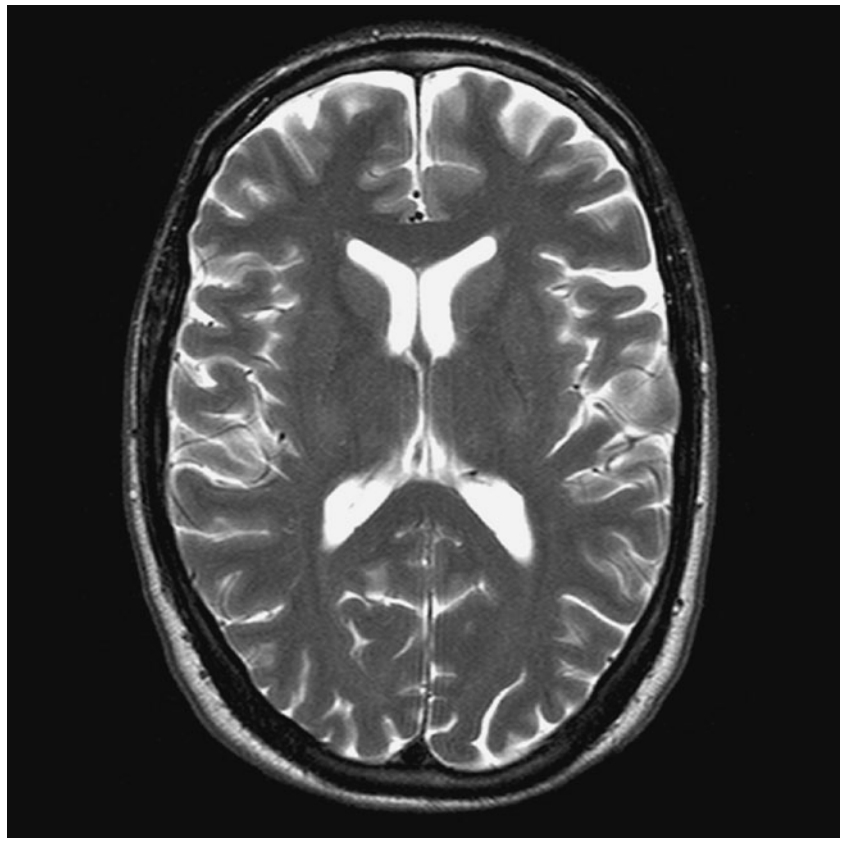

Figure 8.3 Axial/oblique FSE T2-weighted image of the brain showing normal appearances.

Suggested protocol

Sagittal SE/FSE/incoherent (spoiled) GRE T1

Medium slices/gaps are prescribed on each side of the longitudinal alignment light from one temporal lobe to the other. The area from below the foramen magnum to the top of the head is included in the image.

L 37 mm to R 37 mm

Axial/oblique SE/FSE PD/T2 (Figure 8.3)

Medium slices/gaps are prescribed from below the foramen magnum to the superior surface of the brain. Slices may be angled so that they are parallel to the anterior–posterior commissure axis. This enables precise localization of lesions from reference to anatomy atlases (Figures 8.4 and 8.5). Many sites have replaced the PD sequence with T2-FLAIR. T2-FLAIR sequences can be helpful when acquired following the injection of a contrast agent. Due to the T1 contribution of inversion sequences, 'enhancing' lesions and structures are hyper-intense. This aids the visualization of leptomeningeal metastasis and/or meningitis. The only caveat is that 'enhancement' of meningiomas is not seen on post-contrast

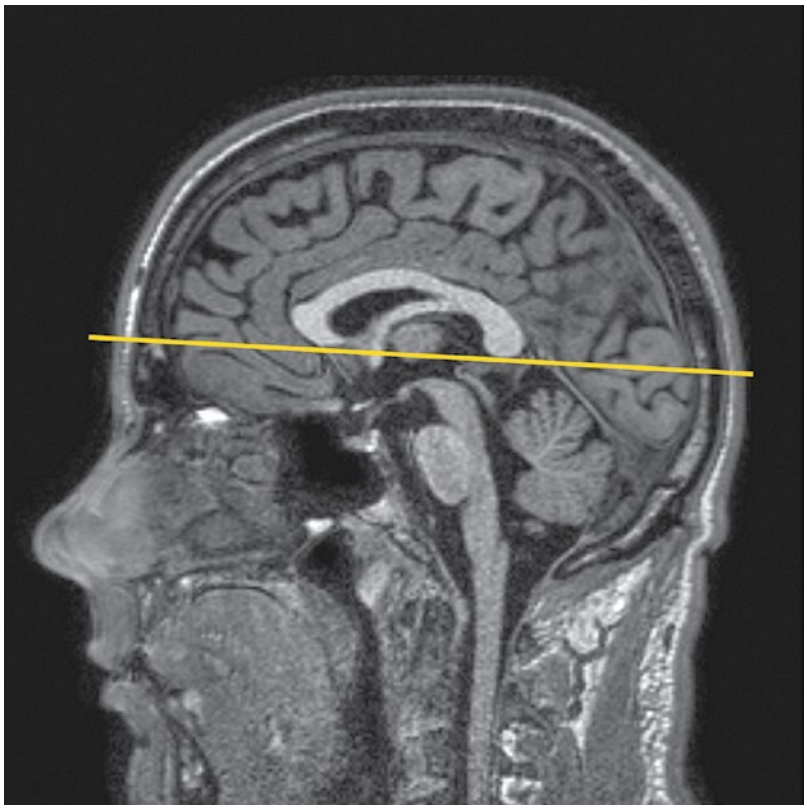

Figure 8.4 Sagittal SE T1-weighted midline slice of the brain showing the axis of the anterior and posterior commissures.

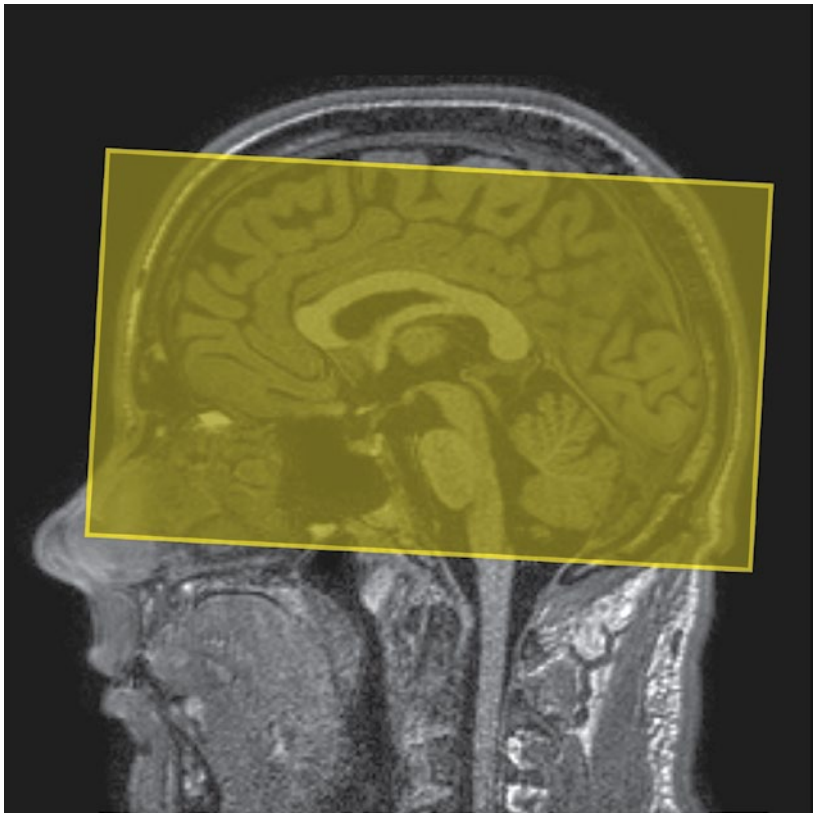

Figure 8.5 Sagittal SE T1-weighted midline slice of the brain showing slice prescription boundaries and orientation for axial/oblique imaging.

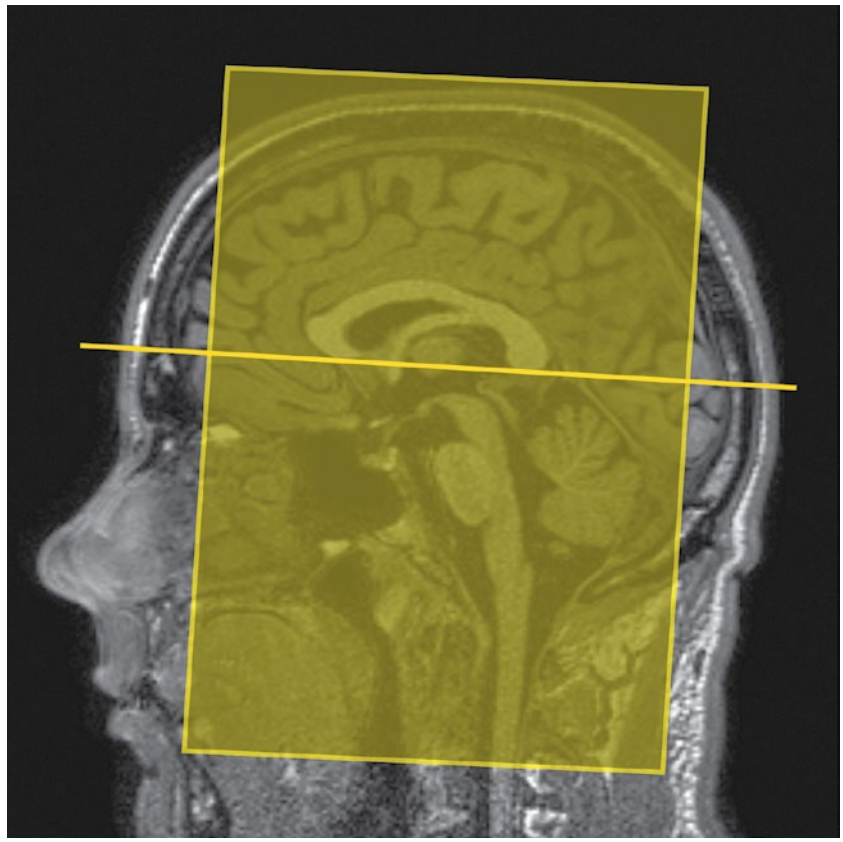

Figure 8.6 Sagittal SE T1-weighted image showing slice prescription boundaries and orientation for coronal imaging.

T2-FLAIR due to their short T2 relaxation times. SS-FSE or SS-EPI may be a necessary alternative for a rapid examination in uncooperative patients.

Coronal SE/FSE PD/T2

As for axial PD/T2, **except** prescribe slices from the cerebellum to the frontal lobe (Figure 8.6).

Additional sequences

Axial/oblique IR T1 (Figure 8.7)

Slice prescription as for axial/oblique T2.

This sequence is especially useful in imaging the paediatric brain. White matter does not fully myelinate until approximately five years of age; therefore, in very young patients, grey matter and white matter have very similar T1 relaxation times, and the CNR between these tissues is small on SE T1 sequences.

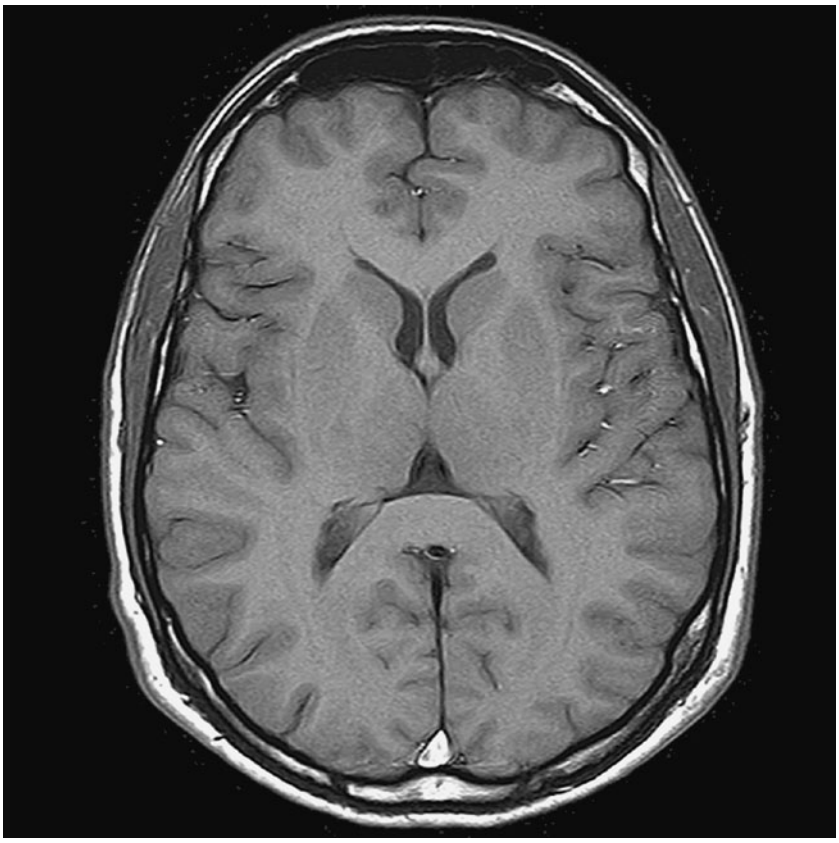

Figure 8.7 Axial IR T1-weighted image using a TI of 700 ms.

Axial/oblique FLAIR/EPI (Figure 8.8)

Slice prescription as for axial/oblique T2.

This sequence provides a rapid acquisition with suppression of CSF signal. It may be useful when examining periventricular or cord lesions such as MS plaques.

Axial/oblique SE/FSE/incoherent (spoiled) GRE T1 (Figure 8.9)

Slice prescription as for axial/oblique T2.

Pre- and post-contrast scans are common especially for tumour assessment.

SS-FSE T2 (Figure 8.10)

Useful for rapid imaging in uncooperative patients.

Axial 3D incoherent (spoiled) GRE T1

This sequence is useful for high-resolution imaging of small structures within the brain. If reformatting of slices is desired, an isotropic data set must be acquired (see *Volume imaging* under *Parameters and trade-offs* in

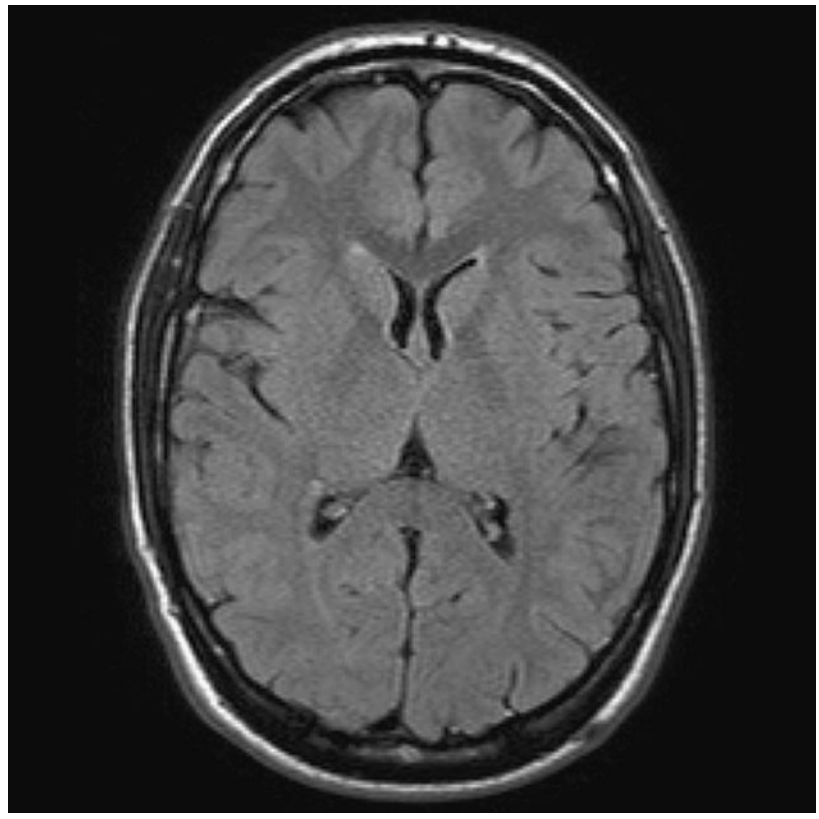

Figure 8.8 Axial/oblique FLAIR image of the brain. Periventricular abnormalities will have a high signal intensity in contrast to the low signal of CSF which has been nulled using a long TI.

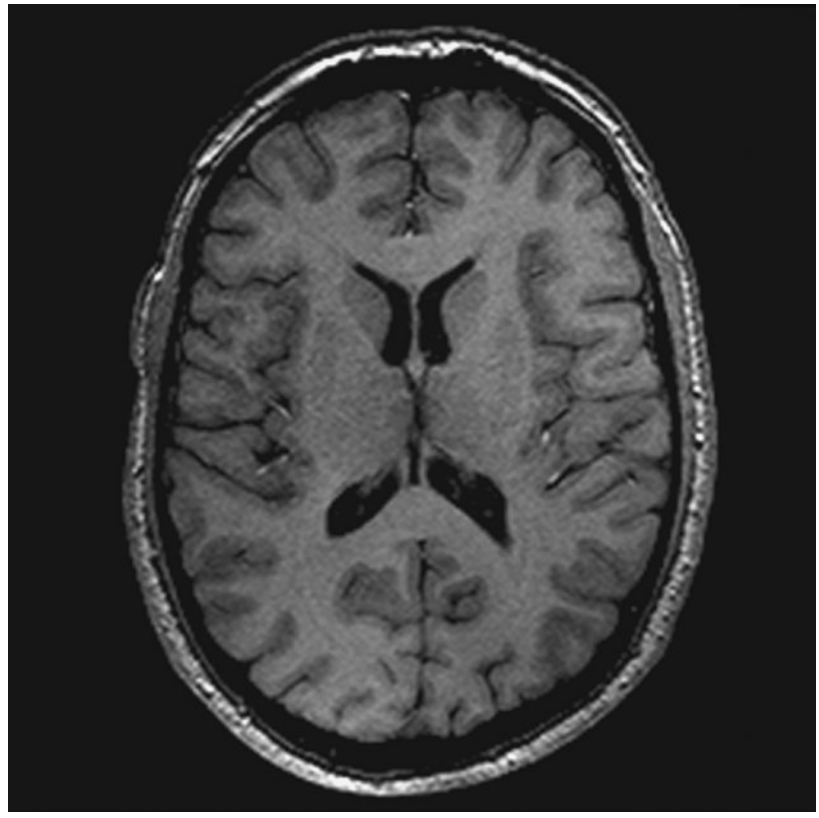

Figure 8.9 Axial/oblique incoherent (spoiled) GRE image of the brain.

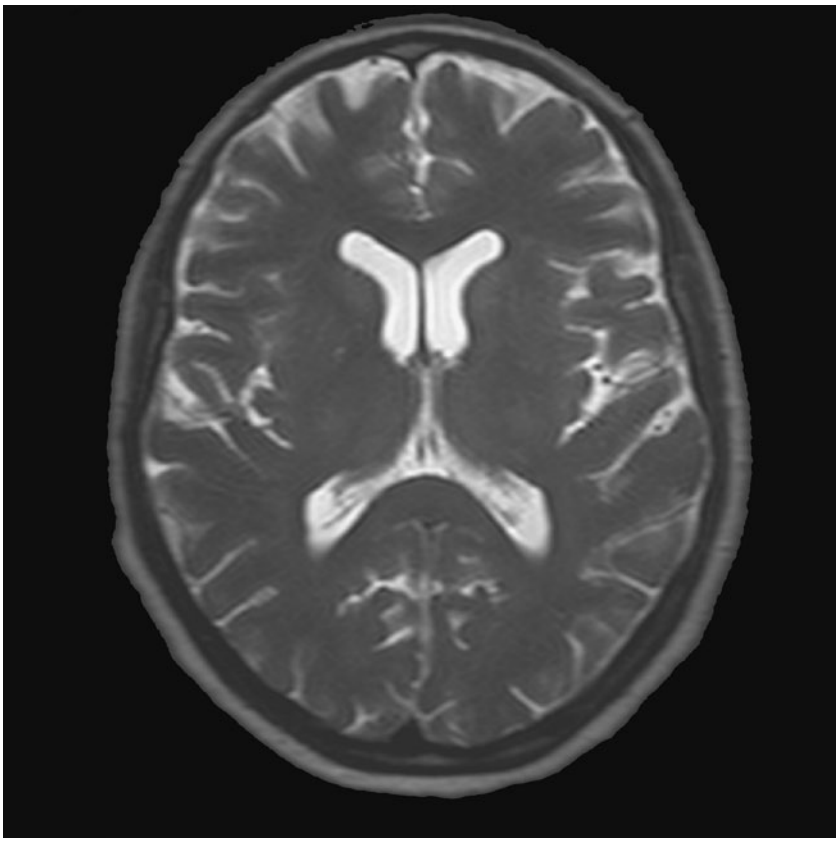

Figure 8.10 SS-FSE T2-weighted image of the brain. The entire brain was scanned in 40 s.

Part 1). Additionally, due to the short TE utilized with the spoiled GRE sequence, flow artefacts are essentially eliminated.

Axial/oblique GRE/EPI T1/T2 (Figure 8.11)

Due to sensitivity to magnetic susceptibilities, these sequences demonstrate haemorrhage better than SE and FSE.

Axial/oblique SE MT

Slice prescription as for axial/oblique T2.

MT is a useful sequence to improve visualization of lesions such as metastasis, and some low-grade tumours, as grey and white matter loses 30–40% of its signal when a MT pulse sequence is utilized. The CNR between lesions and the surrounding brain is therefore increased (see *Pulse sequences* in Part 1).

Axial DWI (Figures 8.12 and 8.13)

Slice prescription as for axial/oblique T2.

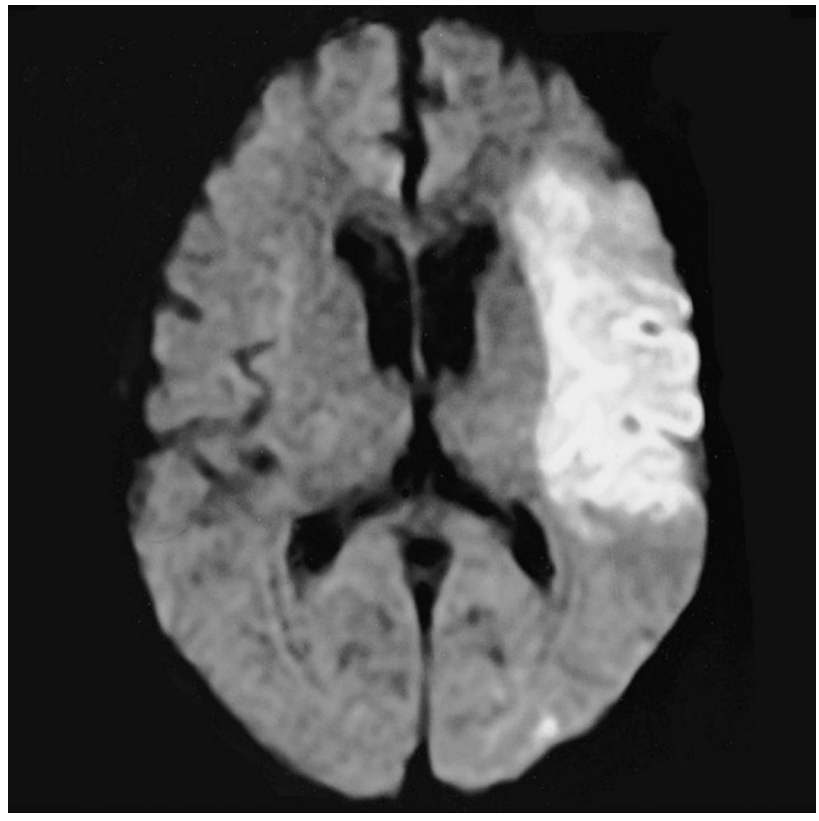

Figure 8.11 SS-EPI image of the brain. The entire brain was scanned in 14 s.

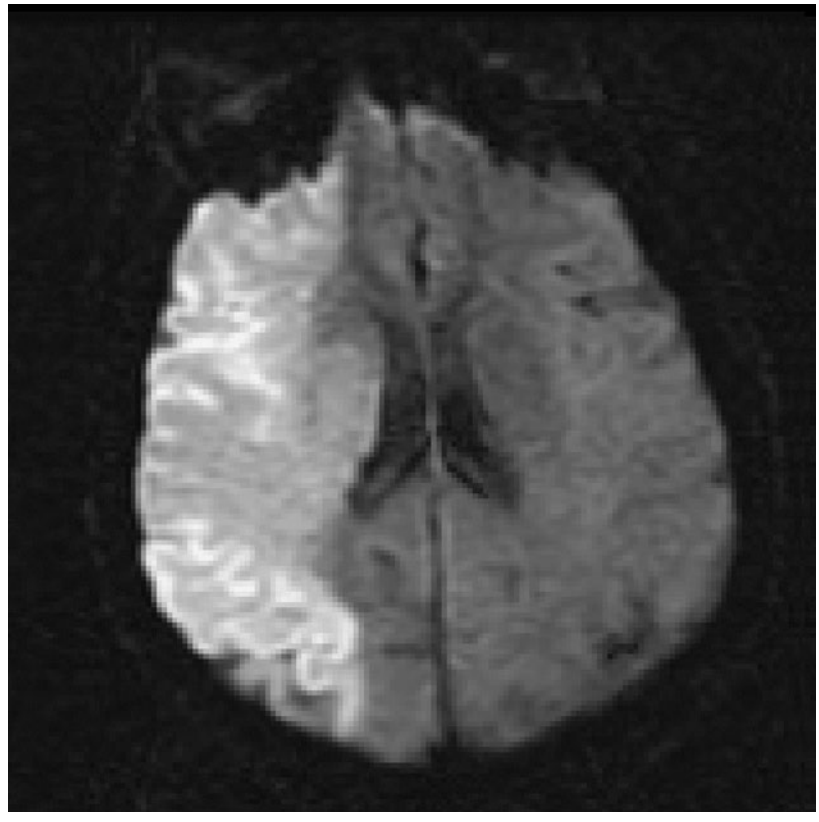

Figure 8.12 DWI showing large area of high signal on right. High signal on a DWI can be the result of restricted diffusion or 'T2 shine-through'.

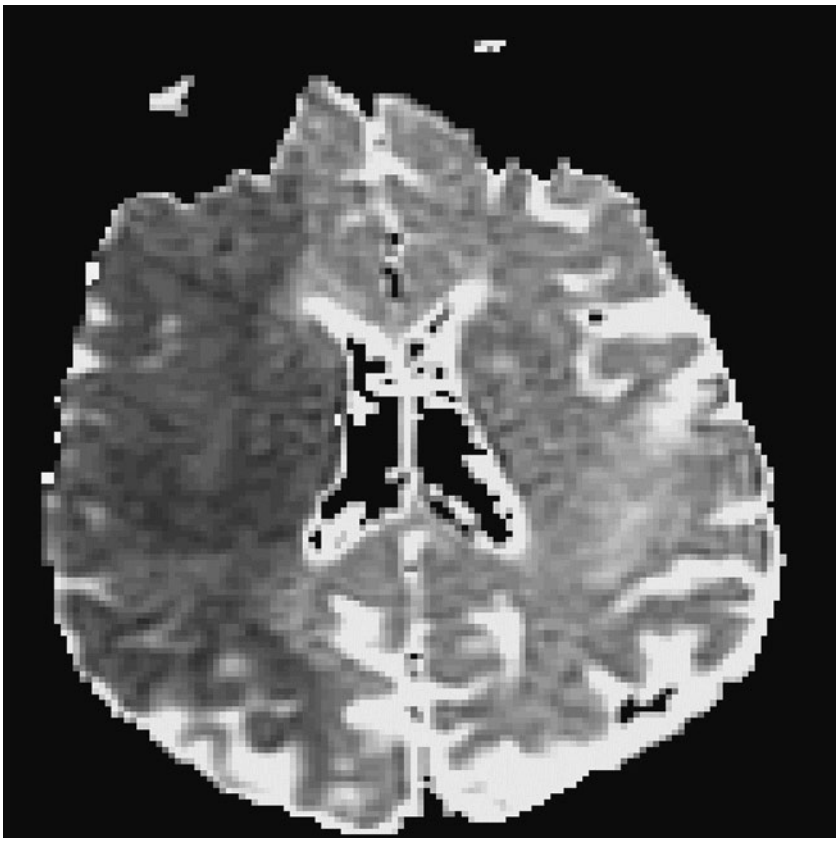

Figure 8.13 Calculated ADC image showing restricted diffusion (acute stroke) as low signal. Small area of high signal in right posterior represents 'T2 shine-through'.

This sequence is important in the investigation of early stroke. It is also utilized in paediatric patients to investigate the effects of hypoxia and myelination patterns. A b-value of 800–1000 s/mm^2 is selected (the higher the b-value, the more diffusion weighting). Isotropic diffusion should be acquired (i.e. diffusion gradients applied in all three axes) (see *Pulse sequences* in Part 1).

A DWI sequence is most often acquired using a T2-weighted EPI sequence. In a standard T2-weighted EPI sequence, there is not enough motion (diffusion) of the extracellular water during the imaging cycle to result in dephasing of the water protons. Diffusion gradients are therefore utilized to increase the sensitivity to the motion of the extracellular water molecules. The b-value controls the amplitude, duration and/or timing of these diffusion gradients and thus determines the amount of diffusion weighting in a diffusion sequence. Increasing the b-value increases the sensitivity to the motion (diffusion) of extracellular water in tissue and thus increases the diffusion weighting. The signal in areas of normal diffusion is reduced due to the dephasing of the water protons in the presence of these diffusion gradients. The more restricted the diffusion, the less dephasing of the water protons and higher signal will be seen on the diffusion image. On most MR systems, both the b = 0 image

(i.e. the T2-weighted EPI image) and the diffusion image with the b value chosen by the operator will be displayed. Some systems may also display three additional images per slice location. These are the images obtained during the diffusion acquisition. The diffusion gradients are applied in each of the three orthogonal planes (X, Y and Z) measuring the diffusion in each of those directions. The data are then averaged to produce the final 'trace' or diffusion-weighted image displayed.

It is important to remember that high signal seen on a diffusion-weighted image may actually be high signal from spins with a long T2 relaxation time 'shining through'. These so-called 'T2 shine-through' effects are eliminated by the calculation and production of an apparent diffusion coefficient (ADC) map or image. The ADC expresses the amount of motion of extracellular water. The ADC image is calculated from the b-value of 0 and the b-value used in the diffusion acquisition (most commonly 1000 mm/s^2 in a DWI exam of the brain) to produce a '2-point' ADC image (Figure 8.13). In some situations, one may acquire a DWI with two b-values. That, along with the b-value of 0, would be used to calculate a '3-point' ADC image. In any event, the pixel values in an ADC image represent the ADC of pixels in the image. In areas with restricted diffusion (i.e. low ADC), the pixel values are dark. A high ADC, seen in the presence of mobile water protons will result in a bright pixel on the ADC image. Calculating and producing an ADC image is very important in distinguishing between acute and chronic stokes. Depending on the MR system, the ADC image may be produced automatically or it may require some minor additional processing steps.

Diffusion tensor imaging (DTI)

When the diffusion of water along the three orthogonal directions of the magnet (X, Y and Z) is measured and the average obtained, only isotropic diffusion information is acquired, that is, diffusion that is random in direction. In the brain, this is seen in grey matter. In white matter, the structure of the tissue 'orders' the diffusion. In white matter, diffusion is ordered along the white matter tracts. This type of ordered diffusion is referred to as anisotropy (anisotropic diffusion). In order to image anisotropic diffusion, diffusion in more than three axes is measured. In physics, a tensor is basically motion as a function of direction. DTI is essentially imaging diffusion that is ordered in direction (anisotropic rather than isotropic). At a minimum, DTI must measure the diffusion along at least six axes. In clinical practice, 12 or more directions are measured. Due to a loss in SNR as the number of directions measured increases, DTI is particularly useful at high field strengths such as 3T. DTI is currently used for mapping white matter tracts as fractional anisotropy (FA) maps, or as tractography images (Figures 8.14, 8.15, 8.16, 8.17 and 8.18).

Axial perfusion imaging

Slice prescription as for axial/oblique T2.

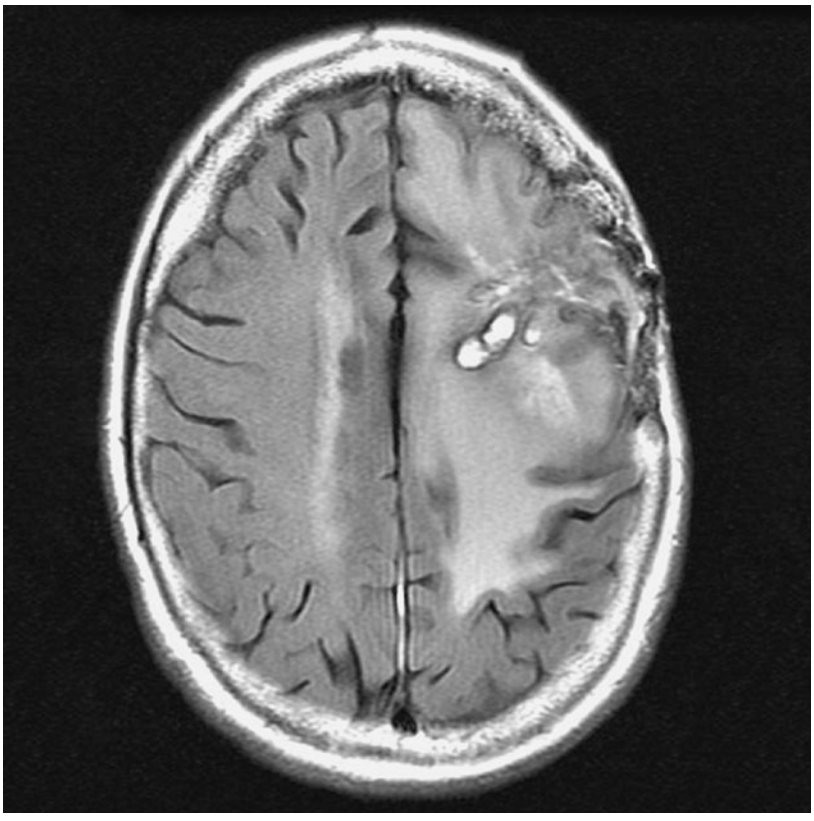

Figure 8.14 T2-weighed FLAIR showing lesion.

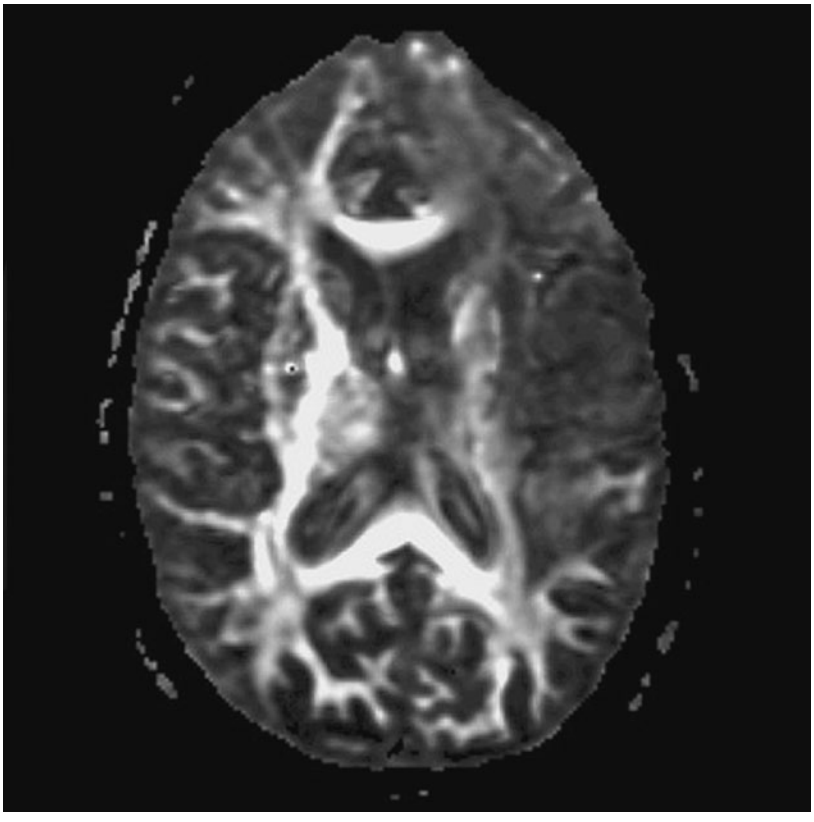

Figure 8.15 Fractional anisotropy (FA) map showing anisotropic (ordered) diffusion in the white matter tracts.

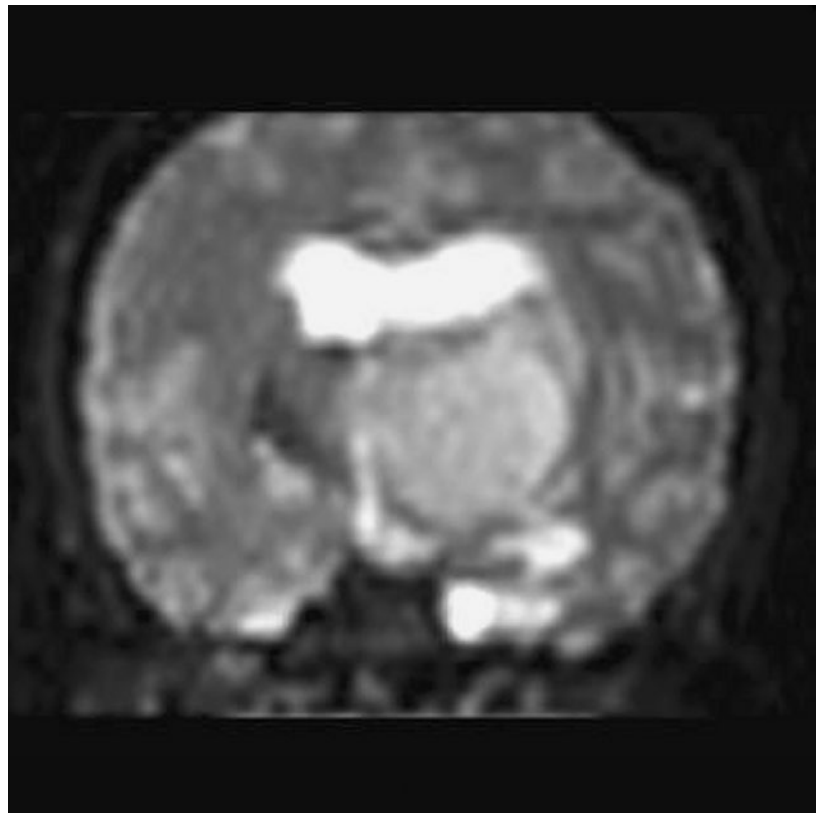

Figure 8.16 Coronal T2-weighted EPI demonstrates lesion.

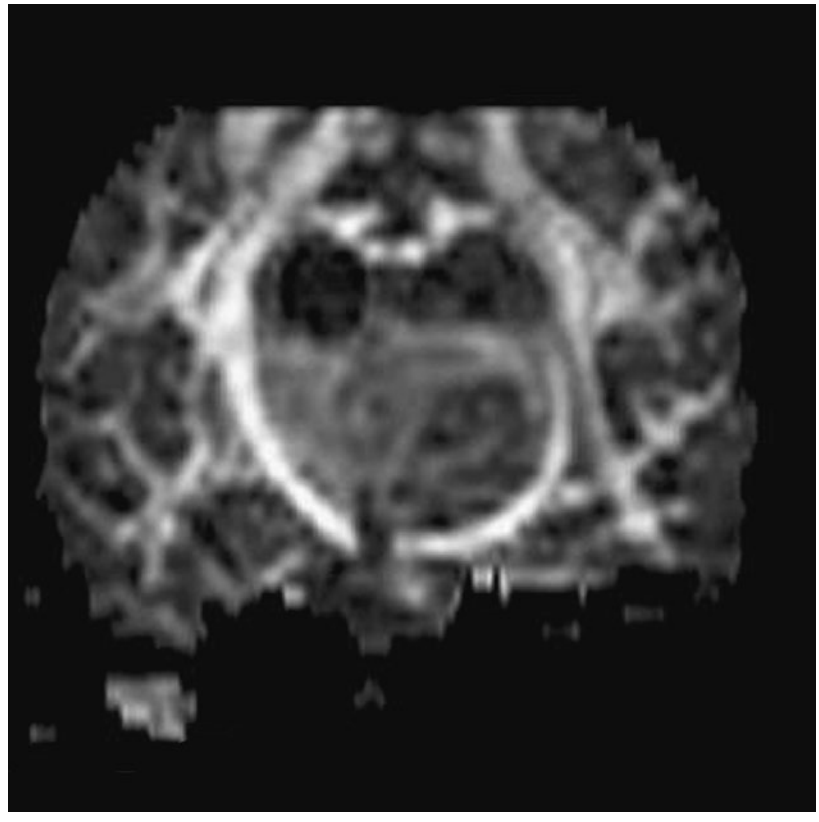

Figure 8.17 FA map shows white matter tracts relative to the lesion.

Figure 8.18 Tractography demonstrates tract orientation relative to the lesion.

This sequence provides temporal resolution of enhancing lesions and indicates activity. Injection of a gadolinium bolus should begin immediately after the scan is initiated. Post-enhancement T1 imaging follows the perfusion series (see *Pulse sequences* and its subheading *Dynamic imaging* in Part 1).

The use of an MR-compatible contrast injector greatly increases the consistency of perfusion information. Furthermore, in order to optimize the susceptibility effects, a rapid bolus of contrast is necessary. A minimum injection rate of 4 ml/s is preferable. The amount or volume injected may vary depending on concentration of the contrast media, relaxivity of the contrast media, field strength, and/or pulse sequence utilized. At 1.5 T, the strongest effects are seen using a GRE-EPI sequence. If such a sequence is used, 0.1 mmol/kg is typically adequate. Due to the increased susceptibility effects seen with a GRE-EPI sequence, only information regarding large vessel perfusion is obtained. If one wishes to obtain information relating to small vessel perfusion, then a SE-EPI sequence should be utilized. It is important to remember however that due to the reduced susceptibility effects obtained with the SE-EPI sequence, a higher dose or concentration of gadolinium may be necessary. Not all gadolinium agents have the same effect on T1 and T2 relaxation times. There

are some agents with higher relaxivities. These agents, when used for perfusion imaging, result in greater signal reduction when compared with the same dose of a standard contrast agent due to the increased relaxivity. At 3.0 T, susceptibility effects are increased as a function of the field strength and allow for either a reduced dose of gadolinium (0.5 mmol/kg) with a GRE-EPI sequence or a standard dose (0.1 mmol/kg) of gadolinium with a SE-EPI sequence. SE-EPI sequences also result in fewer susceptibility artefacts. In summary, the amount of gadolinium used for perfusion imaging is dependent upon the type of contrast agent used, field strength and acquisition technique selected.

When perfusion imaging is utilized for stroke imaging, the area affected by the stroke appears as either an area of late arriving contrast or totally non-perfusing. When imaging a tumour, however, the area of abnormal perfusion will often be demonstrated as an area of hyper-perfusion. The images in Figures 8.19 and 8.20 illustrate this effect. The area of residual tumour is indistinguishable from the adjacent tissue due to oedema and other changes. The perfusion data clearly show an area of increased or hyper-perfusion indicating residual or recurrent tumour.

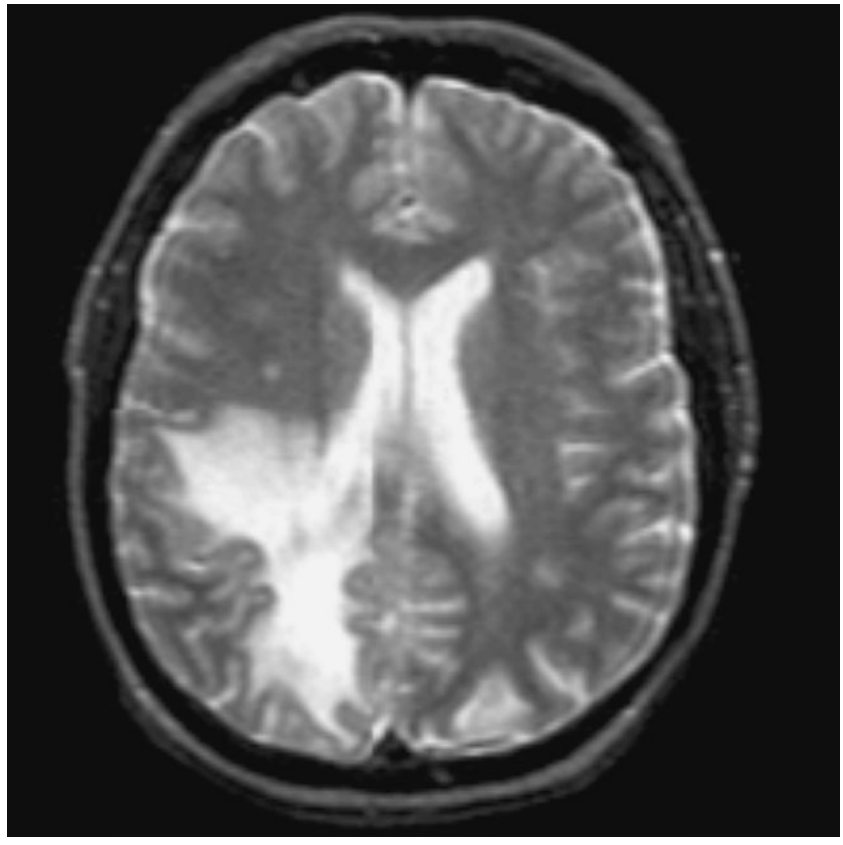

Figure 8.19 T2-weighted image shows large area of oedema following treatment.

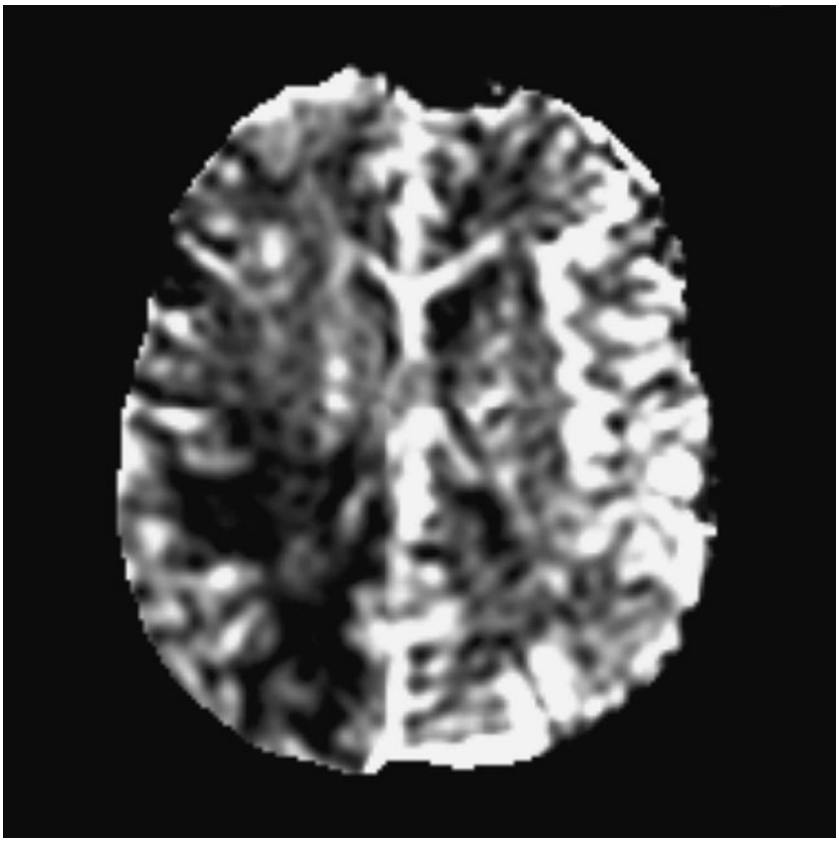

Figure 8.20 Perfusion data shows area of hyper-perfusion within the oedema indicating recurrent tumour.

Image optimization

Technical Issues

Using a quadrature or multi-coil array yields high and uniform signal. Using a multi-coil array with greater than four channels however may require the use of a uniformity correction algorithm to produce an image with uniform signal throughout. Regardless of the coil selected, images with excellent SNR and spatial resolution should be easily attainable in reasonable scan times.

FSE is the pulse sequence most often utilized for acquiring PD- and T2-weighted images due to its shorter scan times compared with CSE. There is some debate as to whether PD- and T2-weighted images should be acquired as part of a dual echo acquisition or separately. TRs in the order of 3500 ms or higher are usually employed in T2-weighted FSE imaging. For PD-weighted images of the brain, however, such a high TR is not optimal. If the TR is increased above 2000 ms, signal intensity of CSF increases due to reduced saturation and the high proton density of CSF. This may reduce contrast between some periventricular lesions such as MS and CSF. This a major reason why T2-FLAIR sequences are now generally preferred over PD-weighted sequences in the brain.

Blurring may be more prominent with the long ETL traditionally associated with T2-weighted FSE. A short ETL and TE are required for PD weighting to minimize T2 effects, whereas a long ETL and TE are required for T2 contrast. Blurring increases the longer the train of echoes goes out in time. Due to T2 dephasing, the echoes that occur a long way out in the train have lower signal amplitude than those at the beginning of the train. If the effective TE does not coincide with these late echoes, data from them are mapped into the resolution lines of k-space and result in blurring. The echo spacing is also important as if the echo spacing is long, the final echoes in the train will occur much later and therefore be of lower signal intensity than if the spacing is short, even in a train containing a relatively small number of echoes. Conversely, if the echo spacing is short, the final echoes are collected earlier and will be of higher signal intensity, even in a train containing a larger number of echoes. (Note: The term 'echo train length' refers to the number of echoes collected rather than the time taken to do so.) The exact method of controlling the echo spacing varies between manufacturers. Faster switching gradients (i.e. higher slew rates) allow for a long ETL with tight echo spacing. Generally speaking, the echo spacing should be kept as low as possible to minimize blurring (typically between 10 and 15 ms).

As a result of these limitations, some advocate acquiring the PD- and T2-weighted images separately as this permits the use of a shorter TR and ETL in the PD acquisition. Alternatively, some manufacturers allow the echo train to be split in dual echo FSE acquisitions so that the PD-weighted image is acquired from the first echoes in the train and the T2-weighted image from the later echoes in the train. This results in more optimal weighting for both images but note that in FSE, unlike CSE, the acquisition time for PD images is shorter than that for T2 or dual echo. This is because a TR of 2000 ms is used rather than 10,000 ms. There is therefore a time-saving to be made when only PD weighting is required. In CSE, in the interests of reducing scan time, T2-weighted images already have a relatively short TR. PD- and T2-weighted images therefore have similar acquisition times and are routinely acquired simultaneously in a dual echo sequence. There is therefore no time-saving to be made by acquiring PD-weighted images on their own.

Despite the time advantages of using FSE in the brain, the multiple 180° pulses in an FSE sequence reduce the sensitivity to haemorrhagic lesions. If haemorrhagic lesions are suspected, a coherent GRE sequence may be acquired in addition to the regular sequences (TEs of 15–25 ms). It should also be noted that in many centres, T2-FLAIR images have replaced PD-weighted images in the brain. T2-FLAIR sequences typically demonstrate subarachnoid blood very well.

Due to the relatively high SNR, only a few NEX/NSA are usually required to achieve adequate image quality. However, this may not be the case when examining small structures with thin slices and/or a smaller FOV. In such a situation, it may be necessary to increase the NEX/NSA. The receive bandwidth may be decreased to increase the SNR without significantly increasing chemical shift artefact. However, generally speaking, as the receive bandwidth is reduced, the echo spacing increases and could result in

an increase in FSE blurring. Rectangular FOV or parallel imaging may be utilized to reduce scan times in axial and/or coronal imaging with the phase encoding direction being R to L.

Artefact problems

The main source of artefact in the brain is from flow motion of the carotid and vertebral arteries. A spatial pre-saturation pulse placed I to the FOV reduces this significantly. In large FOV imaging, there is no need to place spatial pre-saturation pulses anywhere other than I, as there is no flow coming into the FOV from any other direction. If a small FOV is used, S or R and L spatial pre-saturation pulses are sometimes necessary.

GMN also minimizes artefact especially in the posterior fossa. However, it not only increases the signal in vessels but also the minimum TE available and is therefore usually reserved for T2- and T2*-weighted sequences. Pe gating minimizes artefact even further, but as the scan time is dependent on the patient's heart rate, it is rather time-consuming and is not therefore commonly used. Ghosting occurs along the phase encoding axis, which may be swapped in order to remove the artefact away from the ROI. However, in most examinations of the brain, this strategy is unnecessary as flow suppression techniques are satisfactory.

Uncooperative patients are likely to cause motion artefacts unless very rapid sequences are employed. FSE, while faster than SE, often produces more severe motion artefacts because one of the central lines of k-space is being filled during each TR period. SS-FSE techniques greatly reduce the effects of motion and allow the whole brain to be examined in approximately 30 s by using an ETL as high as 128. SS-FSE sequences, although very rapid, may still show some degree of patient motion. In order to eliminate the effect of patient motion completely, SS-EPI techniques should be used. However, EPI sequences are prone to air/tissue magnetic susceptibility artefact (see *Pulse sequences* in Part 1). Newer acquisition techniques, which fill k-space in a different fashion, can also be employed to reduce or even eliminate the effects of patient motion. These techniques are known as PROPELLER, BLADE, MultiVane and JET (depending on the manufacturer).

Off-resonance effects (mainly magnetic susceptibility) contribute greatly to the distortion artefacts commonly seen on SS-EPI sequences used to acquire DWI images. These artefacts increase with higher field strength systems (such as 3 T) but can be reduced by decreasing the number of phase encoding views (e.g. rectangular FOV or parallel imaging techniques). Unfortunately, if one simply reduces the phase matrix, this results in a reduction in spatial resolution.

Patient considerations

Claustrophobia is often troublesome because of the enclosing nature of the head coil. In addition, neurological factors may increase the likelihood of patient movement. Examples of these are epilepsy, Parkinson's

disease and reduced awareness or consciousness. Reassurance, and in extreme circumstances sedation or general anaesthesia, is sometimes required. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment. EPI sequences employ very rapid gradient rise times. The faster the rise times, the greater the chance for inducing peripheral nerve stimulation. To reduce this probability, the frequency encoding direction should be R to L for all axial EPI sequences in the brain. This is not necessary with SS-FSE sequences. Additionally, patients should be instructed to place their arms by their sides and to not cross their ankles to prevent creating a loop that could precipitate excessive induction of current.

Contrast usage

Contrast agents have several uses in standard brain imaging. They are usually required for tumour assessment, inflammatory processes such as MS or the evaluation of vascular abnormalities. Infectious processes, such as abscesses, are very susceptible to enhancement. In addition, the meninges enhance so that infectious tuberculosis, leptomeningeal tumour spread and post-trauma meningeal irritation can be visualized. Contrast is also used to ascertain the age of an infarct. Very recent infarcts may enhance to some degree, but maximum response to contrast usually occurs after the blood–brain barrier has been breached. Old or chronic infarcts do not enhance. Either SE or incoherent (spoiled) GRE T1 is the sequence of choice after contrast. If a 3D incoherent (spoiled) GRE sequence is acquired using isotropic voxels, the data set may be reformatted in other planes and/or slice locations. Perfusion imaging, with a rapidly infused bolus of gadolinium, is useful for measuring the activity of a lesion. In these cases, rapid acquisitions such as SS-FSE or EPI are required.

Temporal lobes

Basic anatomy (Figure 8.21)

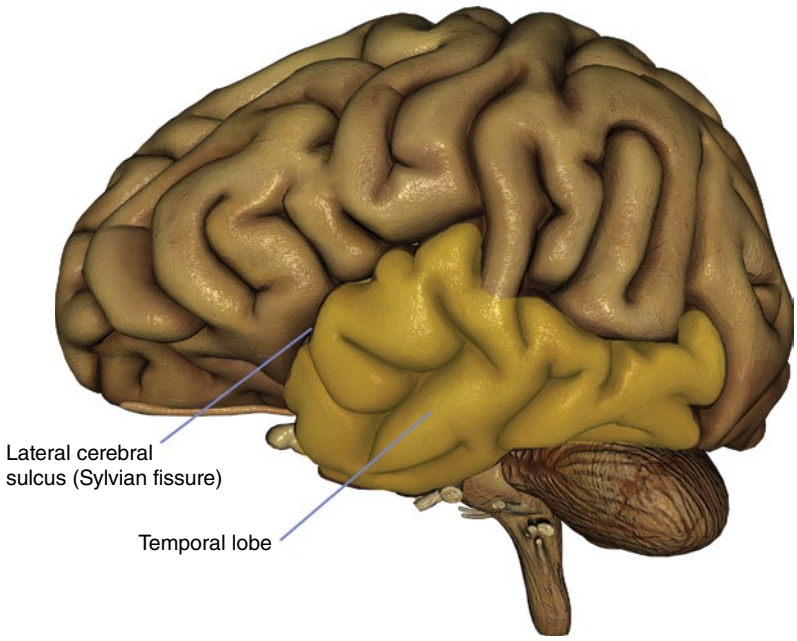

Figure 8.21 The temporal lobe and its relationships.

Common indications

- Diagnosis and evaluation of a lesion specifically in the temporal lobes (tumours, vascular malformations, leucodystrophies and atrophic processes)
- Temporal lobe epilepsy
- Evaluation of signal change in the hippocampus and the temporal lobe
- Measurement of the hippocampal volume (hippocampal atrophy is presently considered the most sensitive indicator of hippocampal disease especially in Alzheimer's disease and schizophrenia)

Equipment

- Head coil (quadrature or multi-coil array)
- Immobilization pads and straps
- Earplugs or headphones

Patient positioning

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the inter-pupillary line is parallel to the couch and the head is straight. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the nasion. Straps and foam pads are used for immobilization.

Suggested protocol

Sagittal SE T1

Medium slices/gaps are prescribed on either side of the longitudinal alignment light through the whole head. The area from the foramen magnum to the top of the head is included in the image.

L 37 mm to R 37 mm

Axial/oblique SE/FSE T2

Thin slices/gap or interleaved slices are angled parallel to the temporal lobe that can be seen on a lateral slice on the sagittal images (Figure 8.22). Prescribe the slices from the inferior aspect of the temporal lobes to the superior border of the body of the corpus callosum.

Coronal/oblique SE/FSE T1

As for the axial/oblique T2, **except** thin slices interleaved are angled perpendicular to the axials (Figure 8.23).

Slices are prescribed from the posterior portion of the cerebellum to the anterior border of the genu of the corpus callosum.

Coronal 3D incoherent (spoiled) GRE T1 (Figure 8.24)

Thin slices are either prescribed through the temporal lobes only (medium number of slice locations), or the whole head (large number of slice locations). For hippocampal measurements, slices are prescribed from the posterior portion of the cerebellum to the anterior border of the genu of the corpus callosum. Hippocampal volumes are measured by using system software to calculate the area of the hippocampus on each slice and multiplying this by the depth of the slice slab. If reformatting of slices is desired, then an isotropic data set should be acquired (see *Volume imaging* under *Parameters and trade-offs* in Part 1).

Axial/oblique/coronal/oblique IR-FSE T2 (Figures 8.25 and 8.26)

Slice prescription as for axial/oblique/coronal/oblique FSE T2.

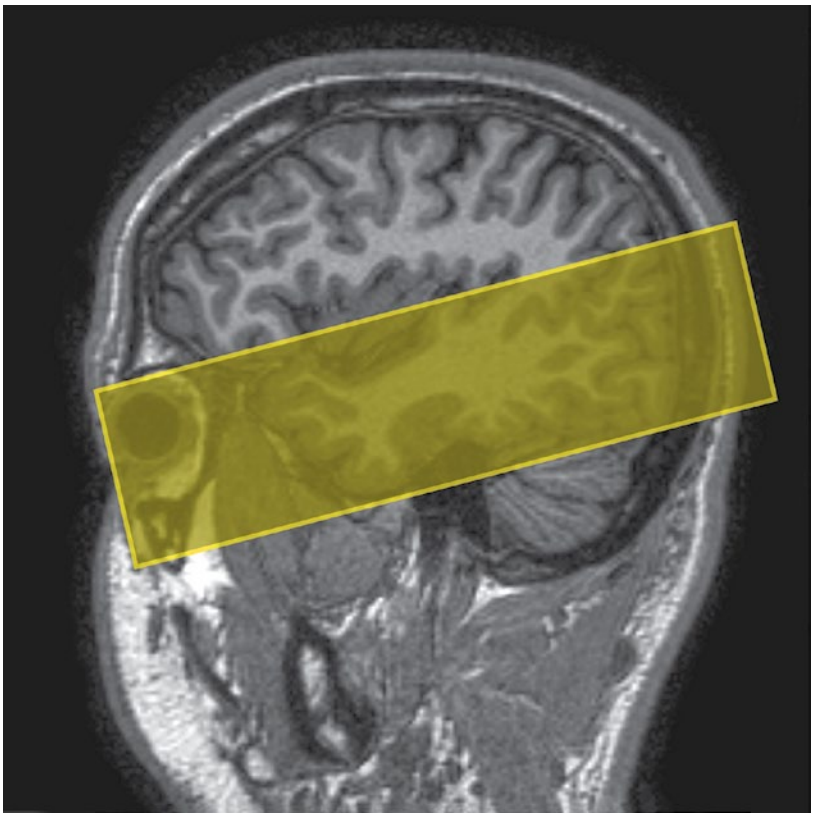

Figure 8.22 Sagittal SE T1-weighted image through a temporal lobe showing slice prescriptions boundaries and orientation for axial/oblique imaging of the temporal lobes.

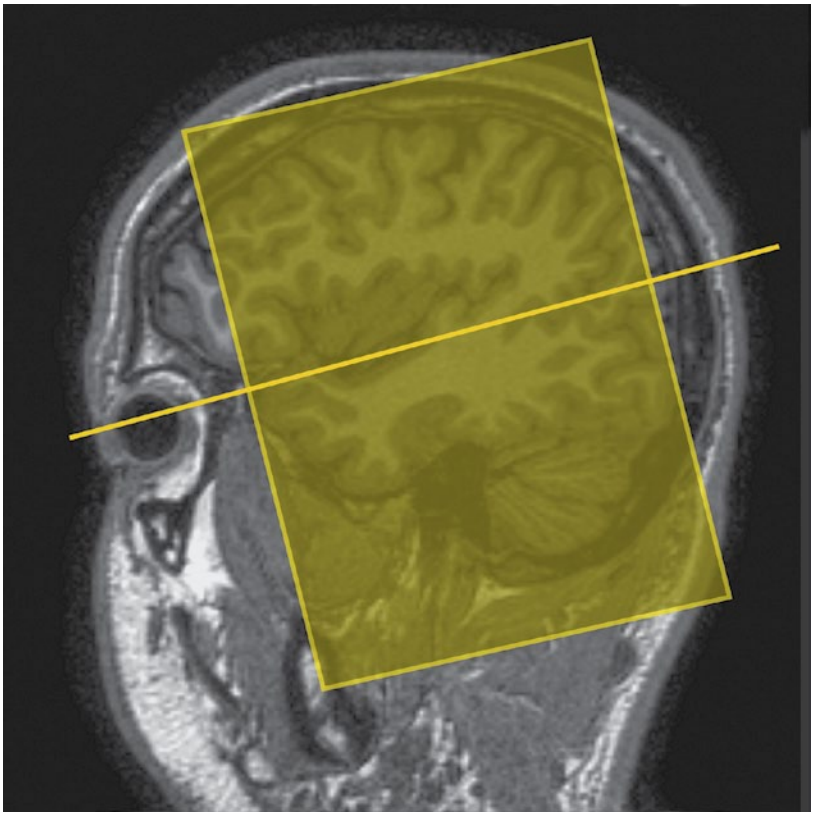

Figure 8.23 Sagittal SE T1-weighted image through a temporal lobe showing slice prescription boundaries and orientation for coronal/oblique imaging of the temporal lobes.

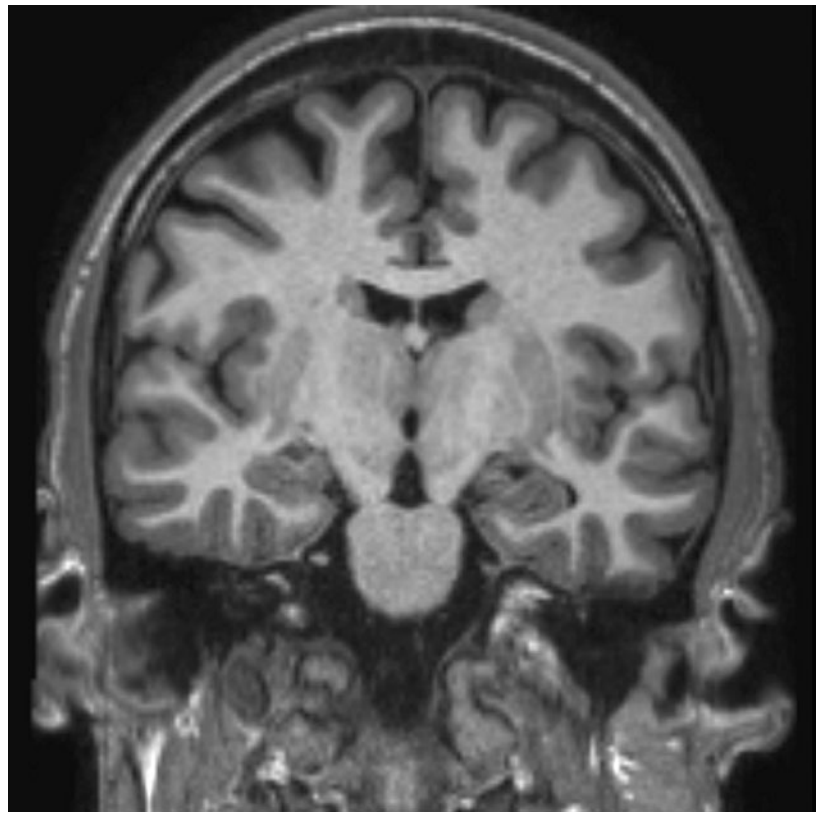

Figure 8.24 Coronal incoherent (spoiled) T1-weighted GRE image through the hippocampi acquired as part of a 3D acquisition.

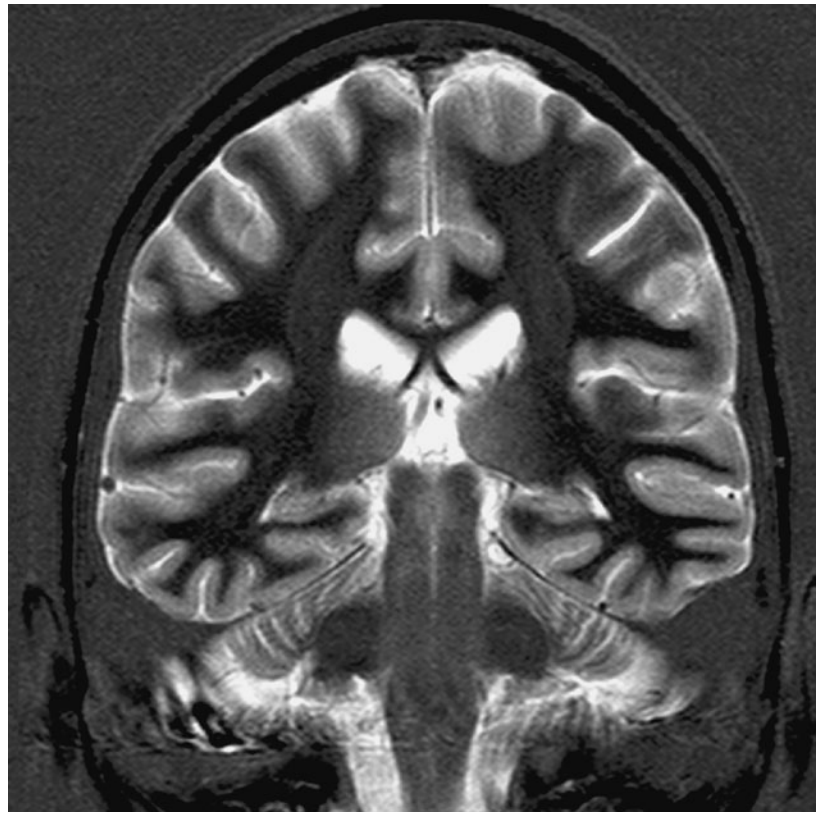

Figure 8.25 Coronal IR-FSE T2-weighted image with a TI selected to null the signal from the white matter (300 ms).

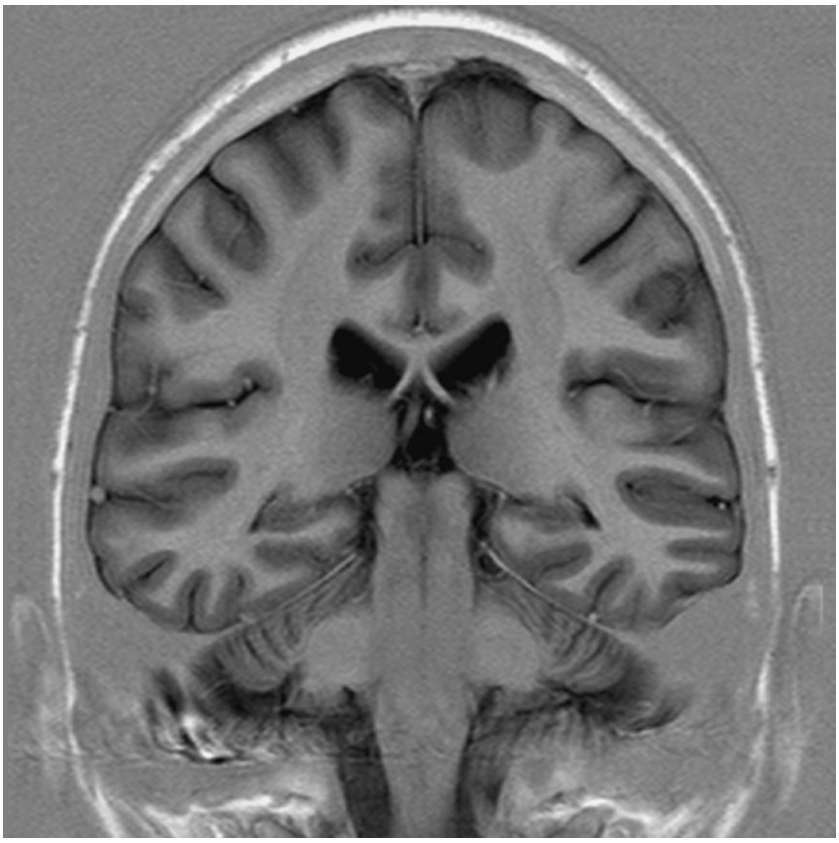

Figure 8.26 Coronal IR-FSE T2-weighted image video inverted to better demonstrate white matter lesions.

This sequence often provides images with high contrast between grey matter and white matter. A TI selected to null the signal from the white matter (about 300 ms) can be used to increase the grey/white (G/W) contrast in the hippocampal region. Images may be video inverted so that the white matter appears white and the grey matter appears grey. This is sometimes useful to increase the conspicuity of white matter lesions, which have a low signal intensity when using this technique and to improve visualization of the basil ganglia.

Image optimization

Technical issues

The SNR and contrast characteristics of the temporal lobes are usually excellent as the quadrature head coil and phased array coil yield high and uniform signal. Good spatial resolution is therefore achievable in relatively short scan times. Surface coils placed directly on the patient's head increase local SNR and resolution, especially in children. However, using this method, other areas of the brain cannot be imaged due to signal fall-off. As lesions within the temporal lobes are often quite small, volume

acquisitions are useful as they allow for very thin slices and no gap. As they are mainly utilized to demonstrate anatomy or contrast enhancement, an incoherent (spoiled) GRE that produces PD and T1 contrast is desirable. Alternatively, angling the slices perpendicular to the sylvian fissure in 2D acquisitions often improves visualization of the temporal lobes.

FSE is a useful pulse sequence especially for T2-weighted images, as FSE in conjunction with fine matrices acquires high-resolution images of the temporal lobes in a relatively short scan time. However, IR sequences can also be utilized to great effect. FLAIR sequences usually demonstrate subtle areas of increased T2 signal intensity better than T2-weighted SE or FSE sequences. As the brain contains no fat (only small amounts occur in the scalp), reducing the receive bandwidth significantly improves the SNR without significantly increasing chemical shift artefact, although there may be increased blurring (see *Flow phenomena and artefacts* in Part 1). A rectangular/asymmetric FOV can be effectively used to reduce scan times in axial and coronal imaging with the phase axis R to L.

Artefact problems

The main source of artefact in the temporal lobes is from flow motion of the carotid and vertebral arteries. A spatial pre-saturation pulse placed I to the FOV reduces this significantly. In large FOV imaging, there is no need to place spatial pre-saturation pulses anywhere other than I, as there is no flow coming into the FOV from any other direction. On coronal images, phase artefact from the carotid and vertebral vessels is often troublesome. Swapping the phase axis so that it lies S to I instead of R to L removes artefact away from the laterally situated temporal lobes, but oversampling is necessary to prevent the neck and the top of the head wrapping into the FOV along the phase axis. This method of swapping the phase direction is used most effectively to reduce artefact in the lateral portion of the temporal lobes. However, phase ghosting can still interfere with the more medially situated hippocampi, and if they are the ROI, there is probably no benefit in swapping the phase axis.

GMN also minimizes artefact in the temporal lobes. However, it not only increases the signal in vessels but also the minimum TE available and is therefore usually reserved for T2- and T2*-weighted sequences. Magnetic susceptibility is often seen at high field strengths on the coronal incoherent (spoiled) GRE images, especially at the border of the petrous ridge and the brain. If slices are prescribed through the temporal lobe only, spatial pre-saturation pulses are brought into the FOV in the volume acquisition to reduce aliasing along the slice select axis (see *Volume imaging* under *Parameters and trade-offs* in Part 1).

Patient considerations

Claustrophobia is often troublesome because of the enclosing nature of the head coil. Careful explanation of the procedure and reassurance is necessary. As many of these patients have drug-resistant epilepsy, careful

observation of the patient throughout the examination is important. The gradient noise and bore and alignment lights are potential sources of epileptic stimuli. If the patient fits during the examination, stop scanning immediately, withdraw the patient from the magnet, call a physician, and instigate first-aid measures. Owing to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is sometimes helpful to demonstrate small lesions in the temporal lobes.

Posterior fossa and internal auditory meatus

Common indications

- Symptoms that require the exclusion of an acoustic neuroma (vertigo, unilateral sensory hearing loss, tinnitus)
- Facial palsy/numbness
- Diagnosis of a posterior fossa lesion
- Haemifacial spasm
- Trigeminal neuralgia

Equipment

- Head coil (quadrature or multi-coil array)
- Immobilization pads and straps
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the inter-pupillary line is parallel to the couch and the head is straight. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the nasion. Straps and foam pads are used for immobilization.

Suggested protocol

Sagittal SE T1 or coherent GRE T2* (Figure 8.27)

Medium slices/gaps are prescribed either on each side of the longitudinal alignment light or through the internal auditory meatus (IAM) on one side only. The area from the foramen magnum to the superior border of the body of the corpus callosum is included in the image.

L 37 mm to L 20 mm (left IAM)
R 37 mm to R 20 mm (right IAM)

Axial SE/FSE T1 (Figure 8.28)

Thin slices/gap or interleaved slices are prescribed through the posterior fossa from the foramen magnum to the superior border of the petrous ridge. Coverage is increased if a large posterior fossa tumour is present.

Axial SE/FSE T1 with contrast

Slice prescription as for axial T1.

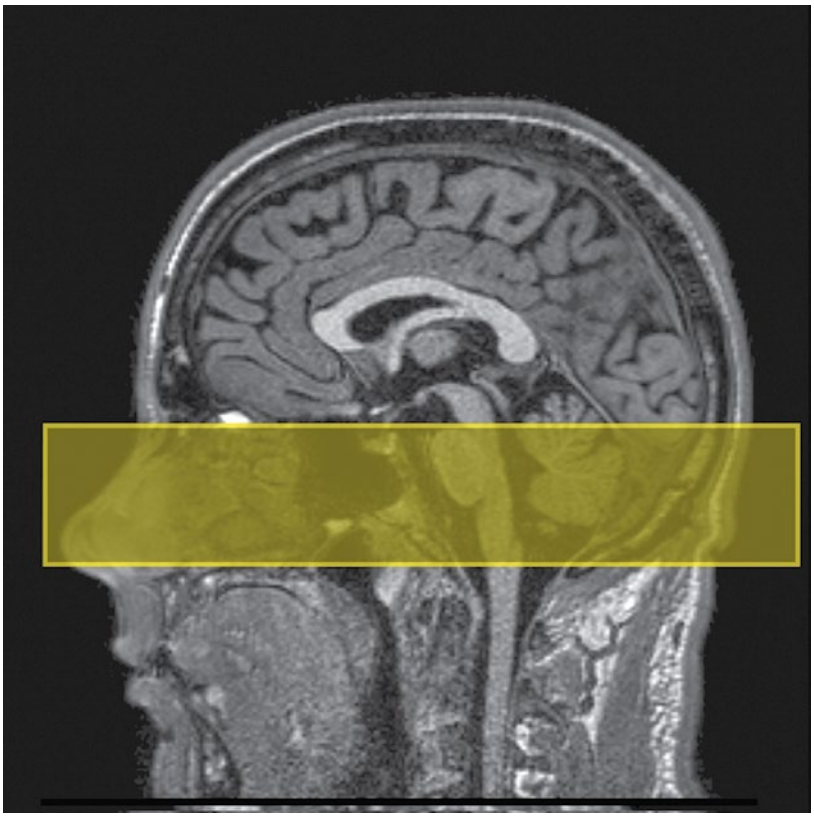

Figure 8.27 Sagittal SE T1-weighted midline slice through the brain showing slice prescription boundaries and orientation for axial imaging of the IAM.

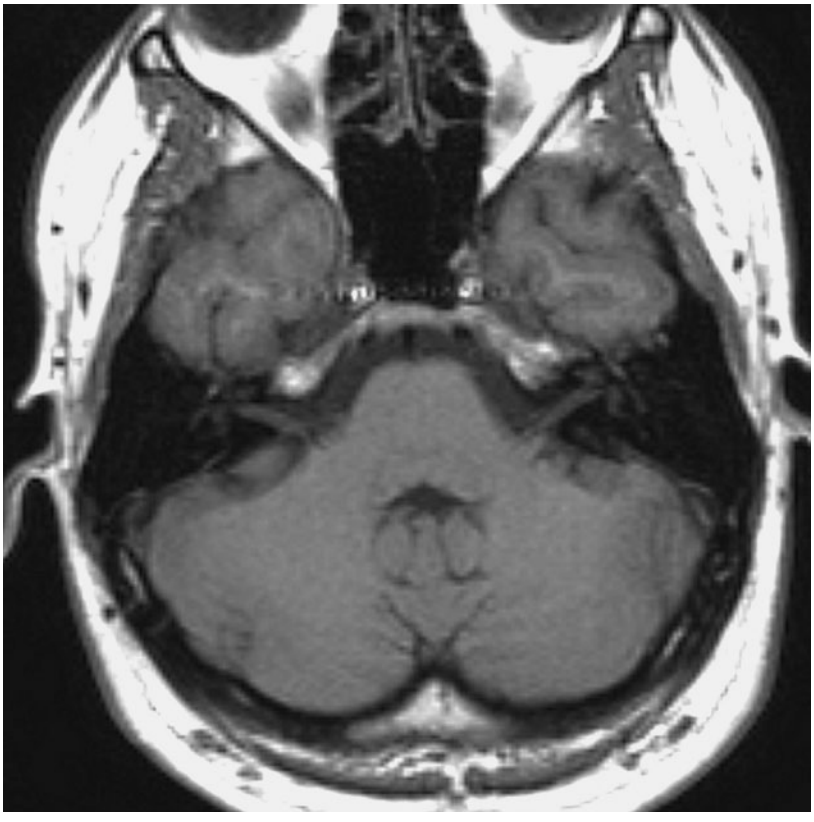

Figure 8.28 Axial SE T1-weighted image through the IAMs.

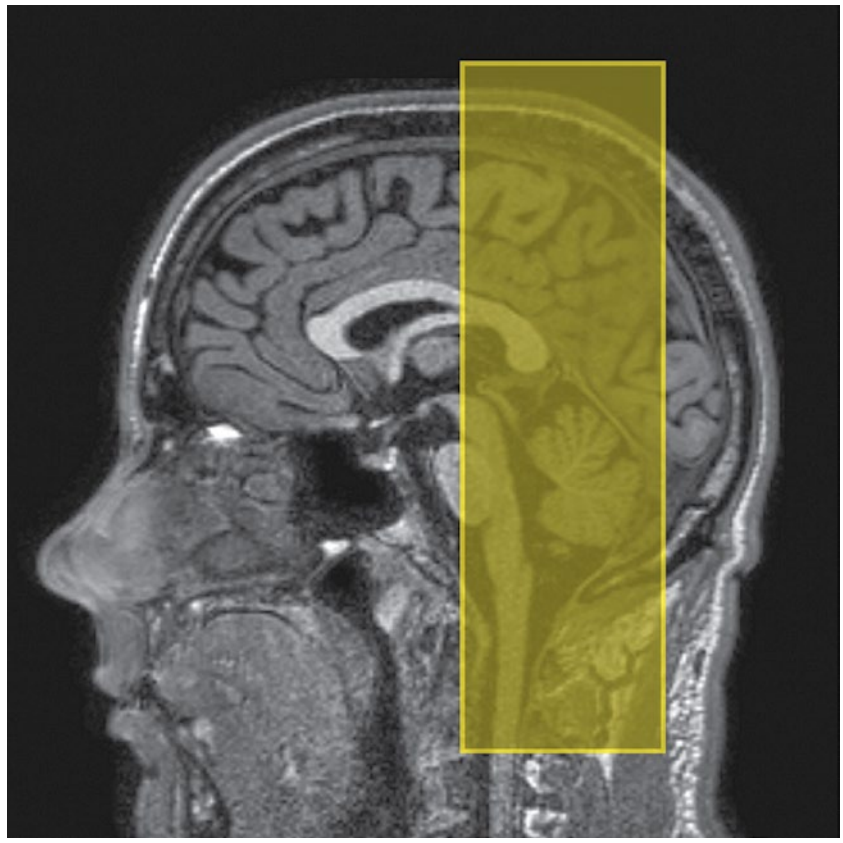

Figure 8.29 Sagittal SE T1-weighted midline slice through the brain showing slice prescription boundaries and orientation for coronal imaging of the IAMs.

Additional sequences

Coronal SE/FSE T1 +/– contrast

As for axial T1, **except** slices are prescribed from the posterior border of the cerebellum to the clivus (Figure 8.29).

3D incoherent (spoiled) GRE T1 +/– contrast

Thin slices and a small or medium number of slice locations are prescribed to cover the area as above (axially or coronally).

High-resolution technique

Axial FSE T2 (Figures 8.30 and 8.31)

Slices prescribed as for axial T1.

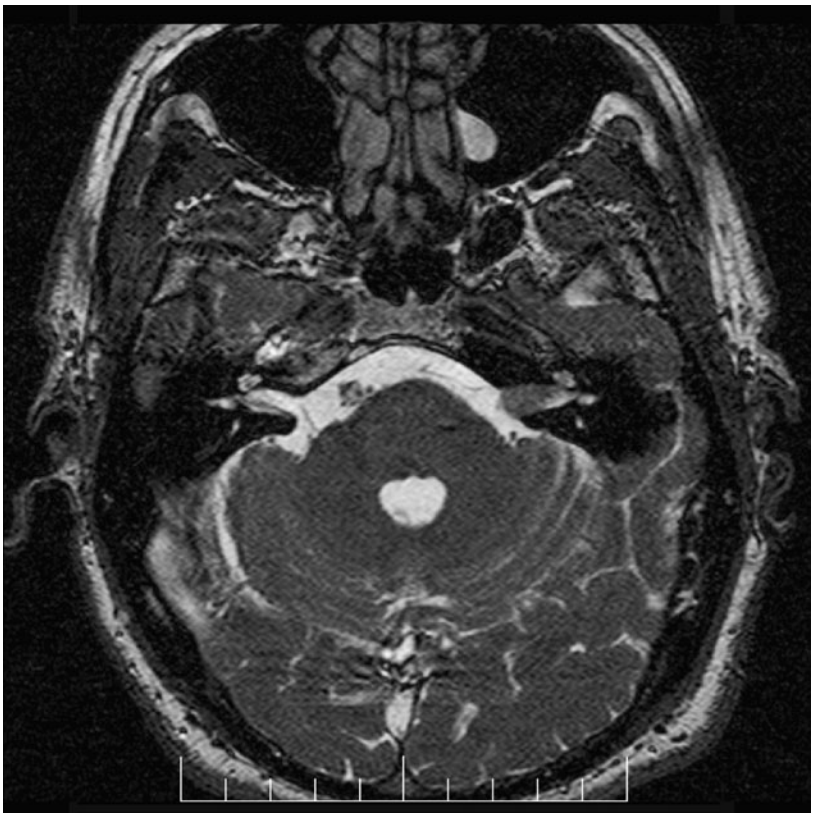

Figure 8.30 Axial FSE T2-weighted high-resolution image of the IAMs demonstrating a large left acoustic neuroma. This examination did not require contrast to confirm the diagnosis.

Thin slices/gap or interleaved	3 mm
Long TE	100 ms
Long TR	4000 ms
Long ETL	16
Matrix	512 × 256 or greater
NEX/NSA	4
FOV	20 cm

Coronal FSE T2

As for axial high-resolution T2, **except** prescribe slices from the posterior border of the cerebellum to the clivus.

3D FSE T2 or GRE T2* (Figure 8.31)

This sequence produces images with high contrast and SNR. Additionally, the images are contiguous and will not suffer from cross-excitation. An isotropic acquisition allows multi-planar reformatting (see *Volume imaging* under *Parameters and trade-offs* in Part 1). GRE sequences such as BGRE are commonly used as flow artefacts from the posterior fossa are reduced.

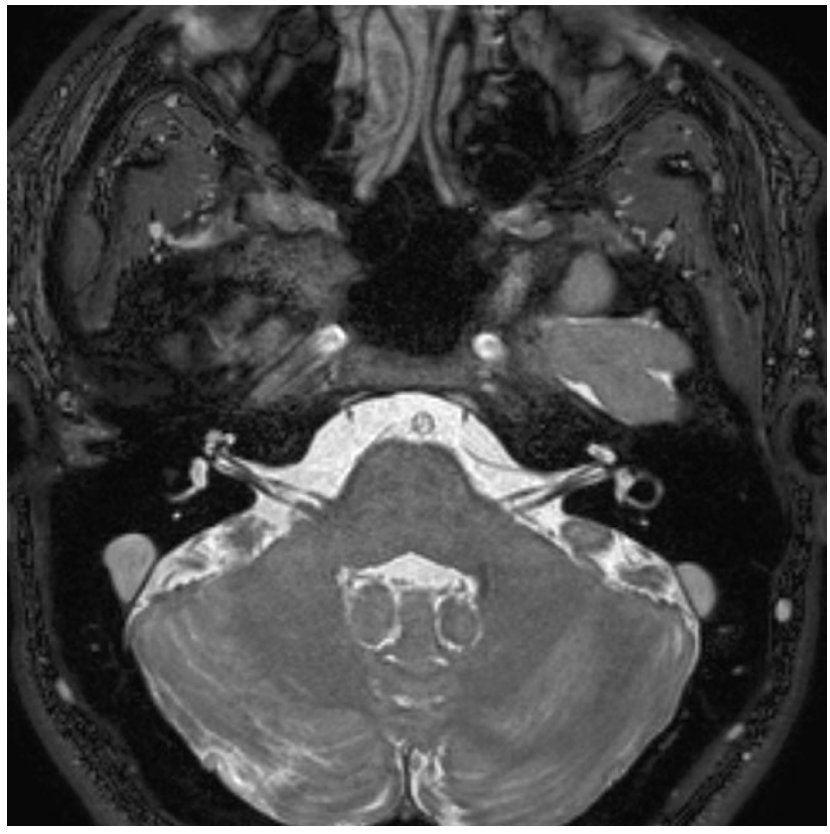

Figure 8.31 Axial FSE T2-weighted high-resolution image of the IAMs clearly showing the acoustic (posterior) and facial (anterior) nerves.

Image optimization

Technical issues

The IAMs are very small structures, and this examination is usually carried out to exclude a small acoustic neuroma situated within the canal. Therefore, it is important to achieve the highest spatial resolution possible in keeping with good SNR. The inherent SNR is usually excellent due to the high proton density of the brain tissue and the quality of the head coil. However, in the region of the IAM, the low proton density of the petrous bones and mastoids reduces the SNR. The thinnest slices and smallest gap or interleaving are used to optimize spatial resolution and visualization of the IAM. A very fine matrix is advisable, although increasing this too much can reduce the SNR to unacceptable levels. To optimize spatial resolution even further, the FOV is reduced compared with standard brain imaging. As a result of all these measures, the NEX/NSA may have to be increased to maintain SNR.

A high-resolution T2 FSE technique usually negates the use of contrast enhancement and the T1 sequence, especially when examining the IAM. When FSE is used in conjunction with matrices of at least 512, extremely good resolution and contrast are achievable. The T2 weighting of the sequence produces excellent contrast between the high signal of the CSF and the relatively low signal of the nerve. The fine matrix gives very good resolution of many of the cranial nerves and vessels in the posterior fossa. The facial and auditory nerves can usually be seen as distinct from each other within the canal, and under these circumstances, contrast may not be necessary. The NEX/NSA is increased to maintain the SNR, but the scan times are still only in the order of a few minutes due to the implementation of FSE. However, at lower field strengths, more NEX/NSA are usually required to achieve satisfactory SNR. This sequence is also useful in the coronal plane when looking specifically at the posterior fossa.

Volume acquisitions eliminate the slice gap and enable very thin slices to be acquired. Incoherent (spoiled) GRE sequences after contrast enhancement are common, but heavily T2-weighted acquisitions using FSE or GRE are often superior. Magnetization prepared sequences may also be of value. If the whole of the posterior fossa is under examination, spatial resolution may not be as important as with the IAM. If the ROI is large (such as a tumour invading the fossa), slightly thicker slices/gap are employed, and a routine brain protocol is often required.

Artefact problems

Flow motion from the venous sinuses is often troublesome in the posterior fossa. GMN minimizes this artefact, but it not only increases the signal in vessels but also the minimum TE available and is therefore reserved for T2-weighted sequences. Spatial pre-saturation pulses placed S and I to the FOV are also beneficial. Pe gating reduces artefact even further, but as the scan time is dependent on the patient's heart rate, it is sometimes rather time-consuming. The implementation of Pe gating is, therefore, best reserved for cases of severe flow artefact that cannot be reduced to tolerable levels by other measures. The use of spoiled GRE also reduces flow artefact due to use a very short TE (see *Pulse sequences* in Part 1).

Patient considerations

Claustrophobia is sometimes troublesome because of the enclosing nature of the head coil, and patients are often very deaf and may not respond to the system intercom. Under these circumstances, careful explanation and reassurance of the patient are important. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

As T1-weighted sequences yield low inherent contrast between the petrous ridge and the IAM and acoustic neuromas demonstrate good enhancement, contrast is usually necessary. However, the high-resolution technique and/or the 3D FSE (or BGRE) sequence often diagnoses or rules out an acoustic neuroma without contrast.

Pituitary fossa

Basic anatomy (Figure 8.32)

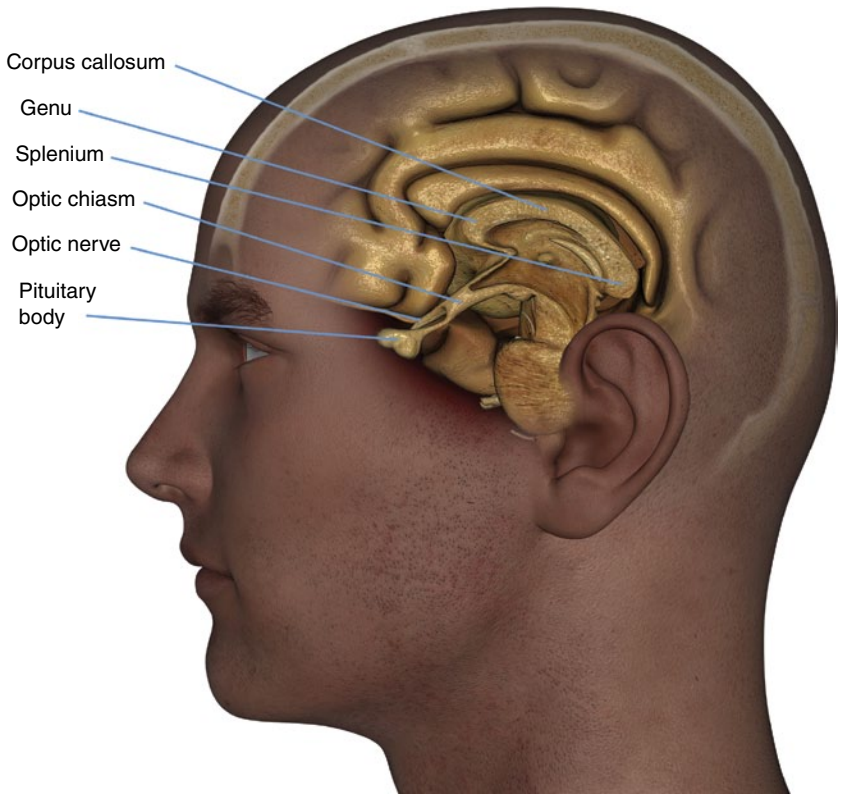

Figure 8.32 The pituitary and its relationships.

Common indications

- Investigation of diseases related to pituitary function (hyperprolactinaemia, Cushing's disease, acromegaly, hypopituitarism, diabetes insipidus, amenorrhoea)
- Hypothalamic disorders
- Visual field defect
- Post-operative assessment of pituitary adenomas

Equipment

- Head coil (quadrature or multi-coil array)
- Immobilization pads and straps
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the inter-pupillary line is parallel to the couch and the head is straight. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the nasion. Straps and foam pads are used for immobilization.

Suggested protocol

Sagittal SE T1 (Figure 8.33)

Thin slices/gap or interleaved slices are prescribed from the left to the right lateral borders of the pituitary fossa. The area from the inferior edge of the sphenoid sinus to the superior portion of the lateral ventricles is included in the image.

L 10 mm to R 10 mm

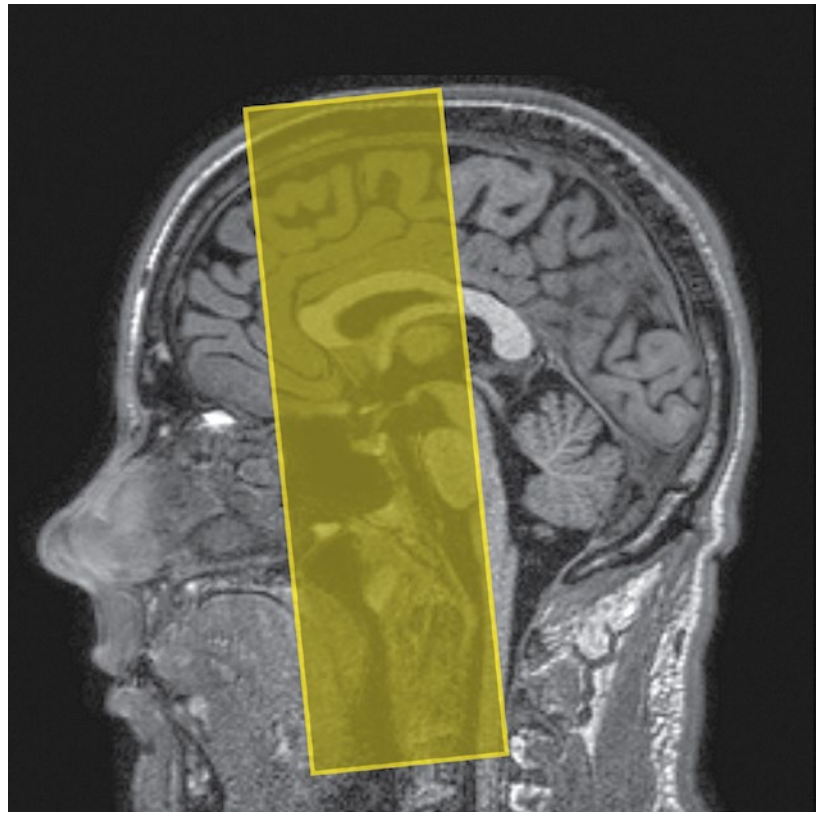

Figure 8.33 Sagittal SE T1-weighted midline slice through the brain showing slice prescription boundaries and orientation for coronal imaging of the pituitary fossa.

Coronal SE/FSE T1 (Figure 8.34)

Thin slices/gap or interleaved slices are prescribed from the posterior clinoids to the anterior clinoids. The inferior border of the sphenoid sinus to the superior portion of the lateral ventricles is included in the image. Use tissue suppression if a high signal mass is seen to exclude intra-sellar dermoid.

Additional sequences

Coronal SE/FSE T1 + contrast

Slice prescription as for coronal T1 without contrast.

Sagittal SE/FSE T1 +/– contrast

Slice prescription as for sagittal T1 without contrast.

3D incoherent (spoiled) GRE T1 +/– contrast

Thin slices and a small number of slice locations are prescribed through the pituitary fossa. Extend coverage anteriorly and posteriorly to allow for slice wrap.

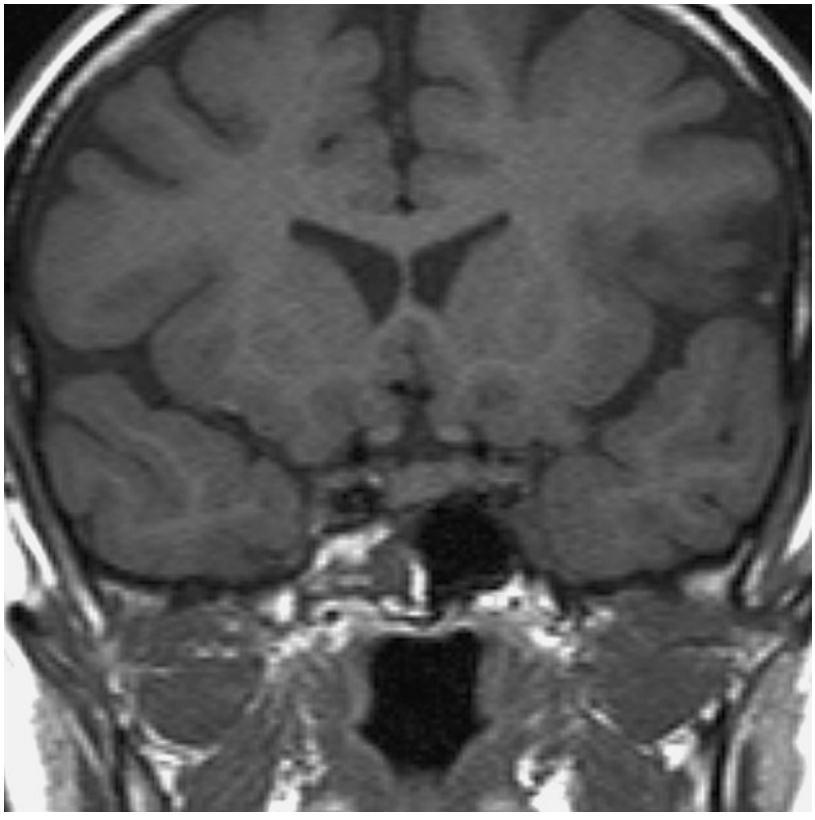

Figure 8.34 Coronal FSE T1-weighted image through the pituitary fossa.

Axial SE/FSE T1 +/– contrast

As for coronal T1, **except** slices prescribed from the floor of the pituitary fossa to the circle of Willis (Figure 8.35).

Image optimization

Technical issues

The pituitary fossa is a relatively small structure and, in addition, microadenomas are often difficult to visualize. As a result, spatial resolution is important. To optimize this, use thin slices interleaved and the smallest FOV possible in keeping with good SNR. In addition, a fine matrix used in conjunction with multiple NEX/NSA is necessary to maintain SNR. Volume acquisitions allow for thinner slices and no gap and are therefore sometimes useful in this area. As anatomical detail and contrast enhancement are important, an incoherent (spoiled) GRE sequence is required.

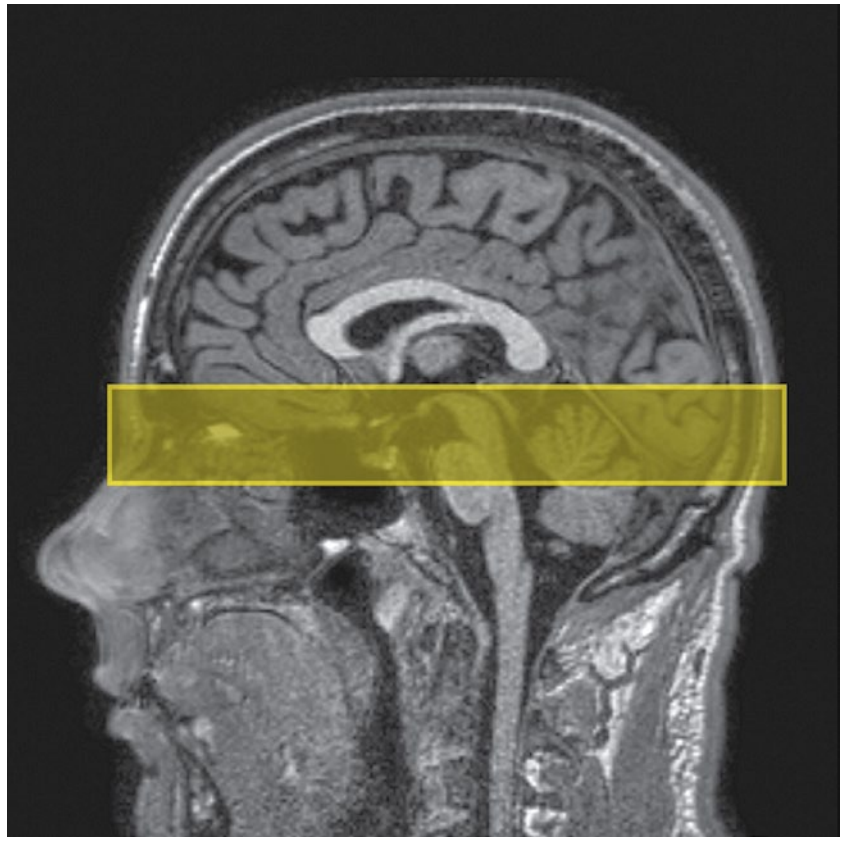

Figure 8.35 Sagittal SE T1-weighted midline slice through the brain showing slice prescription boundaries and orientation for axial imaging of the pituitary fossa.

Artefact problems

The pituitary fossa is located just anterior and inferior to the circle of Willis, and therefore, flow artefact is often more troublesome than in standard brain imaging. In addition, the smaller FOV increases the likelihood of aliasing, so oversampling is necessary if anatomy exists outside the FOV in the phase direction.

In volume acquisitions, only a small slice slab is required, and therefore, slice wrap is usually troublesome. When prescribing slices, always increase coverage to compensate for this. Additionally, extra slices increase SNR. In a 3D sequence, SNR is proportional to the square root of the number of slices. GMN minimizes flow artefact in the pituitary region; however, it not only increases the signal in vessels but also the minimum TE available and is therefore not usually beneficial in T1-weighed sequences. Incoherent (spoiled) GRE sequences through the pituitary fossa may suffer from excessive magnetic susceptibility artefacts when acquired on high field systems (1.0 T and above). This is minimized by using thin slices (i.e. 3 mm or less) and the shortest possible TE. Lower field systems can benefit from the increased SNR provided by 3D acquisitions while taking advantage of the reduced magnetic susceptibility artefacts associated with the reduced field strength.

Patient considerations

Claustrophobia is often troublesome due to the enclosing nature of the head coil. Careful explanation of the procedure and reassurance are required to avoid the necessity of sedation. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely required except for diabetes insipidus and hypothalamic disorders. Contrast is sometimes necessary for Cushing's disease because micro-adenomas are often very small, and not well seen on unenhanced scans. As a general rule, macro-adenomas enhance quickly, but micro-adenomas do not. However, it should be noted that eventually all the pituitary gland enhances as well as the micro-adenoma itself, and therefore, careful timing of post-contrast scans is important. A technique that is often employed is a rapid/dynamic scanning sequence. Thin slices (3 mm) are acquired through the pituitary generally with a scan time of 1.5 min or less. This is repeated three to four times with minimal delay between each dynamic set. In the early images, the normal pituitary gland enhances while the micro-adenoma does not be. As previously mentioned, within a few minutes, the micro-adenoma also enhances rendering it isointense with the pituitary gland. It is common to see a high signal intensity in the posterior lobe of the pituitary on unenhanced images, especially in patients with diabetes. At present, the causes and clinical significance of this have not been fully evaluated. In addition, studies have shown that half-dose gadolinium may be optimal for imaging the pituitary.

Orbits

Basic anatomy (Figures 8.36 and 8.37)

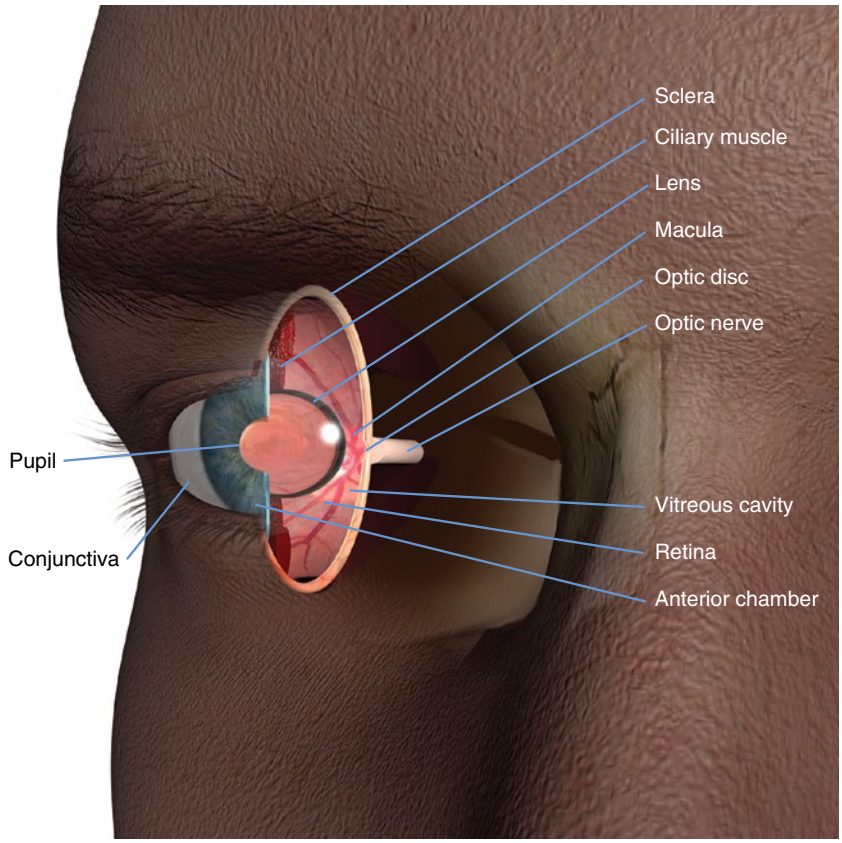

Figure 8.36 The structures of the orbit in sagittal section.

Common indications

- Proptosis
- Visual disturbance
- Evaluation of orbital or ocular mass lesions

Equipment

- Small surface coil for globe and orbit
- Quadrature head coil or multi-coil array coil for orbital apex, chiasm and intracranial optic pathways

- Immobilization straps and foam pads
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch. Both orbits are usually examined at the same time. If surface coils are used, these are placed over each orbit but should not touch the patient. Special holders are often provided by the manufacturers to enable the coils to be placed anteriorly over the eyes. Ensure that the receiving side of the coils faces the orbits, that is, towards the table. The patient assumes a fixed gaze, straight ahead, with the eyes open. This enables the patient to focus and keeps the eyes still, thereby reducing motion artefact. Any eye make-up is removed prior to the examination as this causes image artefact and patient discomfort, especially if it contains metal.

The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the orbits. If surface coils are used, this corresponds to the centre of the coils. Straps and foam pads are used for immobilization.

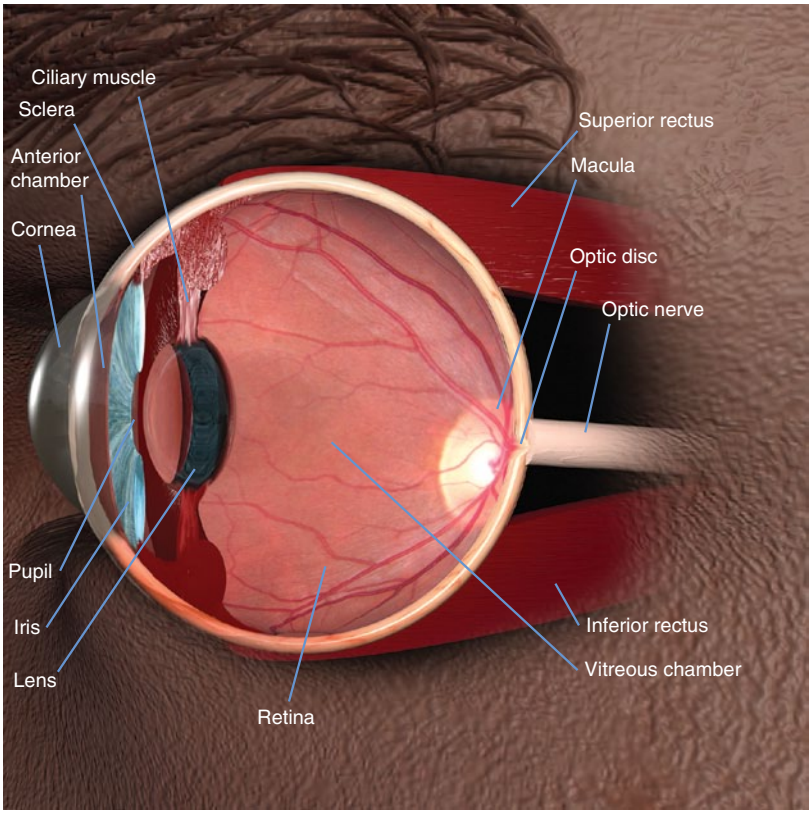

Figure 8.37 Inner structures of the eye.

Suggested protocol

Sagittal SE/FSE T1

Medium slices/gaps are prescribed on either side of the longitudinal alignment light through the whole head. The area from the foramen magnum to the top of the head is included in the image.

L 37 mm to R 37 mm

Axial/oblique SE/FSE T1 or T2 (Figure 8.38)

Thin slices/gap or interleaved slices are prescribed either in the true axial plane or angled to the optic nerve from the inferior margin of the orbit to above the chiasm (Figures 8.39 and 8.40).

Coronal SE/FSE T2 or STIR

As for axial/oblique T1, **except** prescribe slices from the posterior border of the globe to the posterior aspect of the chiasm. Use tissue suppression on SE/FSE sequences (Figure 8.41).

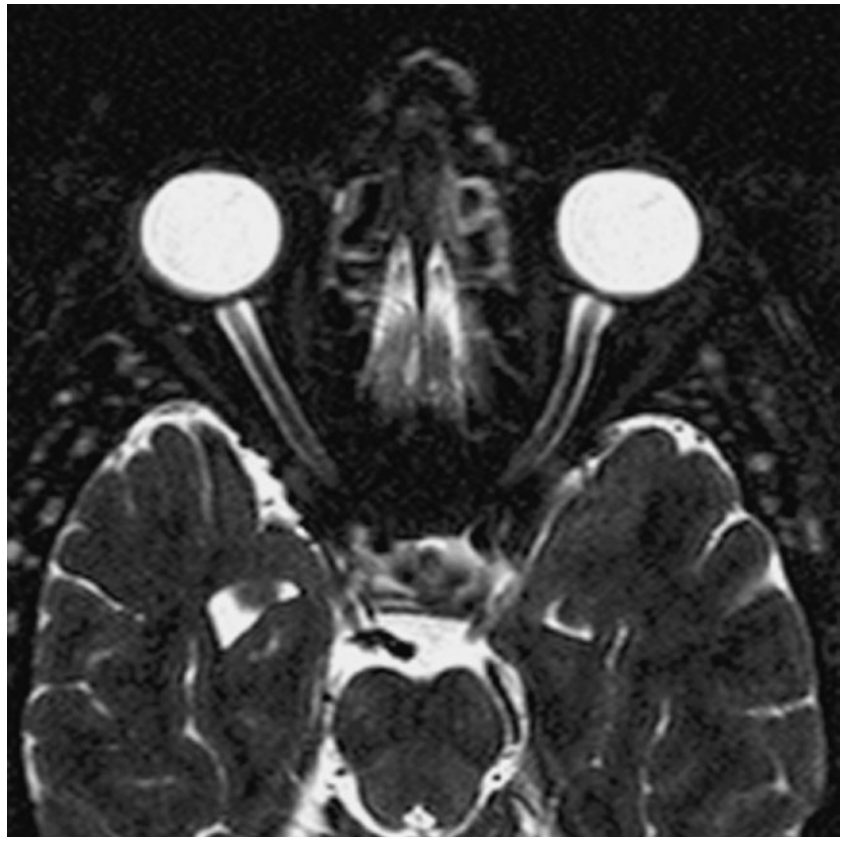

Figure 8.38 Axial/oblique FSE T2 of the orbits clearly demonstrating the lens of the eye, the globe, the optic nerves and the chiasm.

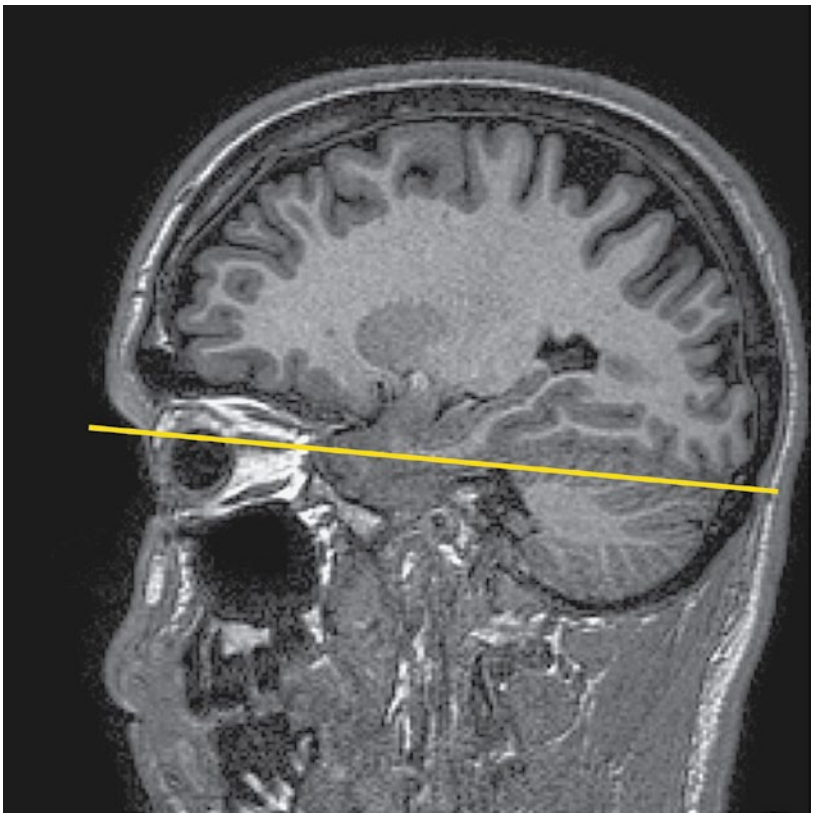

Figure 8.39 Sagittal SE T1-weighted image of the orbit and optic nerve showing the correct orientation of axial/oblique slices parallel to the optic nerve.

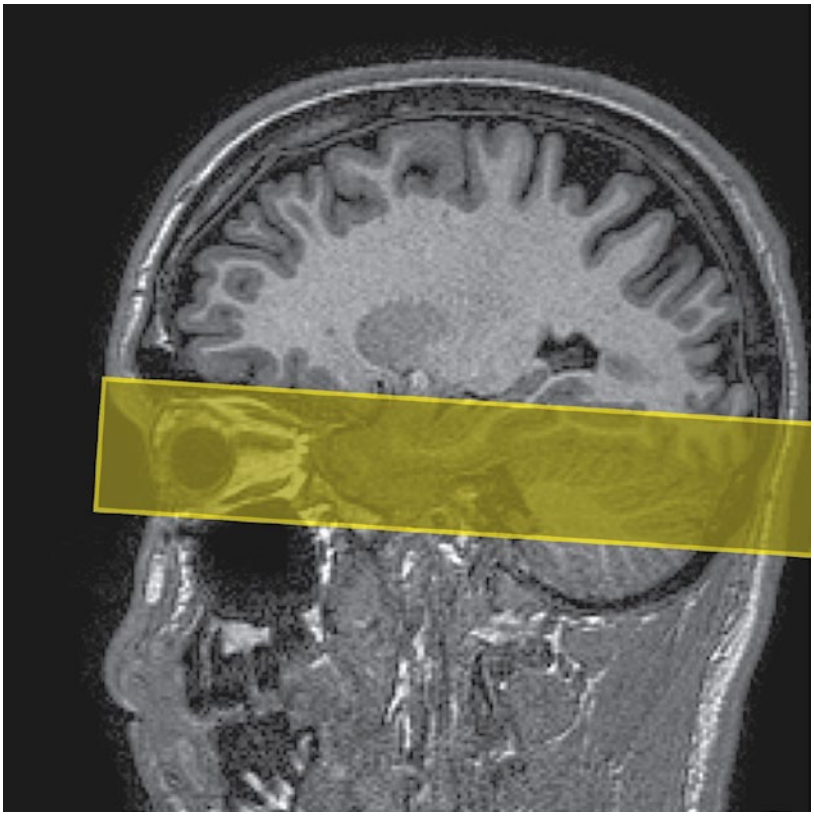

Figure 8.40 Sagittal SE T1-weighted slice through the orbit showing slice prescription boundaries and orientation for axial/oblique imaging of the orbits and optic nerve.

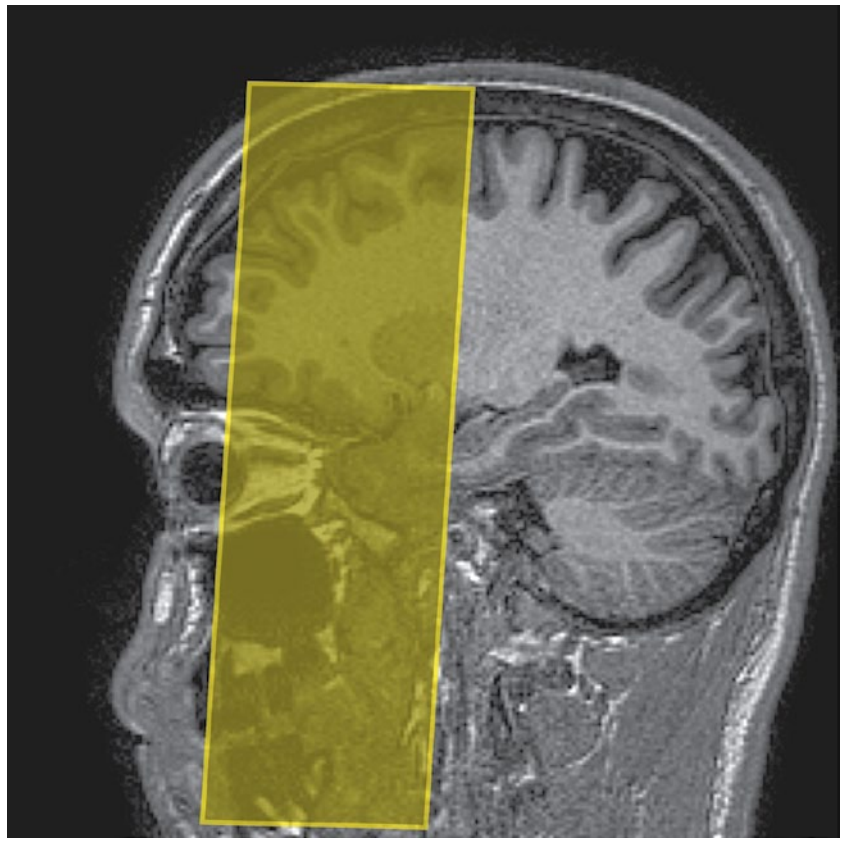

Figure 8.41 Sagittal SE T1-weighted slice through the orbits showing slice prescription boundaries and orientation for coronal imaging of the orbits and optic nerve.

Additional sequences

Coronal/axial SE/FSE T1

As for axial/coronal already mentioned, **except** use contrast and tissue suppression.

If optic neuritis is suspected, scan the whole brain.

Image optimization

Technical issues

If surface coils are used, the SNR in the region of the globe and the anterior aspect of the orbit is high. This allows for excellent spatial resolution of small structures such as the optic nerve, but there is signal fall-off at the orbital apex. Therefore, the choice of coil largely depends on the coverage required. If the globe, the retro-orbital area and the portion of the optic nerve within the orbit are of interest, a surface coil is the best choice. If, however, information about the chiasm and intracranial optic pathways is required, the head coil is necessary. Thin interleaved slices or a very

small gap are needed to obtain the resolution within the orbit and chiasm. Fine matrices and a small FOV are also required to maintain resolution, and therefore, multiple NEX/NSA are necessary to preserve SNR.

FSE is probably the ideal sequence, especially for T2-weighted images, as speed is important due to motion artefact from blinking and eye movement. Due to the high fat content within the orbit, tissue suppression/STIR are often necessary to visualize orbital structures adequately. This is especially true on the FSE T2 sequences, where fat returns a signal similar to the CSF surrounding the optic nerve.

Artefact problems

The main source of artefact is from eye movement. Instruct the patient to focus on the roof of the bore of the magnet and to blink as little as possible. Use the fastest sequence possible in keeping with good contrast, resolution and SNR. FSE is a valuable pulse sequence in achieving this. Flow motion in the circle of Willis is often troublesome in the chiasm, which lies just beneath it. Use spatial pre-saturation bands placed S and P to the FOV to reduce this. In addition, spatial pre-saturation bands placed I to the FOV reduce flow motion from the carotids. GMN also minimizes flow motion, but as it increases the signal in vessels and the minimum TE, it is usually reserved for the T2-weighted sequences.

As a small FOV is commonly used in this area, aliasing is a problem especially if the head coil is employed, because tissue outside the FOV in the phase axis produces signal. Oversampling is therefore required to eliminate this. If any magnetic susceptibility artefact is seen, especially superiorly to the orbit, this may be due to eye make-up left on the eyelid. This must be totally removed prior to the examination. Chemical shift artefact can occur on high field strength systems due to the presence of intra-orbital fat. Fat suppression techniques reduce this, and if they are used, the receive bandwidth can be reduced to increase the SNR. Additional shimming may be required before tissue suppression sequences.

If GRE sequences are utilized, care should be taken to ensure the TE is in phase to eliminate chemical shift artefact. If fat suppression is utilized with a T1-weighted GRE, then the shortest possible TE should be selected (regardless of it being in phase or out of phase) as chemical shift will not be seen because there is no signal for the water signal to shift against.

Patient considerations

Some patients may be blind or partially sighted and consideration should be given to this. The patient is carefully instructed on the importance of keeping the eyes still. Focusing is practised before the examination, and the patient told when, during the examination, blinking is undesirable and when it is allowed. Obviously, if the patient is blind, focusing is not possible, and so the technique is adapted to ensure that the sequences are as fast as possible. All eye make-up must be removed prior to the

examination to avoid artefact and to reduce discomfort, as some make-up can heat up during the examination. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is valuable in assessing the optic nerve and chiasm as well as intra-orbital masses. However, due to the presence of orbital fat, the administration of contrast only serves to increase the signal of these structures so that they are isointense with fat on T1-weighted images. Therefore, some means of suppressing the fat signal is required when using contrast enhancement. It is important to note that STIR cannot be used for this purpose, as contrast decreases the T1 recovery time of the tissue so that it is similar to that of fat. Therefore, the inverting pulse used in STIR sequences sometimes nullifies the signal from enhancing tissues as well as fat. If fat suppression is required, use tissue suppression or any technique that suppresses fat based on resonant frequency. It should also be mentioned that if a contrast agent is given, at least one sequence covering the entire brain should be acquired.

Paranasal sinuses

Basic anatomy (Figure 8.42)

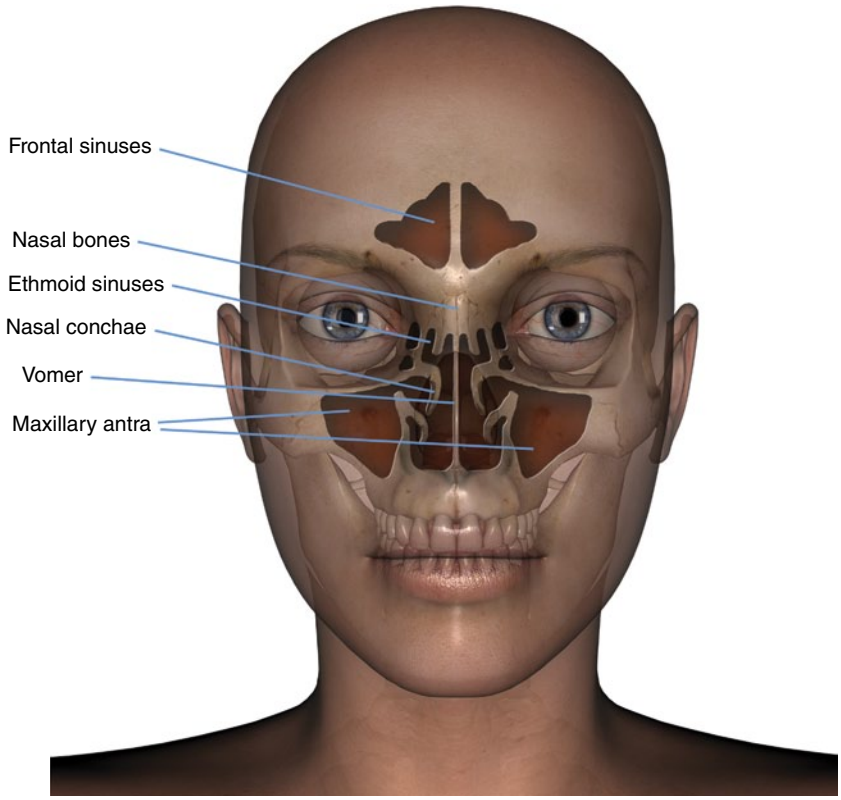

Figure 8.42 Anterior view of the paranasal sinuses.

Common indications

- Staging of neoplasms prior to resection
- Distinction of inflammation from neoplasm

Equipment

- Head coil (quadrature or multi-coil array)
- Immobilization foam pads and straps
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the inter-pupillary line is parallel to the couch and the head is straight. The patient is positioned so that the

longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the nasion. Straps and foam pads are used for immobilization.

Suggested protocol

Sagittal SE T1

Medium slices/gaps are prescribed on either side of the longitudinal alignment light through the whole head. The area from the foramen magnum to the top of the head is included in the image.

L 37 mm to R 37 mm

Coronal SE/FSE T1

Medium slices/gaps are prescribed from the posterior portion of the sphenoid sinus to the tip of the nose. All of the paranasal sinuses are included in the image from the inferior margin of the maxillary sinuses to the superior border of the frontal sinuses (Figure 8.43).

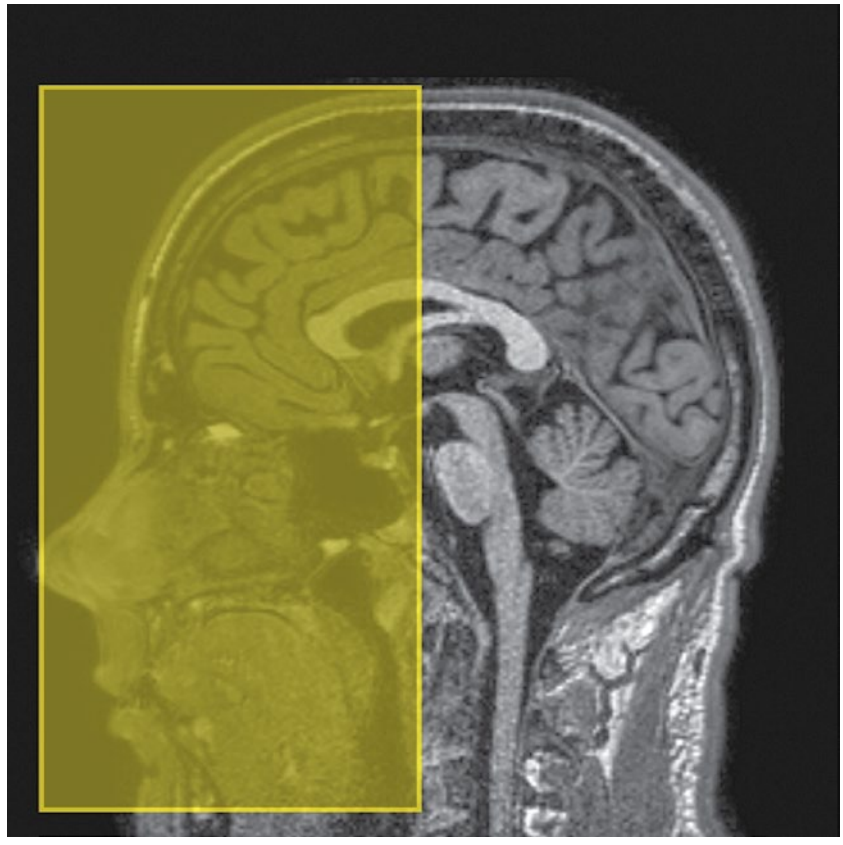

Figure 8.43 Sagittal SE T1-weighted midline slice through the brain showing slice prescription boundaries and orientation for coronal imaging of the paranasal sinuses.

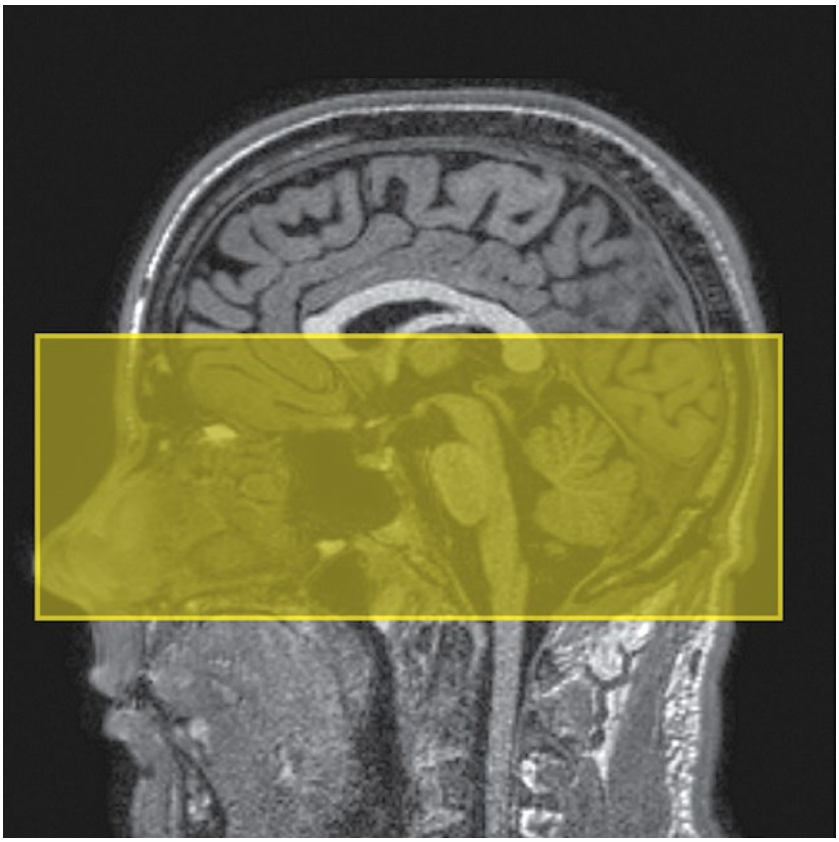

Figure 8.44 Sagittal SE T1-weighted midline slice through the brain showing slice prescription boundaries and orientation for axial imaging of the paranasal sinuses.

Axial SE/FSE T1

As for coronal T1, **except** prescribe slices from the inferior border of the maxillary sinuses to the superior edge of the frontal sinuses (Figure 8.44).

Coronal/axial SE/FSE PD/T2

Slice prescription as for axial and coronal T1.

Additional sequences

The use of MR to image the sinuses has recently extended into interventional procedures. The use of open magnet systems that allow near real-time imaging has proved beneficial in functional endoscopic sinus surgery. The multi-planar capabilities of MR enable rapid visualization of the optic nerve in three planes so that this type of surgery has become safer and quicker.

Image optimization

Technical issues

The SNR and CNR of the sinuses are often poor due to the low proton density of the air-filled cavities. MRI does not demonstrate bony resolution as well as computer tomography (CT), but it is useful for visualizing the nature and extent of soft tissue masses. Spatial resolution is not usually as important as good SNR in this region. Medium slices are selected to maintain SNR, and multiple NEX/NSA are employed as long as the scan time is kept within reasonable limits. The use of FSE enables the implementation of fine matrices and multiple NEX/NSA while maintaining relatively short scan times.

Artefact problems

The main source of artefact is from the carotid, vertebral and jugular vessels. The use of spatial pre-saturation pulses placed I to the FOV usually reduces this to acceptable levels. GMN may be employed, but as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences. On the axial and coronal images, phase artefact occurs in the R to L direction, which may obscure the maxillary sinuses. However, the strategy of swapping the phase direction places this artefact S and I, which can then interfere with the frontal, ethmoid and sphenoid sinuses. Under these circumstances, swapping the phase axis rarely has merits unless the maxillary sinuses are under examination and flow artefact is a particular problem. If the phase axis is swapped on the coronal images, oversampling is necessary to prevent wrap from the neck and top of the head. Magnetic susceptibility artefact from dental fillings sometimes interferes with the maxillary sinuses. Susceptibility artefacts can be reduced by increasing the receive bandwidth and avoiding GRE sequences if possible.

Patient considerations

Claustrophobia is often troublesome because of the enclosing nature of the head coil. Under these circumstances, reassurance and a careful explanation of the procedure are required. Some patients may have profuse nasal secretions so that they need to swallow or blow their nose frequently during the examination.

Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast enhances the mucous lining of the sinuses, but it is not commonly used for sinus disease. It is, however, useful to distinguish between enhancing tumour and non-enhancing effusion.

Pharynx

Basic anatomy (Figure 8.45)

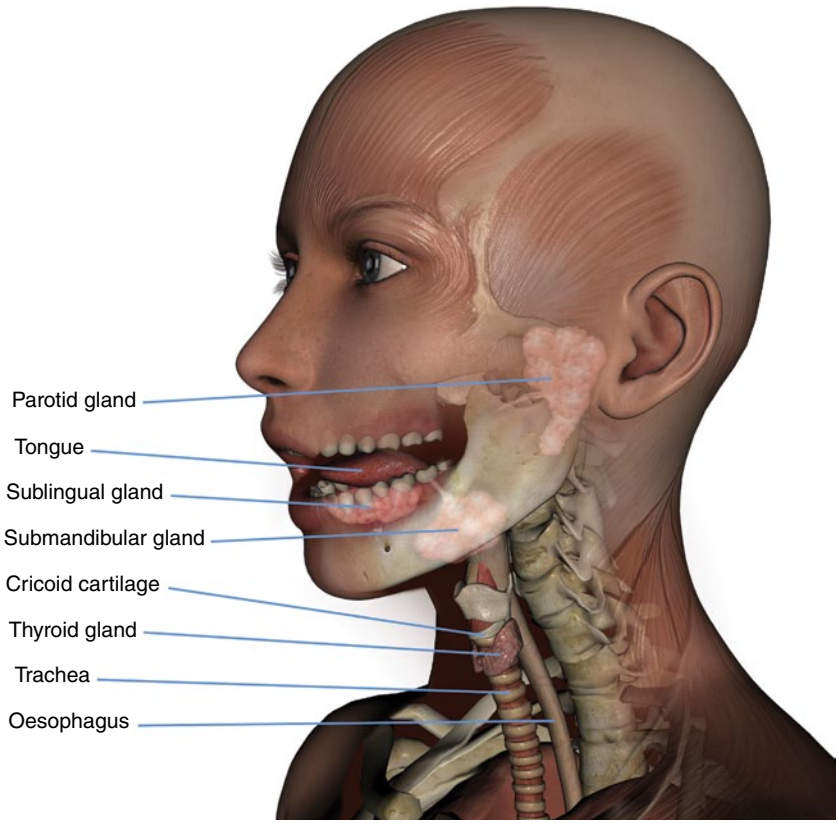

Figure 8.45 Sagittal/Oblique section through the mouth, larynx and pharynx.

Common indications

- Staging of oropharyngeal carcinoma
- Pharyngeal and parapharyngeal masses
- Investigation of sleep apnoea
- Swallowing disorders

Equipment

- Anterior neck coil/volume neck coil for cervical nodal involvement
- Head coil (quadrature or phased array) for pharyngeal area and base of skull
- Immobilization pads and straps
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the inter-pupillary line is parallel to the couch and the head is straight. If the neck is to be imaged for nodal involvement, the anterior or volume neck coil is placed around or anterior to the patient's neck. Care should be taken to include the base of the skull within the coil. The patient's head is straightened as this usually straightens the neck as well.

The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the angle of the jaw. When imaging the cervical nodes, the vertical alignment light should be located midway between the posterior and anterior surfaces of the neck. A soft pad may be placed under the patient's neck to facilitate this, although many dedicated coils ensure that the neck naturally assumes the correct position. Straps and foam pads are used for immobilization.

Suggested protocol

Coronal SE/FSE T1 (Figure 8.46)

Thin slices/gaps are prescribed from the posterior border of the cervical cord to the anterior surface of the neck. This distance is measured relative to the vertical alignment light before the examination. The area from the skull base to the sterno-clavicular joints is included in the image (Figure 8.47).

P 25 mm to A 25 mm

Axial SE/FSE PD/T2

Thin slices/gaps are prescribed from the thyroid cartilage to the base of the skull (Figure 8.48).

Sagittal SE/FSE PD/T2

As for axial PD/T2, **except** prescribe slices from the left to the right lateral walls of the pharynx.

The coverage is increased if nodal or parapharyngeal disease is suspected. The area from the skull base to the thyroid cartilage is included in the image (Figure 8.49).

Additional sequences

When assessing tumour, spread the scan plane, and slice coverage is altered depending on the site of the primary tumour as follows:

- Oral tumours include cervical nodes in the axial and coronal plane.
- Nasopharyngeal tumours include the sphenoid sinus in the sagittal and axial plane.

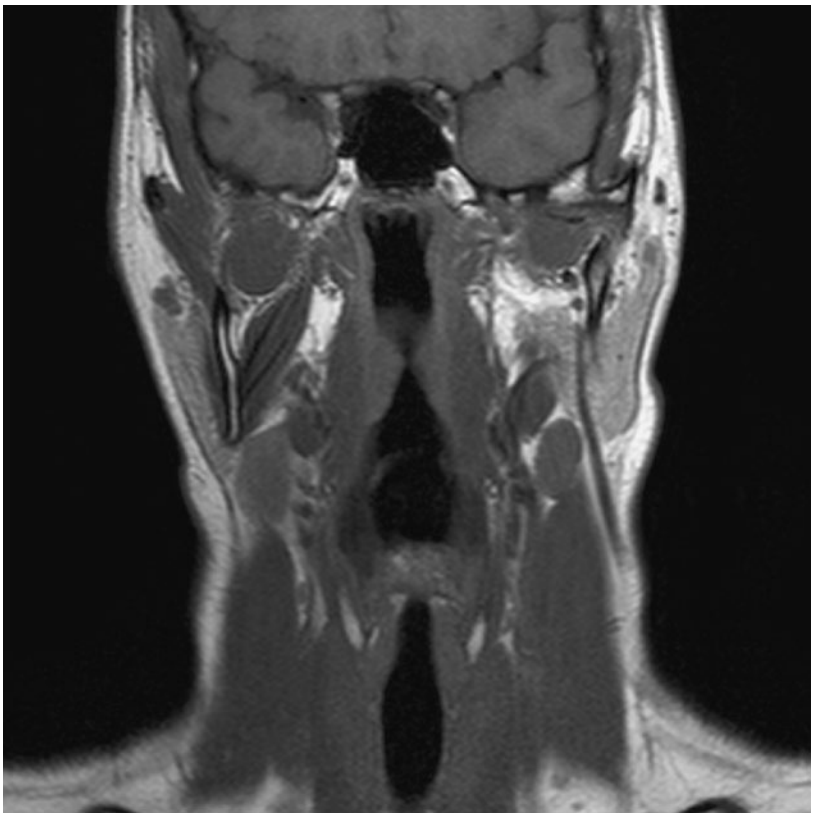

Figure 8.46 Coronal FSE T1-weighted localizer of the pharynx.

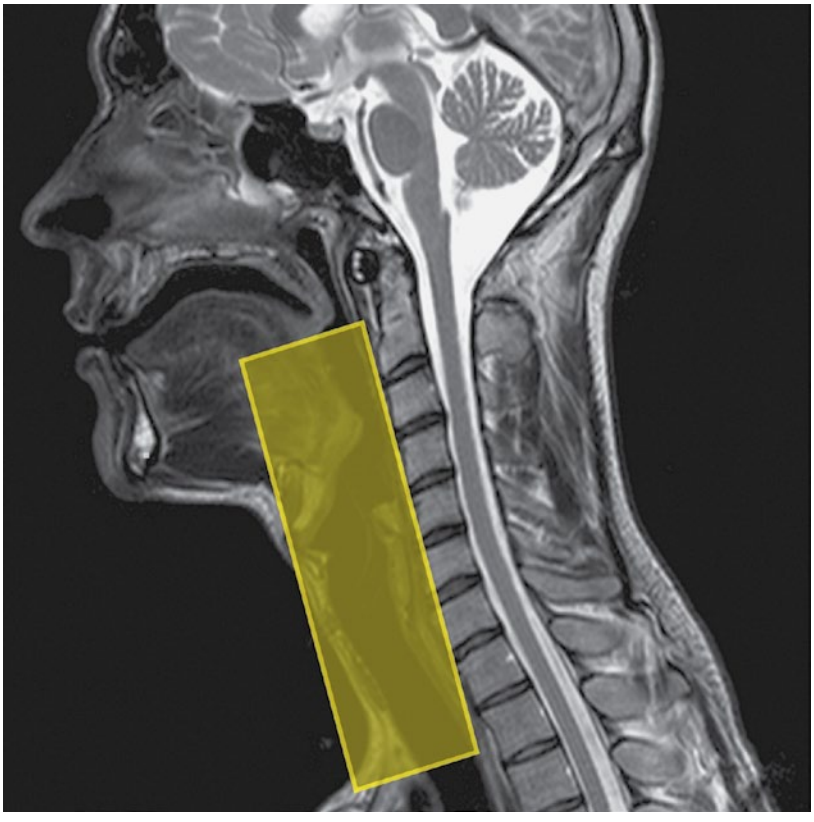

Figure 8.47 Sagittal FSE T2-weighted localizer showing slice prescription boundaries and orientation for coronal imaging of the pharynx.

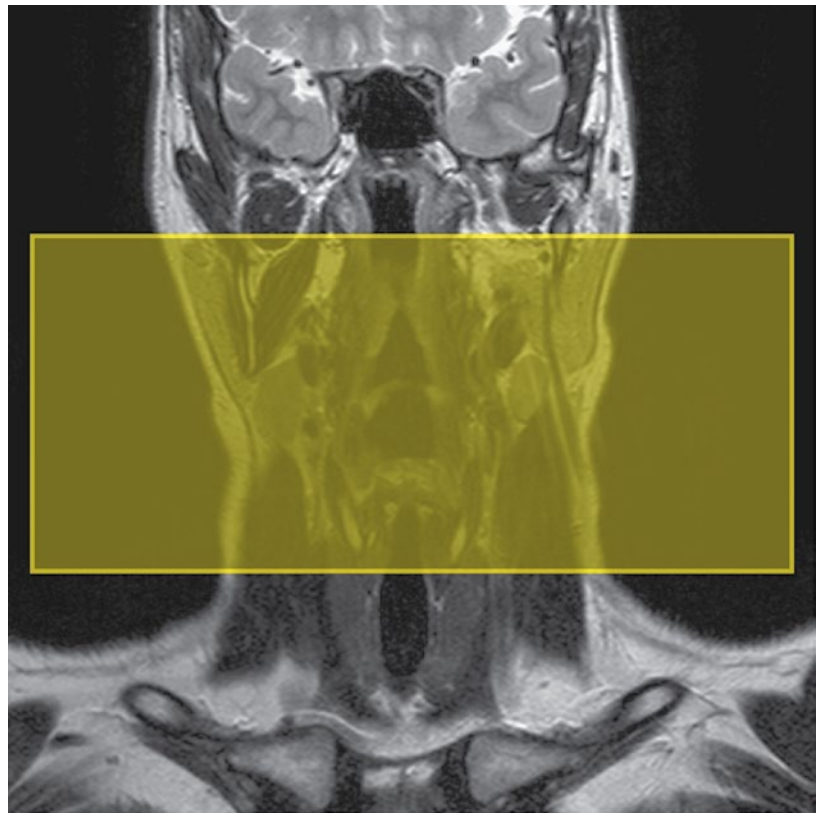

Figure 8.48 Coronal FSE T1 localizer showing slice prescription boundaries and orientation for axial imaging of the pharynx.

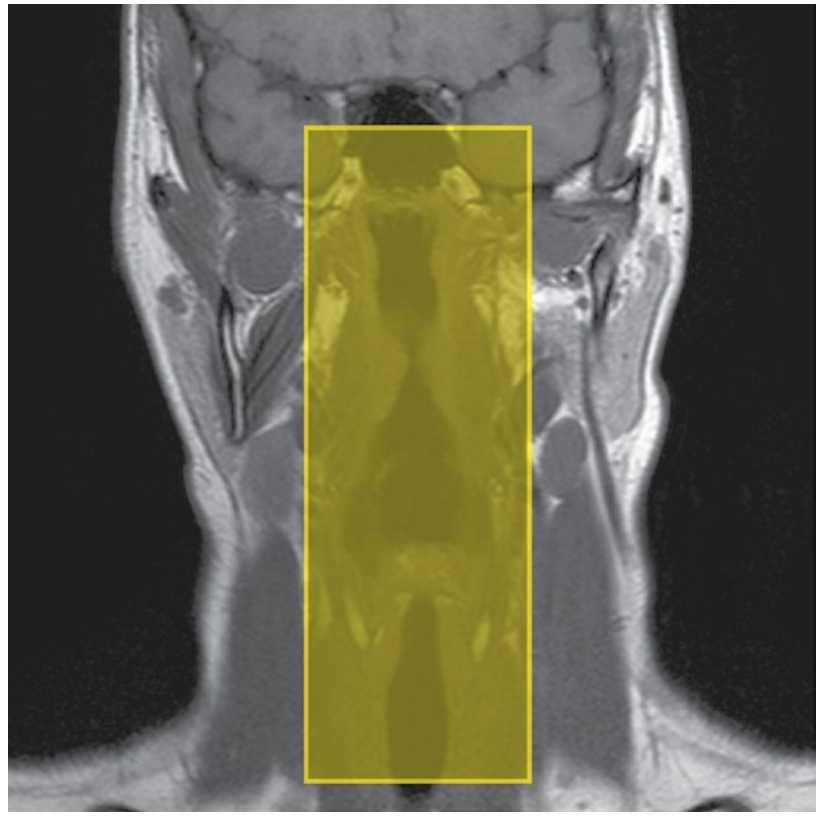

Figure 8.49 Coronal FSE T1 localizer showing slice prescription boundaries and orientation for sagittal imaging of the pharynx.

- Oropharyngeal tumours include the parapharyngeal space, the base of the middle cranial fossa and the anterior triangle of the neck in the axial and coronal plane.

Rapid sequences are proving useful in dynamic imaging of the pharynx to assess swallowing. The patient is instructed to swallow bread or mashed potato soaked in gadolinium and the bolus imaged during swallowing. As the upper pharyngeal phase of swallowing is very rapid, sequences such as EPI, which can acquire 20–25 images per second, are necessary in combination with good resolution. In addition, 3D imaging of the pharynx may be utilized to assess anatomy during sleep.

Image optimization

Technical issues

The anterior portion of the neck is a notoriously difficult area to examine. The SNR is often poor, especially if a substandard coil is used. The head coil is probably the best coil for this examination, although an anterior or volume coil moulded to the face and neck is necessary to best visualize the cervical lymph nodes and inferior tumour spread. However, even with the best coils, multiple NEX/NSA are often necessary to maintain SNR. Spatial resolution is also important in this area, and therefore, thin slices/gap and a fairly fine matrix are required to optimize resolution. The use of these matrices and multiple NEX/NSA often leads to long scan times.

A solution to these problems is to use FSE in conjunction with a rectangular/asymmetric FOV. FSE reduces the scan time significantly and yields higher SNR, especially on the T2-weighted sequences. A rectangular/asymmetric FOV allows the acquisition of fine matrices in shorter scan times. In coronal and axial imaging, the long axis of the rectangle is placed S to I and A to P, respectively.

Artefact problems

Artefact in this region arises from flow motion in the carotid, vertebral and jugular vessels, and from swallowing. Spatial pre-saturation pulses placed S and I to the FOV reduce flow artefact significantly. Bringing the spatial pre-saturation pulses into the FOV increases their effectiveness, but care must be taken that they do not obscure important anatomy. GMN further reduces artefact, but as it also increases the signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences.

Swallowing is a common problem in this area. If the patient swallows too often, motion artefact interferes with the image. Using multiple NEX/NSA to average out this artefact reduces phase ghosting, but leads to longer scan times. If the patient does not swallow at all, pooling of saliva in the pyriform fossae can sometimes lead to difficulties in image interpretation. The patient should be advised to swallow as little as possible during the

examination but to try to clear the mouth of saliva when they do. Respiratory motion may move the anterior neck coil during the acquisition of data. If this is a problem, instruct the patient to breathe shallowly. In addition, small foam pads placed between the chest and the coil help to reduce coil movement. Magnetic susceptibility artefact from dental fillings sometimes interferes with important anatomy. Susceptibility artefacts can be reduced by increasing the receive bandwidth and avoiding GRE sequences if possible.

Patient considerations

Some patients with oral or pharyngeal pathology produce copious saliva and have difficulty swallowing. This often leads to choking or major swallowing artefact. Try to calm and reassure the patient as much as possible before the examination. Give the patient plenty of tissues and, in extreme circumstances, consider examining the patient prone. The patient is instructed to swallow as little as possible during the examination but to ensure that they clear the mouth of saliva when they do. This prevents saliva pooling in the pyriform fossae.

Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

This is rarely indicated but may be useful to distinguish the extent or nature of a lesion.

Larynx

Basic anatomy (Figure 8.45)

Common indications

- Carcinoma of the larynx
- Assessment prior to reconstruction of the larynx
- Disorders of the vocal cords and phonation

Equipment

- Anterior neck coil/volume neck coil
- Immobilization foam pads and straps
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch. The coil is placed around or anterior to the patient's neck. The patient's head is straightened as this usually straightens the neck as well. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the thyroid cartilage (Adam's apple). The vertical alignment light should be located midway between the posterior and anterior surfaces of the neck. A soft pad may be placed under the patient's neck to facilitate this, although many dedicated coils ensure that the neck naturally assumes the correct position. Straps and foam pads are used for immobilization.

Suggested protocol

Sagittal SE/FSE T1/T2 (Figure 8.50)

Thin slices/gaps are prescribed on either side of the longitudinal alignment light from the left to the right lateral skin surfaces of the neck. The area from the superior border of the hard palate to the sterno-clavicular joints is included in the image.

L 25 mm to R 25 mm

Axial SE/FSE T1

Thin slices/gaps are prescribed through the laryngeal cartilages and vocal cords (Figure 8.50). The slices may be angled parallel to the larynx for tumours limited to the cords.

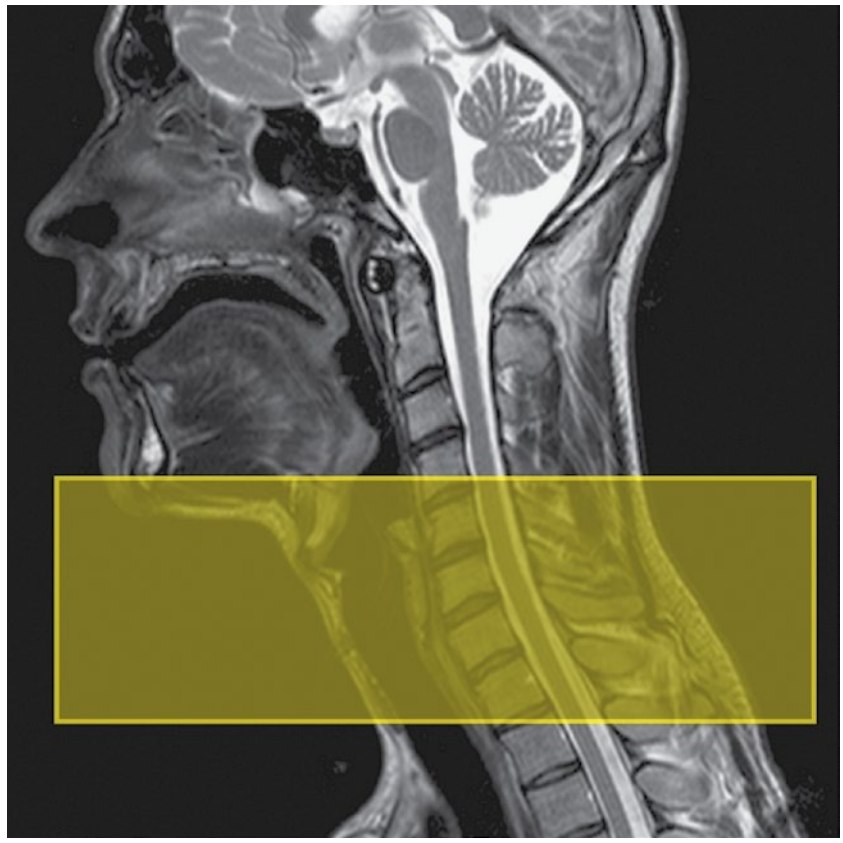

Figure 8.50 Sagittal FSE T2-weighted image through the neck showing slice prescription boundaries and orientation for axial imaging of the larynx.

Coronal SE/FSE T1

As for the axial T1, **except** prescribe slices from posterior surface of the trachea to anterior surface of the neck.

The slices may be angled so that they are parallel to the larynx for tumours limited to the vocal cords (Figure 8.51). The area from the superior border of the hard palate to the sterno-clavicular joints is included in the image.

Axial/coronal SE/FSE PD/T2

Slice prescription as for SE/FSE T1. Useful to distinguish advanced tumour from muscles and the thyroid gland.

Additional sequences

Fast incoherent (spoiled) GRE/EPI T1

During phonation to assess function of the vocal cords.

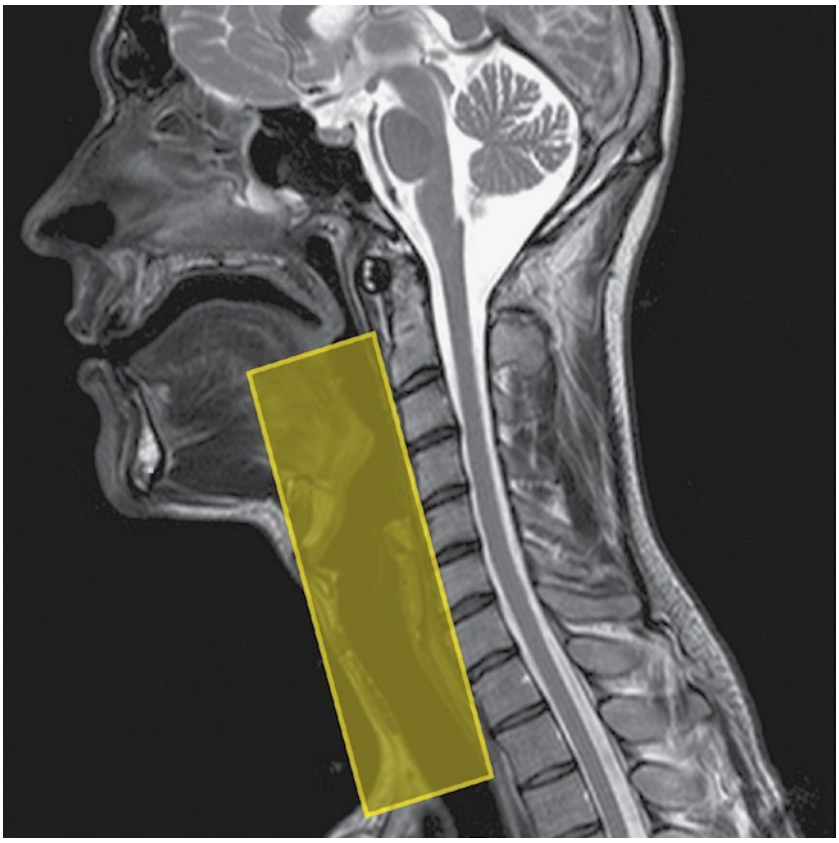

Figure 8.51 Sagittal FSE T2-weighted image through the neck showing slice prescription boundaries and orientation for coronal/oblique imaging of the larynx.

Image optimization

Technical issues

The anterior portion of the neck is a notoriously difficult area to examine. The SNR is often poor, especially if a substandard coil is used. An anterior neck coil moulded to the face and neck is probably the best coil for this examination. However, even with these coils, multiple NEX/NSA are often necessary to maintain SNR. Spatial resolution is also important in this area, and therefore, thin slices/gap and a fairly fine matrix are required to optimize resolution. The use of these matrices and multiple NEX/NSA often leads to long scan times.

A possible solution to these problems is to use FSE in conjunction with a rectangular/asymmetric FOV. FSE reduces the scan time significantly and yields higher SNR, especially on the T2-weighted sequences. A rectangular/asymmetric FOV allows the acquisition of fine matrices in shorter scan times. In coronal and axial imaging, the long axis of the rectangle is placed S to I and A to P, respectively.

Artefact problems

Artefact in this region arises from flow motion in the carotid, vertebral and jugular vessels, and from swallowing. Spatial pre-saturation pulses placed S and I to the FOV reduce flow artefact significantly. Bringing the spatial pre-saturation pulses into the FOV increases their effectiveness, but care must be taken that they do not obscure important anatomy. GMN further reduces artefact, but as it also increases the signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences.

The patient should be advised to swallow as little as possible during the examination. The implementation of multiple NEX/NSA averages out any phase ghosting but leads to longer scan times. Respiratory motion may move the anterior neck coil during the acquisition of data. If this is a problem, instruct the patient to breathe shallowly. In addition, small foam pads placed between the chest and the coil help to reduce coil movement.

Patient considerations

A careful explanation of the procedure and the importance of minimizing swallowing during the examination is important. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

This is rarely indicated but may be useful to distinguish the extent or nature of a lesion.

Thyroid and parathyroid glands

Basic anatomy (Figures 8.52 and 8.53)

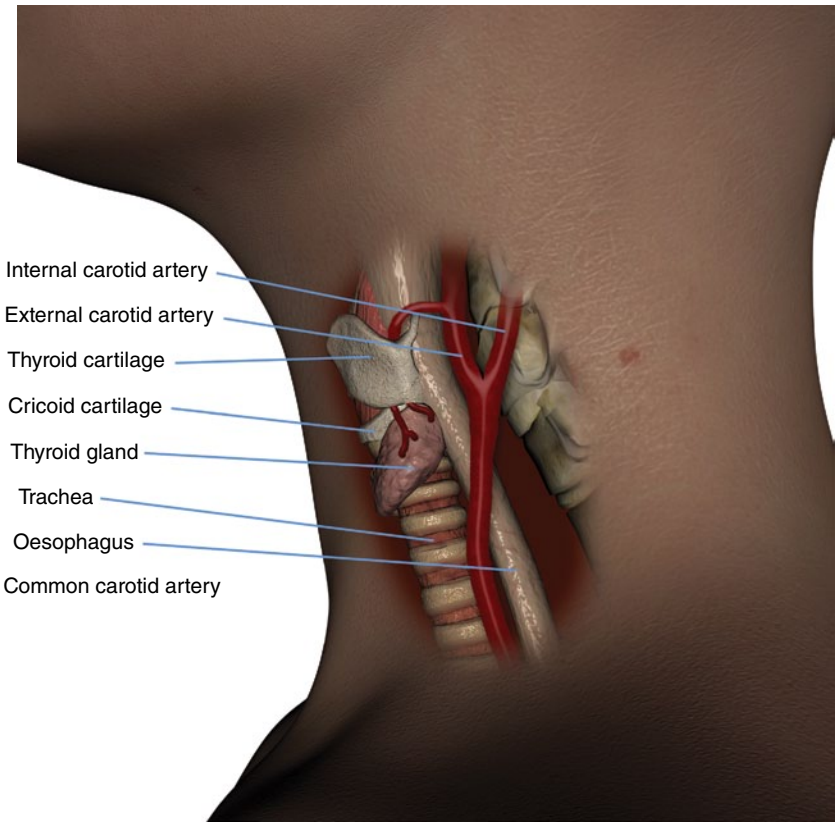

Figure 8.52 Sagittal view of the thyroid gland and its relationships.

Common indications

- Retrosternal goitre
- Evaluation of recurrent thyroid carcinoma
- Detection and characterization of parathyroid adenoma

Equipment

- Anterior neck coil/volume neck coil
- Immobilization foam pads and straps
- Earplugs/headphones

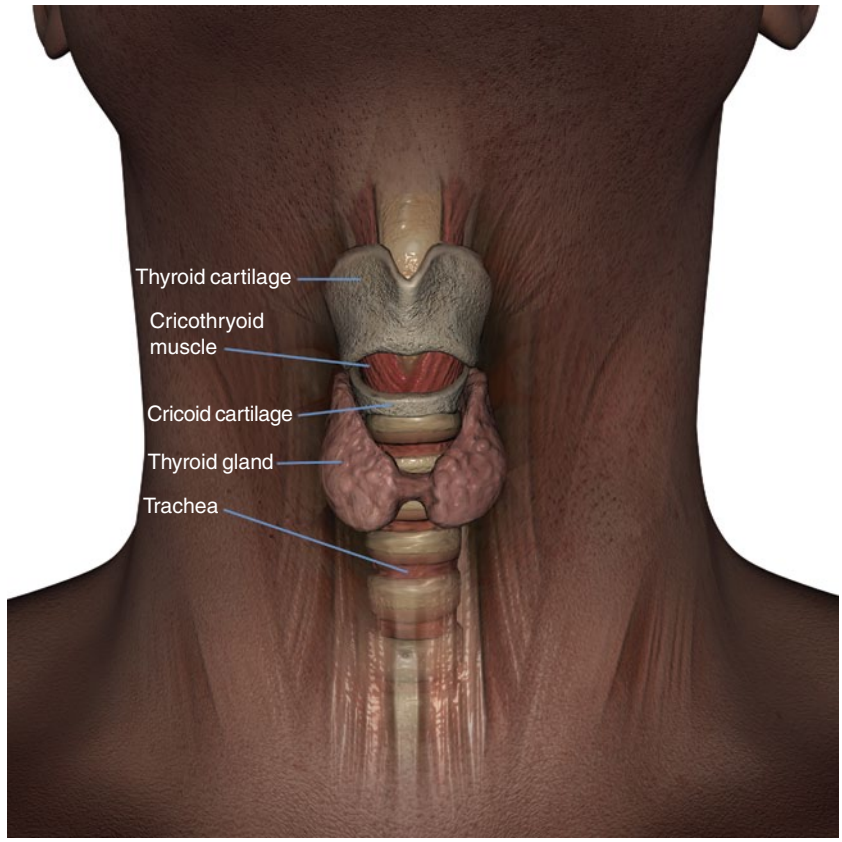

Figure 8.53 Anterior view of the thyroid gland and its relationships.

Patient positioning

The patient lies supine on the examination couch. The coil is placed around or anterior to the patient's neck. The patient's head is straightened as this usually straightens the neck as well. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes just inferior to the thyroid cartilage (Adam's apple). The vertical alignment light should be located midway between the posterior and anterior surfaces of the neck. A soft pad may be placed under the patient's neck to facilitate this, although many dedicated coils ensure that the neck naturally assumes the correct position. Straps and foam pads are used for immobilization.

Suggested protocol

Coronal SE/FSE T1

Thin slices/gaps are prescribed through the thyroid relative to the vertical alignment light. The area from the mandible to the arch of the aorta is included in the image.

A 0 mm to A 20 mm

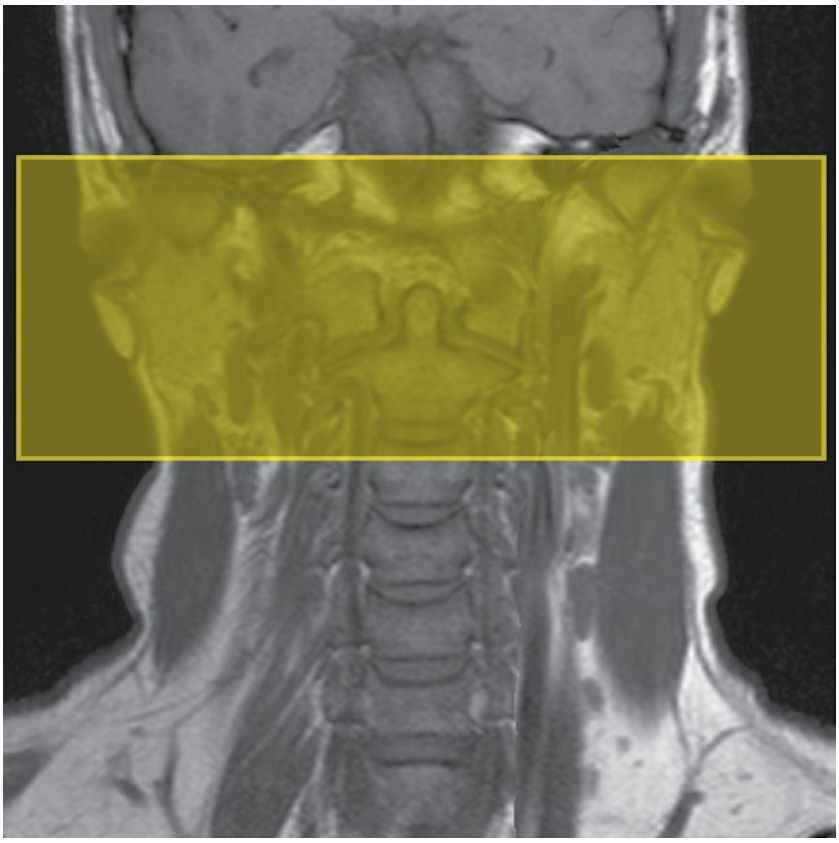

Figure 8.54 Coronal T1-weighted image showing slice prescription boundaries and orientation for axial imaging of the larynx.

Axial/coronal SE/FSE T1

Thin slices and gap are prescribed through the thyroid or ROI. Slices are displaced inferiorly for retrosternal goitre (Figure 8.54).

Axial/coronal SE/FSE PD/T2

Slice prescription as for the axial/coronal T1.

Tissue suppression/STIR is sometimes required for the parathyroid glands.

Image optimization

Technical issues

The anterior portion of the neck is a notoriously difficult area to examine. The SNR is often poor, especially if a substandard coil is used. An anterior neck coil moulded to the face and neck is probably the best coil for this examination. However, even with these coils, multiple NEX/NSA are often necessary to maintain SNR. Spatial resolution is also important in this area, and therefore, thin slices/gap and a fairly fine matrix are

required to optimize resolution. The use of these matrices and multiple NEX/NSA often leads to long scan times.

A solution to these problems is the use of FSE in conjunction with a rectangular/asymmetric FOV. FSE reduces the scan time significantly and yields higher SNR, especially on the T2-weighted sequences. A rectangular/asymmetric FOV allows the acquisition of fine matrices in shorter scan times. In coronal and axial imaging, the long axis of the rectangle is placed S to I and A to P, respectively. The parathyroid gland sometimes returns a very high signal on FSE T2-weighted sequences, necessitating the use of tissue suppression techniques.

Artefact problems

Artefact in this region arises from flow in the carotid, vertebral and jugular vessels, and from swallowing. Spatial pre-saturation pulses placed S and I to the FOV reduce flow artefact significantly. Bringing the spatial pre-saturation pulses into the FOV increases their effectiveness, but care must be taken that they do not obscure important anatomy. GMN further reduces artefact, but as it also increases signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences.

Swallowing is commonly troublesome in this area. Using multiple NEX/NSA to average out motion artefact reduces phase ghosting but leads to longer scan times. The patient should be advised to swallow as little as possible during the examination. Respiratory motion may move the anterior neck coil during the acquisition of data. If this is a problem, instruct the patient to breathe shallowly. In addition, small foam pads placed between the chest and the coil help to reduce coil movement.

Patient considerations

A careful explanation of the procedure and the importance of minimizing swallowing during the examination are important. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

This is rarely indicated but may be useful to distinguish the extent or nature of a lesion.

Salivary glands

Common indications

- Detection of salivary gland masses
- Staging of neoplasms and nodal involvement

Equipment

- For parotid glands: Quadrature or multi-coil array head coil. Foam pads and immobilization straps
- For submandibular glands and cervical nodes: Anterior/volume neck coils. Foam pads and immobilization straps
- Earplugs/headphones

Patient positioning

For parotid glands

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the inter-pupillary line is parallel to the couch and the head is straight. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the external auditory meatus. Straps and foam pads are used to immobilize the patient.

For submandibular glands and cervical nodes

The patient lies supine on the examination couch. The coil is placed around or anterior to the patient's neck. Care should be taken to include the floor of the mouth within the coil. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the angle of the jaw. The vertical alignment light should be located midway between the posterior and anterior surfaces of the neck. A soft pad may be placed under the patient's neck to facilitate this, although many dedicated coils ensure that the neck naturally assumes the correct position.

Suggested protocol

Sagittal SE T1

Thin slices/gaps are prescribed on either side of the longitudinal alignment light. The area from the base of the skull to the hyoid bone is included in the image to visualize both the parotid and submandibular glands.

L 37 mm to R 37 mm

Coronal SE/FSE T1

Mainly demonstrates the parotid glands. Thin slices/gaps are prescribed from the vertebral bodies posteriorly to the superior alveolar process. The cervical lymph node chain and the skull base are included in the image.

Axial SE/FSE T1

Thin slices/gap are prescribed from the superior aspect of the external auditory meatus to the angle of the jaw for the parotid glands, or through the submandibular glands (located just below the mandible). Coverage is extended for tumour spread.

Axial SE/FSE PD/T2

Demonstrates abnormal tissue and dilated ducts in the diagnosis of salivary gland masses. Thin slices/gaps are prescribed through both glands. Coverage is extended for tumour spread. Tissue suppression/STIR is sometimes necessary in imaging of the parotid gland.

Additional sequences

SS-FSE/FSE T2

MR sialography may be of use in investigating ductal obstruction of the salivary system. Heavily T2-weighted images are acquired and post-processed (see *Liver and biliary system* and *Kidneys and adrenals* and *Pancreas* in Part 2 for the use of this technique in other areas).

Image optimization

Technical issues

The salivary glands are relatively small structures, and therefore, spatial resolution is important. The SNR is optimized by using the correct coil. The parotid glands are commonly examined using a quadrature or phased array head coil that yields high and uniform signal. The submandibular glands can sometimes be imaged using this coil, as long as the patient is able to move well inside it; otherwise an anterior neck coil is necessary. Thin slices and fine matrices are important to maintain the necessary resolution and, as a result, multiple NEX/NSA are commonly required to maintain SNR. The use of FSE in conjunction with a rectangular/asymmetric FOV also improves SNR and facilitates the acquisition of fine matrices in relatively short scan times. Fat suppression techniques are sometimes required in FSE T2-weighted sequences as the fatty components of the parotid gland return a signal similar to pathology. The ductal salivary system may be effectively visualized using heavily T2-weighted

FSE images (MR sialography). The use of long TEs (250 ms), TRs (10 s) and ETLs (16–20) produces images where the only signal returned is from fluid within the duct. As the ducts are small, good resolution is also required; therefore, 3D acquisitions may be superior to 2D.

Artefact problems

The main source of artefact in this area is from the carotid, jugular and vertebral vessels. Spatial pre-saturation pulses placed S and I to the FOV diminish this. GMN further minimizes flow artefact, but as it also increases the signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences. Phase ghosting occurs along the R to L axis in axial and coronal imaging, and interferes with the laterally situated parotid glands. Swapping the phase axis so that it lies S to I reduces this problem, but oversampling is often necessary. Swallowing is often troublesome especially when examining the submandibular glands. Spatial pre-saturation bands placed carefully over the throat help to reduce this but may obscure the glands themselves. Instructing the patient to swallow as little as possible during the acquisition of data is advisable.

Patient considerations

Some patients with oral pathology produce copious saliva and have difficulty swallowing. This often leads to choking or major swallowing artefact. Try to calm and reassure the patient as much as possible before the examination. Give the patient plenty of tissues and, in extreme circumstances, consider examining the patient prone. Due to excessively loud gradient noise associated with some sequences, earplugs must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely given but may be helpful to distinguish pathology from normal anatomy.

Temporomandibular joints

Basic anatomy (Figure 8.55)

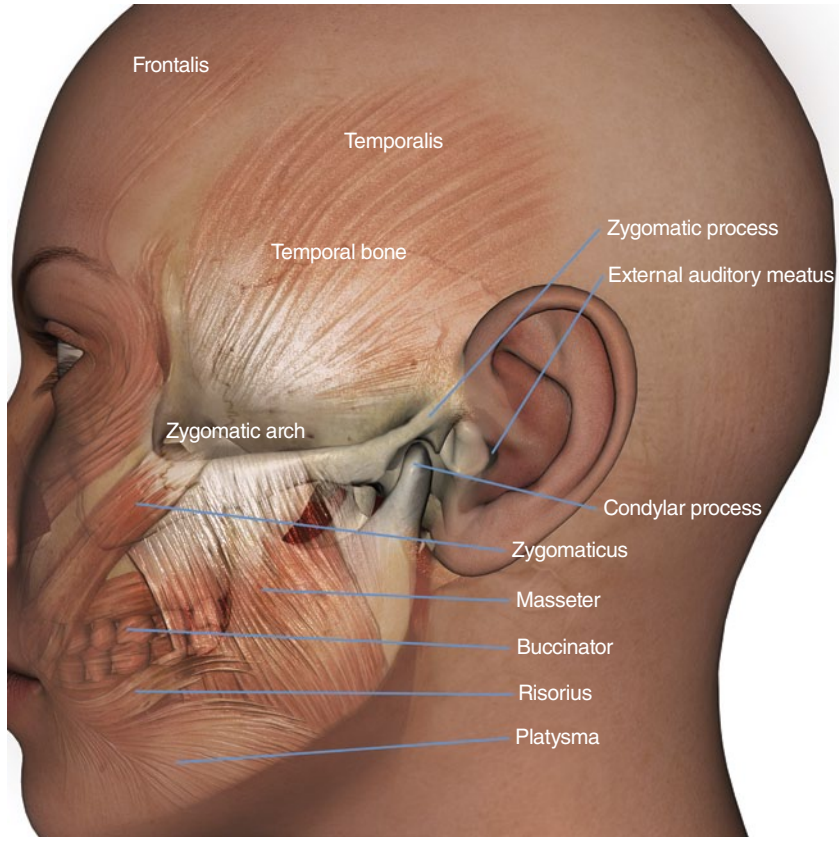

Figure 8.55 Sagittal view of the TMJ and its relationships.

Common indication

- Suspected internal meniscal derangement

Equipment

- Dual three inch coils/multi-coil array temporomandibular joint (TMJ) coils
- Mouth-opening device
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with the coils secured over the TMJs. These can be located by placing fingers just anterior to the external auditory meatus and asking the patient to open and close their

mouth. The coils are placed as close as possible, but not touching the face, with the receiving side of the coils towards the patient. Both joints are imaged together so the patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the TMJs (which is the centre of the coils). Straps and foam pads are used for immobilization.

Before the examination, the function of the mouth opener is explained to the patient. The patient practises the opening of the device before the examination to minimize the risk of movement after the examination has begun. The first closed mouth acquisition should be made without the device in the patient's mouth. In some cases of anterior dislocation, it is possible that the meniscus will recapture immediately upon insertion of the device into the patient's mouth. When ready, the patient is asked to open their mouth with the opening device until they feel their jaws about to click. The operator can advise the patient when to do this over the system intercom. If a mouth-opening device is not available, various-size syringe barrels can be used to hold a patient's mouth open at various stages as desired.

Suggested protocol

Axial SE/FSE T1 (mouth closed) (Figure 8.56)

Include the whole head so that the correct position of both coils is ascertained. Medium slices/gaps are prescribed on either side of the horizontal alignment light. Both TMJs are included in the image.

I 15 mm to S 15 mm

Sagittal/oblique T1 (mouth closed)

Thin slices/gap or interleaved slices are prescribed through each joint. Slices are angled so that they are perpendicular to the mandibular condyles (do not over-oblique these).

Sagittal/oblique T1 (mouth open)

Slice prescription as for mouth closed.

Additional sequences

Coronal/oblique T1

As for the sagittal/obliques, **except** slices are either prescribed perpendicular to the sagittal/obliques or in the orthogonal coronal plane through both joints. Mouth open or closed.

Sagittal/oblique FSE/SS-FSE/EPI during mouth opening and closing

For dynamic imaging of the TMJ.

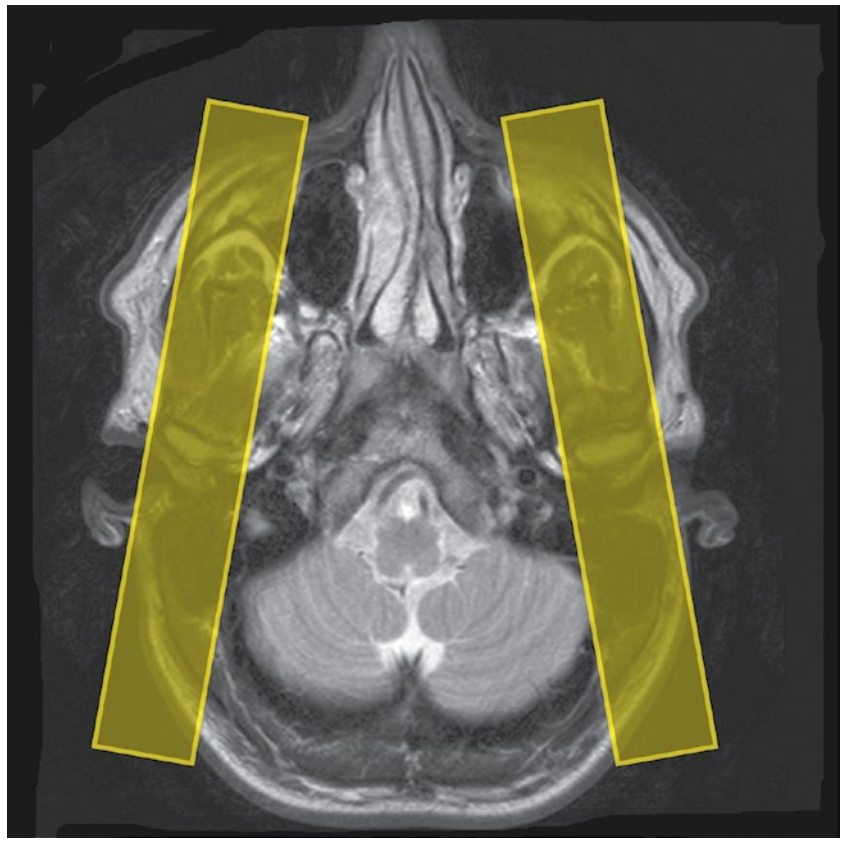

Figure 8.56 Axial SE T1-weighted localizer through the TMJs showing correct placement of sagittal/oblique slices perpendicular to the mandibular condyles.

3D incoherent (spoiled) GRE/FSE T1

For thinner slices than 2D acquisitions and reformatting in other planes.

Image optimization

Technical issues

The SNR depends largely on the quality of the coils. Spatial resolution is important as the structures within the joint are small, and therefore, a small FOV, thin slices, interleaving and relatively fine matrices are necessary. As the FOV is small, multiple NEX/NSA are often required to maintain adequate SNR, and therefore, scan times may be of several minutes' duration. A common mistake is to over-oblique the sagittal/oblique slices. Ensure that they are perpendicular to the mandibular condyles. Dynamic imaging of the TMJs may be useful in assessing meniscal derangement. However, unless the sequence used is very rapid, temporal resolution may be insufficient and a pseudo-dynamic set of images are produced, that is, where a single slice is acquired at each static position of mouth opening and the images are viewed sequentially in a cine

mode. This type of acquisition may not show true movement of the disc during mouth opening. In order to achieve this, the temporal resolution must be high, and real-time imaging using sequences such as EPI is required (see *Dynamic imaging* under *Pulse sequences* in Part 1).

Artefact problems

Pulsation from the carotid vessels often interferes with the image. Spatial pre-saturation pulses placed S and I to the FOV are effective, but ghosting is sometimes seen. GMN also minimizes flow artefact, but as it increases signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences. As the images are obliqued, there may be no operator control over the phase and frequency axes. If, however, the system allows for axes control, placing phase S to I is probably the best option as this largely removes the artefact from the joint. As a small FOV is used, oversampling is usually necessary.

Patient considerations

Patient cooperation is important during this examination. The patient should practise using the mouth-opening device before the examination. The technologist must explain that the mouth is opened until the patient feels that the jaw is about to click, and then relaxed so that the upper and lower jaws rest against the opener. As scan times are often lengthy, swallowing whilst the mouth is open can cause motion artefact. Obviously the patient must swallow if absolutely necessary, but it should be discouraged if possible. Another common problem is that the patient often moves from the localizer position when he or she opens his or her mouth. It is wise to obtain a second localizer with the mouth open to ensure adequate coverage of the second set of sagittal/obliques.

Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not commonly used in this area. However, arthrography of the joints may prove useful in the future. The joint is injected with a small amount of gadolinium followed by sagittal/oblique T1-weighted imaging.

Vascular imaging

Common indications

- Evaluation of the carotid arteries especially at the bifurcation
- Intracranial vascular assessment of aneurysms and infarcts
- Arteriovenous malformation (AVM)
- Intracranial vessel occlusion including sagittal sinus thrombosis

Equipment

- Quadrature or phased array head coil (brain imaging)
- Anterior neck coil (neck imaging)
- Immobilization foam pads and straps
- Earplugs/headphones

Patient positioning

Brain imaging

The patient lies supine on the examination couch with their head within the head coil. The head is adjusted so that the inter-pupillary line is parallel to the couch and the head is straight. The longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the nasion. Straps and foam pads are used to immobilize the patient as much as possible.

Neck imaging

The patient lies supine on the examination couch, and an anterior neck coil is secured so that the parts from the base of the skull to the arch of the aorta are included within the volume of the coil. The longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the angle of the jaw.

Suggested protocol

Vascular imaging in the brain (Figures 8.57, 8.58 and 8.59)

A sagittal SE T1 series can be performed as a localizer. This is then followed by either 3D TOF or PC images. 3D acquisitions allow for increased SNR and very thin contiguous slices, so improving the spatial resolution. Depending on the coverage required, 28 to 124 thin slice locations may be selected. In PC-MRA, all three axes are usually flow

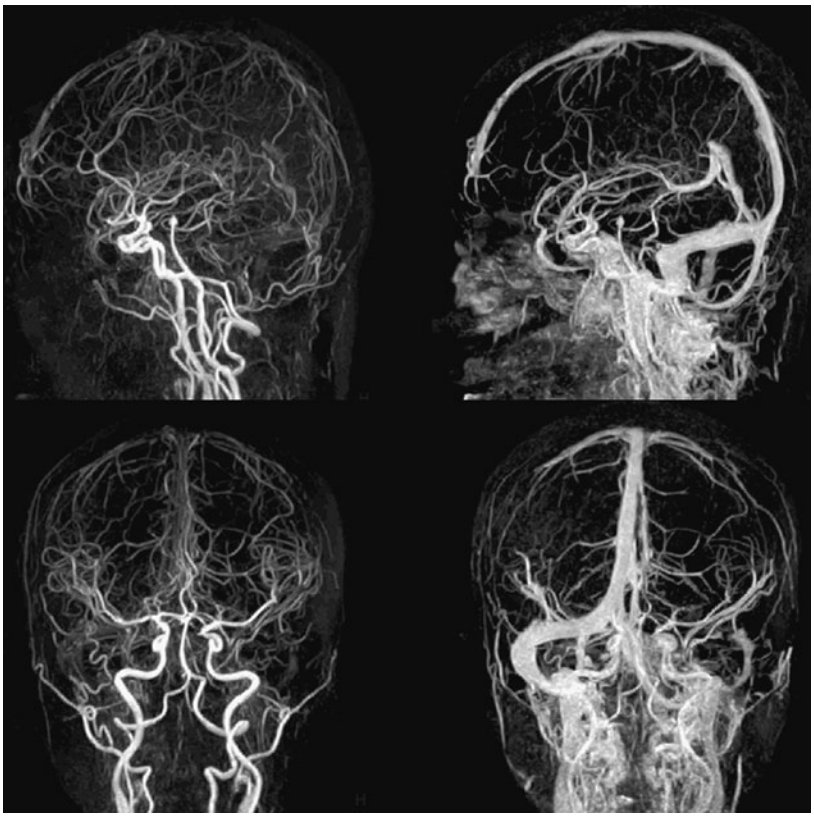

Figure 8.57 Contrast-enhanced multiphase images of the brain.

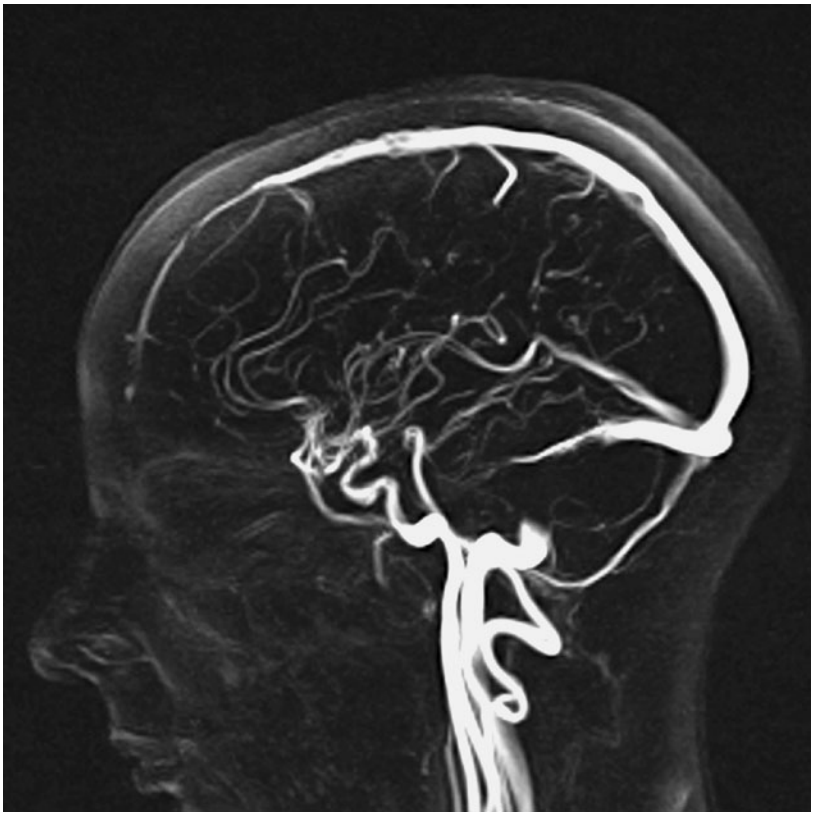

Figure 8.58 Phase contrast venogram of the brain.

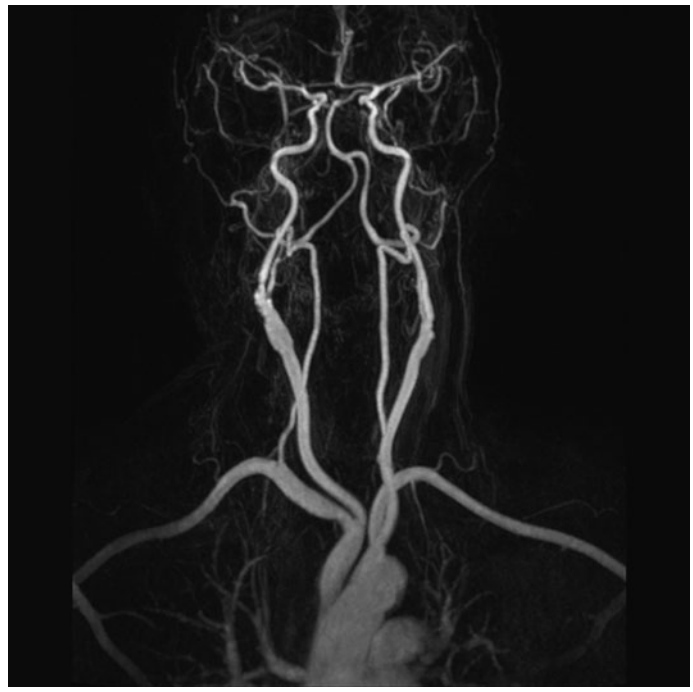

Figure 8.59 Coronal contrast-enhanced MRA of the neck vessels.

encoded. Due to the increased likelihood of intra-slab flow saturation with 3D TOF-MRA, PC-MRA is usually the sequence of choice for volume imaging in the head. However, intra-slab flow saturation in 3D TOF-MRA is improved by the implementation of ramped (or variable) flip angles, or acquiring multiple smaller slabs (multi-slab). 2D TOF-MRA is reserved for visualizing intracranial venous flow or small peripheral vessels. If MRA software is not available, cine or ultrafast coherent GRE T2* sequences in conjunction with GMN are beneficial, especially in the visualization of sagittal sinus thrombosis and post-embolization of giant aneurysms. When used in conjunction with SE sequences, spatial pre-saturation pulses produce black blood. If signal persists in a vessel, it may indicate either slow flow or occlusion. When used in conjunction with GRE sequences, GMN produces bright blood. If a signal void is seen within the vessel, it may indicate either slow flow or occlusion.

Vascular imaging in the neck

A coronal coherent GRE sequence can be performed as a localizer. Axial 2D TOF-MRA using thin slices prescribed through the carotid and bifurcation are required, followed by 3D TOF-MRA for improved resolution of the bifurcation. Spatial pre-saturation pulses should be placed S to the FOV to saturate venous flow entering the slice stack from above.

If MRA software is not available, the carotid vessels can sometimes be adequately visualized using conventional 3D coherent GRE T2* sequences in conjunction with GMN, although the resolution is not as good as in conventional MRA imaging. In addition, when used in conjunction with SE sequences, spatial pre-saturation pulses produce black blood. If signal persists in a vessel, it may indicate either slow flow or occlusion. When used in conjunction with GRE sequences, GMN produces bright blood. If a signal void is seen within the vessel, it may indicate either slow flow or occlusion.

Contrast-enhanced MRA of the carotids (Figure 8.59)

CE-MRA is often used to acquire images of the arch, vertebral arteries, carotid arteries and subclavian arteries. Using a larger FOV (approximately 280 mm), images may be acquired covering from the arch to the circle of Willis. Images are typically acquired using a rapid coronal 3D spoiled GRE. A gadolinium-based contrast agent is delivered (standard weight-based dose) in a bolus fashion (1.5–2 ml/s) followed by a bolus of saline flush (minimum of 20 ml delivered at the same rate as the gadolinium-based agent).

When performing a CE-MRA, it is important to time the acquisition of the 3D data so that maximum concentration of gadolinium in the vessels of interest coincides with the acquisition of the low-frequency data (centre of k-space). In order to ensure this occurs, a timing bolus sequence may be required prior to the CE-MRA scan. Additional techniques may also be available to ensure proper timing (SmartPrep, Care Bolus, Bolus Tracking, Fluoro Triggering, depending on manufacturer). It should also be noted that these timing or triggering techniques will vary by MR system manufacturer and may also not be available on every system.

While it may not be entirely necessary to utilize a power injector for these studies, its use can greatly increase consistency with regard to bolus timing. Although large volumes of contrast media and rapid injection rates are typically not utilized in CE-MRA studies (unlike CTA), care should be taken to insure proper IV access. Care should also be taken to ensure no air remains in the syringes and/or line.

Image optimization

Technical issues

The quality of MRA images depends on a variety of factors. First, the type of sequence used is important. Most examinations require both TOF and 3D PC sequences to visualize all the cerebral vasculature adequately. TOF-MRA is beneficial when imaging flow that moves perpendicular to the slice plane. Therefore, it should be reserved for the circle of Willis and peripheral intracranial vessels. 3D TOF-MRA

can result in a loss of signal from nuclei becoming saturated within the slice stack, and is mainly valuable on faster arterial flow unless ramped flip angles are available.

Spatial pre-saturation pulses are carefully placed so as only to saturate unwanted flow. The use of GMN and MT in TOF-MRA sequences improves image contrast by increasing the signal within vessels (GMN), and suppressing background signal (MT) (see *Pulse sequences* in Part 1). Scan times are lengthy, especially in PC-MRA where the scan time is dependent (among other things) on the number of flow encoding axes implemented. Image quality also depends on the accurate setting of flow encoding axis and VENCs. Fast 2D images acquired before the 3D acquisition often help to determine the direction and speed of flow.

Artefact problems

In TOF-MRA, signal from the fatty components of the orbit and the scalp are commonly not saturated adequately and therefore interfere with the image. This is due to the short recovery times of these tissues. Tissue suppression often successfully reduces this unwanted signal, but on some systems may also saturate the vessels. Alternatively, using a TE when the fat and water signals are out of phase with each other and applying MT usually adequately suppresses background signal. Motion artefact is sometimes troublesome especially on 3D PC-MRA images as their acquisition times are very long, and any motion of flowing nuclei within the vessels produces signal.

Patient considerations

Some of these patients may be incapacitated by their illness especially if this involves tumours, AVM or stroke. A careful explanation of the examination and the approximate length of the study are required. In brain imaging, claustrophobia is sometimes troublesome due to the enclosing nature of the head coil. Ensure that the coil mirror is adjusted and that the patient is provided with an alarm bell.

Due to excessively loud gradient noise associated with some sequences, earplugs must always be provided to prevent hearing impairment.

Contrast usage

Due to the inherent contrast between vessels and background tissue, these examinations do not usually require IV contrast. However, the use of contrast increases vessel conspicuity as it shortens the T1 of blood, increases vessel signal and improves image contrast in TOF-MRA sequences (Figures 8.57 and 8.59).

Key points

- T2-FLAIR: Gadolinium-enhancing lesions will show as hyperintense. This can be extremely useful for demonstrating meningeal enhancement. Additionally, both the enhancing lesion and oedema are well demonstrated.
- T1-weighted IR sequences provide excellent G/W contrast particularly in paediatric patients and for all patients when imaging at 3 T.
- Spoiled GRE sequences can provide for excellent G/W contrast as well as greatly reduced flow artefacts due to the very short TE.
- Motion reduction techniques (such as PROPELLER and BLADE) are very useful particularly when imaging patients who are unable to remain motionless for extended periods of time.
- 3D (or volume) acquisitions are useful when very thin contiguous slices are required (such as when imaging the IACs). When acquired in an isotropic fashion, image data may be retrospectively into multiple planes.
- Metal artefacts from dental work may be reduced by increasing the receiver bandwidth, reducing slice thickness and avoiding GRE sequences when possible.

9

Spine

Handbook of MRI Technique, Fourth Edition. Catherine Westbrook.

Companion website: www.wiley.com/go/westbrook/mritechnique

Table 9.1 Summary of parameters

1.5T		3T	
SE		**SE**	
Short TE	Min–30 ms	Short TE	Min–15 ms
Long TE	70 ms+	Long TE	70 ms+
Short TR	600–800 ms	Short TR	600–900 ms
Long TR	2000 ms+	Long TR	2000 ms+
FSE		**FSE**	
Short TE	Min–20 ms	Short TE	Min–15 ms
Long TE	90 +	Long TE	90 ms+
Short TR	400–600 ms	Short TR	600–900 ms
Long TR	4000 ms+	Long TR	4000 ms+
Short TEL	2–6	Short TEL	2–6
Long ETL	16+	Long ETL	16+
IR T1		**IR T1**	
Short TE	Min–20 ms	Short TE	Min–20 ms
Long TR	3000 ms+	Long TR	300 ms+
TI	200–600 ms	TI	Short or null time of tissue
Short ETL	2–6	Short ETL	2–6
STIR		**STIR**	
Long TE	60 ms+	Long TE	60 ms+
Long TR	3000 ms+	Long TR	3000 ms+
Short TI	100–175 ms	Short TI	210 ms
Long ETL	16+	Long ETL	16+
FLAIR		**FLAIR**	
Long TE	80 ms+	Long TE	80 ms+
Long TR	9000 ms+	Long TR	9000 ms + (TR at least 4 × TI)
Long TI	1700–2500 ms (depending on TR)	Long TI	1700–2500 ms (depending on TR)
Long ETL	16+	Long ETL	16+
Coherent GRE		**Coherent GRE**	
Long TE	15 ms+	Long TE	15 ms+
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Incoherent GRE		**Incoherent GRE**	
Short TE	Minimum	Short TE	Minimum
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Balanced GRE		**Balanced GRE**	
TE	Minimum	TE	Minimum
TR	Minimum	TR	Minimum
Flip angle	>40°	Flip angle	>40°
SSFP		**SSFP**	
TE	10–15 ms	TE	10–15 ms
TR	<50 ms	TR	<50 ms
Flip angle	20–40°	Flip angle	20–40°

(*Continued*)

Table 9.1 (*Contd.*)

1.5T and 3T			
Slice thickness 2D		**Slice thickness 3D**	
Thin	2–4 mm	Thin	<1 mm
Medium	5–6 mm	Thick	>3 mm
Thick	8 mm		
FOV		**Matrix**	
Small	<18 cm	Coarse	256 × 128/256 × 192
Medium	18–30 cm	Medium	256 × 256/512 × 256
Large	>30 cm	Fine	512 × 512
		Very fine	>1024 × 1024
NEX/NSA		**Slice number 3D**	
Short	1	Small	<32
Medium	2–3	Medium	64
Multiple	>4	Large	>128
PC-MRA 2D and 3D		**TOF-MRA 2D**	
TE	Minimum	TE	Minimum
TR	25–33 ms	TR	28–45 ms
Flip angle	30°	Flip angle	40–60°
VENC venous	20–40 cm/s	**TOF-MRA 3D**	
VENC arterial	60 cm/s	TE	Minimum
		TR	25–50 ms
		Flip angle	20–30°

The figures given are for 1.5T and 3T systems. Parameters are dependent on field strength and may need adjustment for very low or very high field systems.

Cervical spine

Basic anatomy (Figures 9.1 and 9.2)

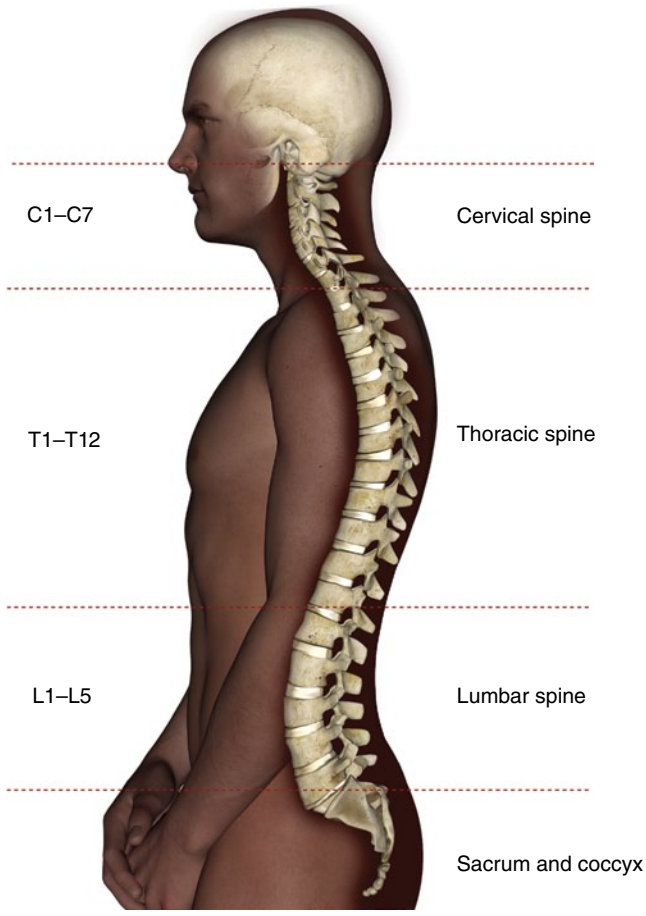

Figure 9.1 Sagittal view of the spine showing vertebral levels.

Common indications

- Cervical myelopathy
- Cervical radiculopathy
- Cervical cord compression or trauma
- Assessment of extent of spinal infection or tumour
- Diagnosis of Chiari malformation and cervical syrinx. (Total extent of syrinx must be determined. Whole spine imaging may be necessary.)
- MS plaques within the cord

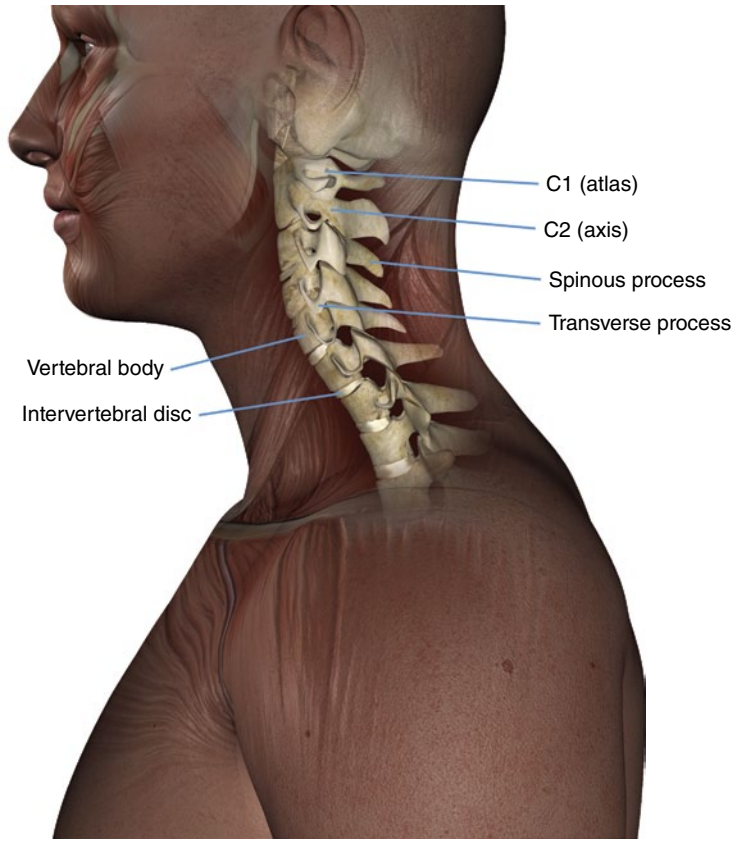

Figure 9.2 The components of the cervical spine and spinal cord.

Equipment

- Posterior cervical neck coil/volume neck coil/multi-coil array spinal coil
- Immobilization pads and straps
- Pe gating leads if required
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with the neck coil placed under or around the cervical region. Coils are often moulded to fit the back of the head and neck so that the patient is automatically centred to the coil. If a flat coil is used, placing supporting pads under the shoulders flattens the curve of the cervical spine so that it is in closer proximity to the coil. The coil should extend from the base of the skull to the sterno-clavicular joints in order to include the whole of the cervical spine.

The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the hyoid bone (this can usually be felt above the thyroid cartilage/Adam's

apple). The patient's head is immobilized with foam pads and retention straps. Pe gating leads are attached if required.

Suggested protocol

Sagittal/coronal SE/FSE T1 or coherent GRE T2*

Acts as a localizer if three-plane localization is unavailable. The coronal or sagittal planes may be used.

Coronal localizer: Medium slices/gaps are prescribed relative to the vertical alignment light, from the posterior aspect of the spinous processes to the anterior border of the vertebral bodies. The area from the base of the skull to the second thoracic vertebra is included in the image.

P 20 mm to A 30 mm

Sagittal localizer: Medium slice thickness/gaps are prescribed on either side of the longitudinal alignment light, from the left to the right lateral borders of the vertebral bodies. The area from the base of the skull to the second thoracic vertebra is included in the image.

L 7 mm to R 7 mm

Sagittal SE/FSE T1 (Figure 9.3)

Thin slices/gaps are prescribed on either side of the longitudinal alignment light, from the left to the right lateral borders of the vertebral bodies (unless the paravertebral areas are required). The area from the base of the skull to the second thoracic vertebra is included in the image.

L 22 mm to R 22 mm

Sagittal SE/FSE T2 or coherent GRE T2* (Figure 9.4)

Slice prescription as for sagittal T1.

Axial/oblique SE/FSE T1/T2 or coherent GRE T2* (Figure 9.5)

Thin slices/gaps are angled so that they are parallel to the disc space or perpendicular to the lesion under examination (Figures 9.6 and 9.7). For disc disease, three or four slices per level usually suffice. For larger lesions such as tumour or syrinx, thicker slices covering the lesion and a small area above and below may be necessary.

Additional sequences

Sagittal/axial oblique SE/FSE T1

Slice prescription as for axial/oblique T2* with contrast enhancement for tumours.

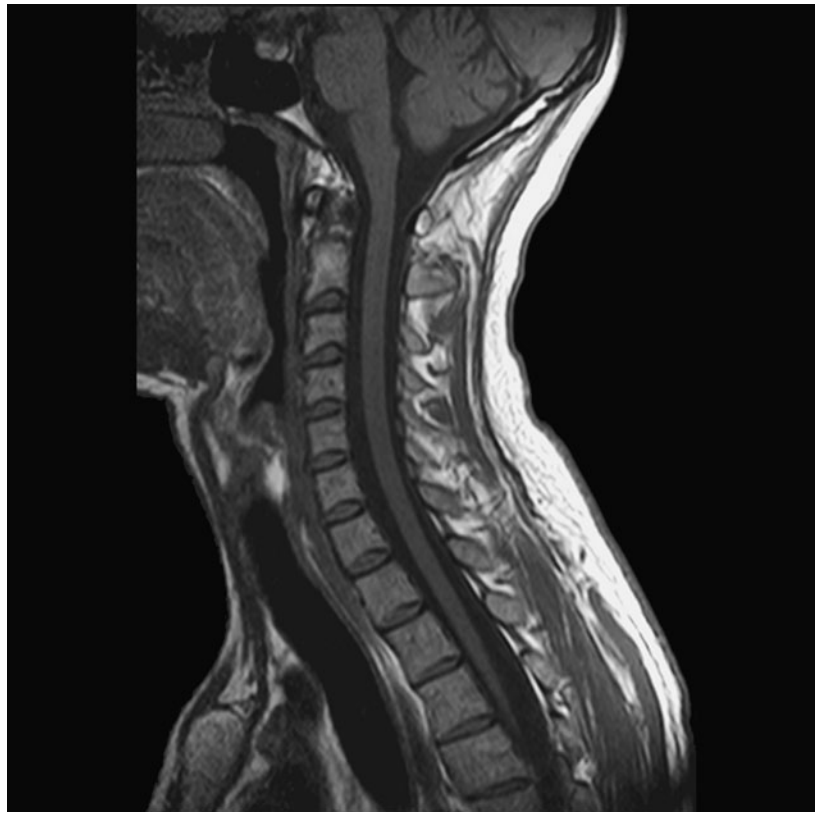

Figure 9.3 Sagittal SE T1-weighted midline image through the cervical spine.

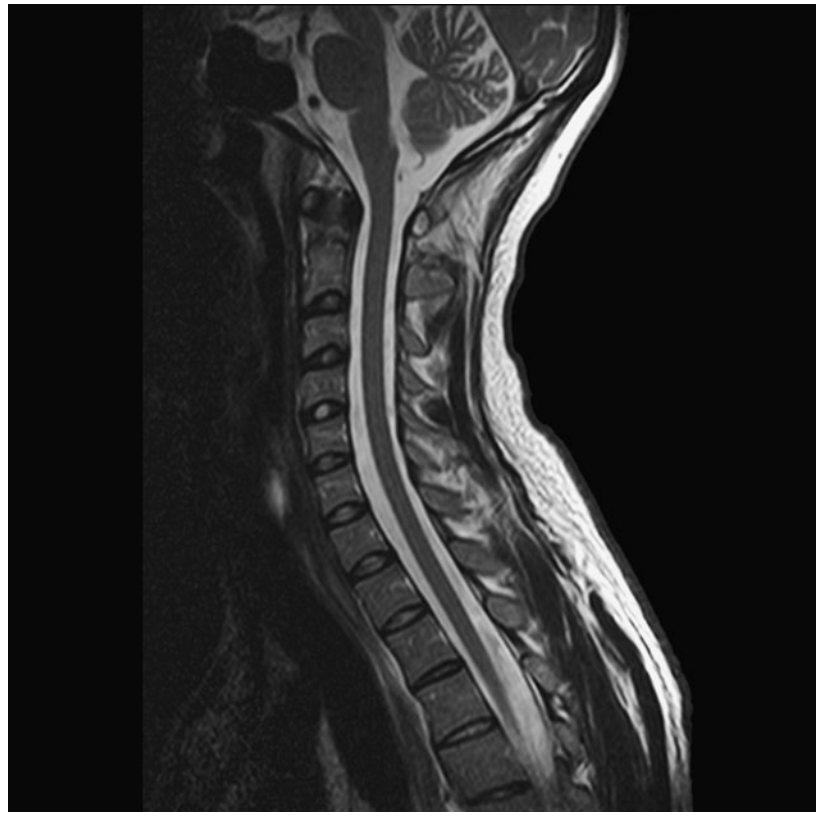

Figure 9.4 Sagittal FSE T2-weighted midline image through the cervical cord.

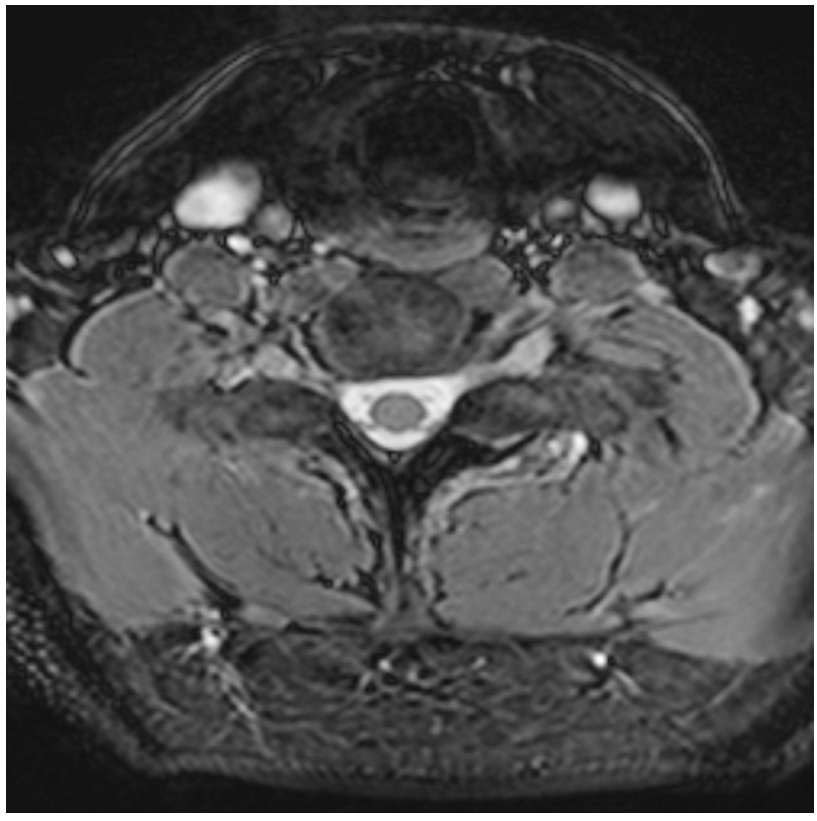

Figure 9.5 Axial/oblique coherent GRE T2*-weighted image through the cervical cord.

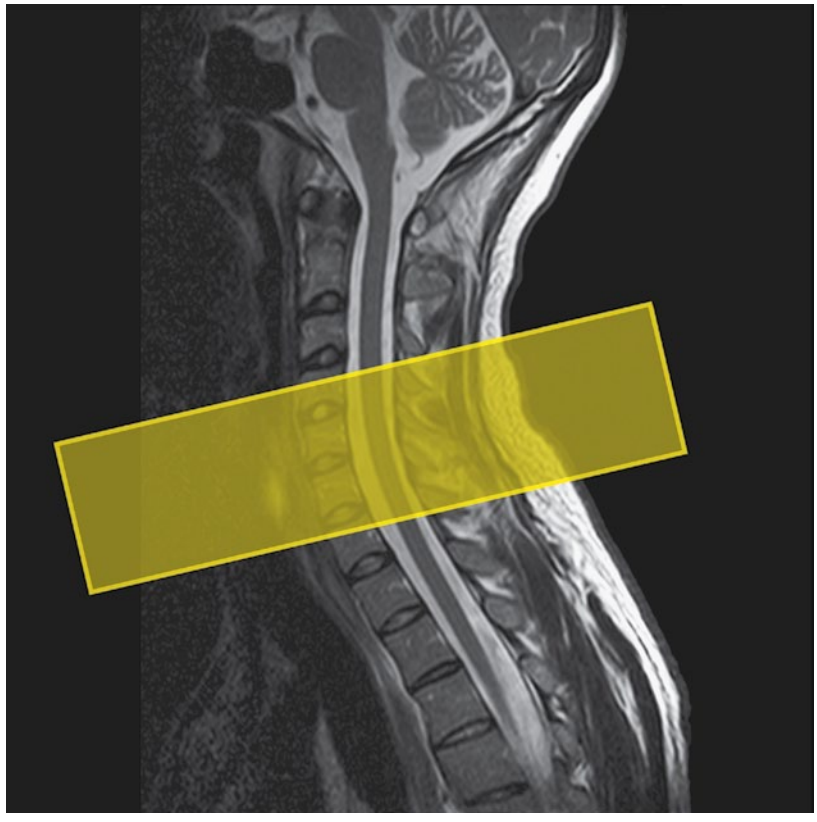

Figure 9.6 Sagittal FSE T2-weighted image showing slice prescription boundaries and orientation for axial imaging of the cervical cord.

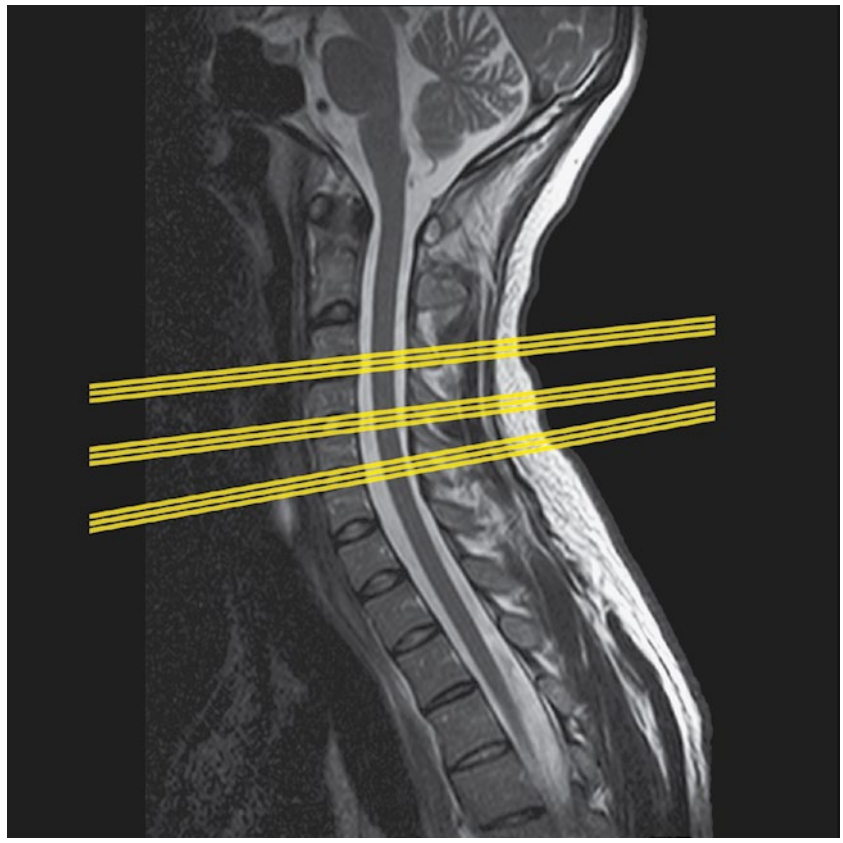

Figure 9.7 Sagittal coherent GRE T2*-weighted image of the cervical spine showing axial/oblique slice positions parallel to each disc space.

Sagittal SE/FSE T2 or STIR

Slice prescription as for sagittal T2*. An alternative to coherent GRE T2*. A sagittal STIR may be useful for trauma to demonstrate muscular injuries. STIR sequences are typically much better than T2 FSE sequences for visualization of fractures and/or lesions in the vertebra. Additionally, MS plaques are almost always better visualized on a sagittal STIR sequence compared to an FSE T2-weighted sequence.

3D coherent/incoherent (spoiled) GRE T2*/T1

Thin slices and a few or medium number of slice locations are prescribed through the ROI. If PD or T2* weighting is desired, then a coherent or steady-state sequence is utilized. If T1 weighting is required an incoherent or spoiled sequence is necessary. These sequences may be acquired in any plane but, if reformatting is required, isotropic data sets must be acquired.

Sagittal SE/FSE T1 or fast incoherent (spoiled) GRE T1/PD

Slice prescription as for sagittal T1, T2 and T2*, **except** neck in flexion and extension to correlate the potential relevance of spondylotic changes to signs and symptoms.

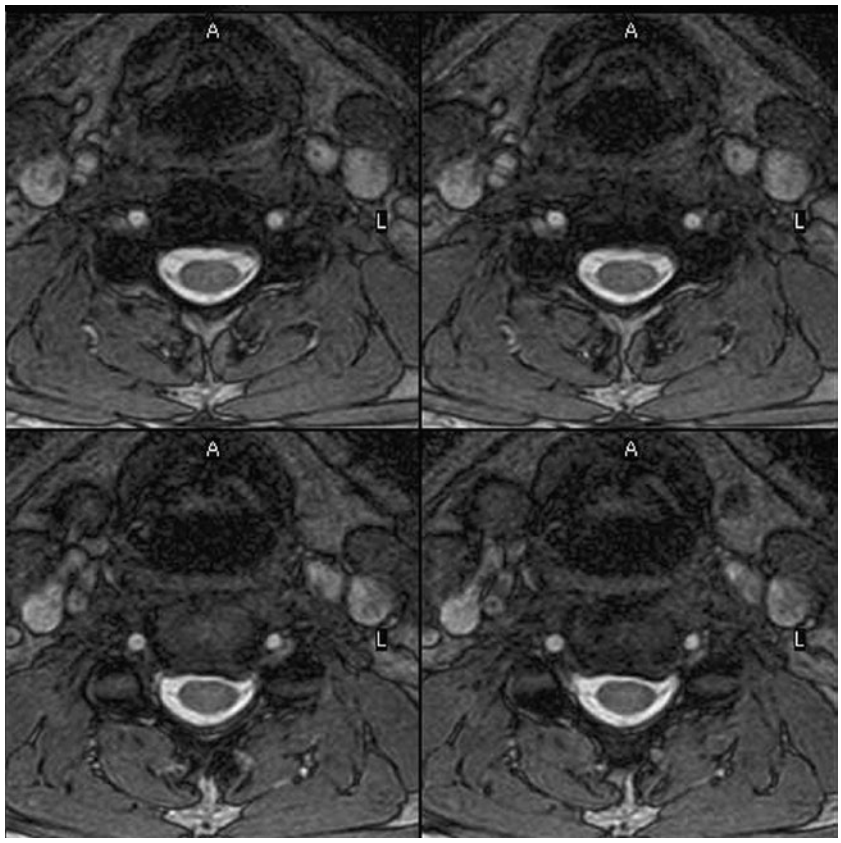

Figure 9.8 Axial balanced GRE through the cervical spine.

3D balanced gradient echo (BGRE) (Figure 9.8)

The contrast characteristics of a BGRE sequence provide for high signal from CSF (high T2/T1 ratio) and thus produce images with high contrast between CSF and nerve roots. It is important to remember that because these images are not T2 weighted but rather weighted for the ratio of T1 to T2. Spins with a high T1 to T2 ratio appear bright (blood and CSF). Cord lesions such as MS plaques will not be seen. As such, they are typically utilized when imaging a patient for radiculopathy (disc disease) rather then myelopathy (cord lesions).

Image optimization

Technical issues

The SNR in this region is mainly dependent on the quality of the coil. Posterior neck coils give adequate signal for the cervical spine and cord, but signal usually falls off at the anterior part of the neck, so they are not recommended for imaging structures such as the thyroid or larynx. In addition, flare from the posterior skin surface can be

troublesome in sagittal T1 imaging, where the large fat pad situated at the back of the neck returns a high signal. Volume coils produce even distribution of signal, but the SNR in the cord is sometimes reduced compared with a posterior neck coil. Multi-coil array combinations commonly produce optimum SNR, and may be used with a large FOV to include the thoracic spine. This strategy is important when pathology extends from the cervical to the thoracic areas of the cord, for example, syrinx.

Spatial resolution is also important, especially in axial/oblique imaging, as the nerve roots in the cervical region are notoriously difficult to visualize. Thin slices with a small gap and relatively fine matrices are employed to maintain spatial resolution. Ideally, 3D imaging is used as this allow very thin slices with no gap, and the volume may be viewed in any plane (see *Volume imaging* in *Parameters and trade-offs* in Part 1). Multiple NEX/NSA are also advisable if the inherent SNR is poor. Therefore, unless FSE is utilized, scan times are often of several minutes duration.

Fortunately, a rectangular/asymmetric FOV is used very effectively in sagittal imaging as the cervical spine fits into a rectangle with its longitudinal axis running S to I. This facilitates the acquisition of fine matrices in short scan times. With a reduced FOV in the phase direction, aliasing may be a problem. In sagittal imaging, this artefact originates from the chin and the back of the head wrapping into the FOV. Increasing the size of the overall FOV or utilizing oversampling (if available) may eliminate or reduce this artefact. In addition, spatial pre-saturation pulses brought into the FOV to nullify signal coming from these structures are effective (see *Flow phenomena and artefacts* in Part 1).

The multiple 180° RF pulses used in FSE sequences cause lengthening of the T2 decay time of fat so that the signal intensity of fat on T2-weighted FSE images is higher than in CSE. This sometimes makes the detection of marrow abnormalities difficult. Therefore, when imaging the vertebral bodies for metastatic disease, a STIR sequence should be utilized (see *Pulse sequences* in Part 1).

Artefact problems

The cervical area is often plagued with artefact. Not only does aliasing from structures outside the FOV obscure the image, but the periodic, pulsatile, motion of CSF within the spinal canal produces phase ghosting. The speed of flow is usually quite rapid in the cervical region, and therefore, conventional flow-reducing measures, such as spatial pre-saturation and GMN, are less effective than in the lumbar region where CSF flow is slower. On T1-weighted images, spatial pre-saturation pulses placed S and I to the FOV are usually sufficient. However, on T2-weighted sequences, flow artefact is commonly troublesome. In addition, selecting an S–I phase direction along with oversampling can also reduce CSF flow artefact in sagittal imaging and in that scenario, spatial pre-saturation pulses are not needed.

T2-weighted FSE sequences, when acquired in the axial plane, do not usually provide consistently high signal from the CSF throughout the range of slices primarily due loss of signal based on flow. Additionally, T2W FSE sequences do not usually provide optimal G/W contrast in the cord resulting in poor visualization of spinal cord lesions (such as MS plaques). T2W FSE sequences are also less sensitive with regard to the detection of bony spurs and osteophytes. For these reasons, GRE T2*W sequences are often utilized.

When using GRE T2* sequences, GMN should be implemented as this not only increases the signal from CSF, but also reduces artefact from CSF flowing down the canal within the slice. In addition, the use of balanced GRE reduces flow artefact due to the implementation of balancing gradients (see *Pulse sequences* in Part 1). This rapid sequence also works well in 3D imaging as a large volume may be acquired in a short scan time. However, the conspicuity of nerve roots in the exit foramina may reduce when using a GRE sequence due to the magnetic susceptibility effects. Pe gating minimizes artefact even further but, as the scan time is dependent on the patient's heart rate, it is sometimes rather time-consuming. The implementation of Pe gating is therefore best reserved for cases of severe flow artefact that cannot be reduced to tolerable levels by other measures.

Multiple NEX/NSA reduce artefact from signal averaging, but result in an increase in the scan time. Nevertheless their implementation is often necessary, especially where the SNR is poor, and flow artefact severe. Swallowing during data acquisition is a common source of artefact. Spatial pre-saturation pulses placed over the throat largely eliminate this, but care must be taken not to nullify signal from important anatomy. Another problem in the cervical region is truncation artefact (or Gibbs artefact) that produces a thin line of low signal in the cord and mimics a syrinx. Truncation artefact is reduced by selecting a higher phase matrix (see *Flow phenomena and artefacts* in Part 1).

Patient considerations

Some patients have difficulty placing their neck over the posterior neck coil, especially in cases of fixed deformity. It is important that the neck is as close to the coil as possible to achieve maximum SNR. Placing pads under the patient's shoulders flattens the spine and therefore positions the back of the neck nearer to the coil. Patients with cervical cord trauma, cord compression or tumours are often severely disabled. The magnetic safety of any stabilization devices should be established before the examination. Great care must be taken when transferring these patients on to the examination couch, and they should be moved as little as possible. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely given for disc disease. However, in cases of leptomeningeal spread of certain tumours such as medulloblastoma, contrast is invaluable. Other cord lesions such as ependymomas and pinealoblastomas also enhance well with contrast, as do infectious processes and active MS plaques. Bony tumours, especially those that return a low signal on T1-weighted images, enhance with contrast, but this often increases their signal intensity so that they are isointense with the surrounding vertebra. Under these circumstances, tissue suppression should be implemented to reduce the signal from fatty marrow in the vertebral bodies. Inversion recovery sequences that suppress fat (STIR) should not be used in conjunction with contrast, as their inverting pulses may nullify the signal from the tumour that, as a result of contrast enhancement, now has a similar T1 recovery time to fat. As a general rule, incoherent/spoiled GRE sequences with very short TEs can be used to acquire axial T1W images post contrast as they are much less prone to flow artefacts. If fat saturation is not utilized, care should be taken to ensure the shortest possible in-phase TE is selected.

Thoracic spine

Common indications

- Thoracic disc disease
- Thoracic cord compression
- Visualization of a MS plaque in the thoracic cord
- Thoracic cord tumour
- To visualize the inferior extent of cervical syrinx

Equipment

- Posterior spinal coil/multi-coil array spinal coil
- Pe gating leads if required
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with the spinal coil extending from the top of the shoulders to the lower costal margin to ensure total coverage of the thoracic spine and conus. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the centre of the coil, which corresponds approximately to the level of the fourth thoracic vertebra. Pe gating leads are attached if required.

Suggested protocol

Sagittal/coronal SE/FSE T1 or coherent GRE T2*

Acts as a localizer if three-plane localization is unavailable. The coronal or sagittal planes may be used.

Coronal localizer: Medium slices/gaps are prescribed relative to the vertical alignment light, from the posterior aspect of the spinous processes to the anterior border of the vertebral bodies. The area from the seventh cervical vertebra to the conus is included in the image.

P 40 mm to A 30 mm

Sagittal localizer: Medium slices/gaps are prescribed on either side of the longitudinal alignment light, from the left to the right lateral borders of the vertebral bodies. The area from the seventh cervical vertebra to the conus is included in the image.

L 7 mm to R 7 mm

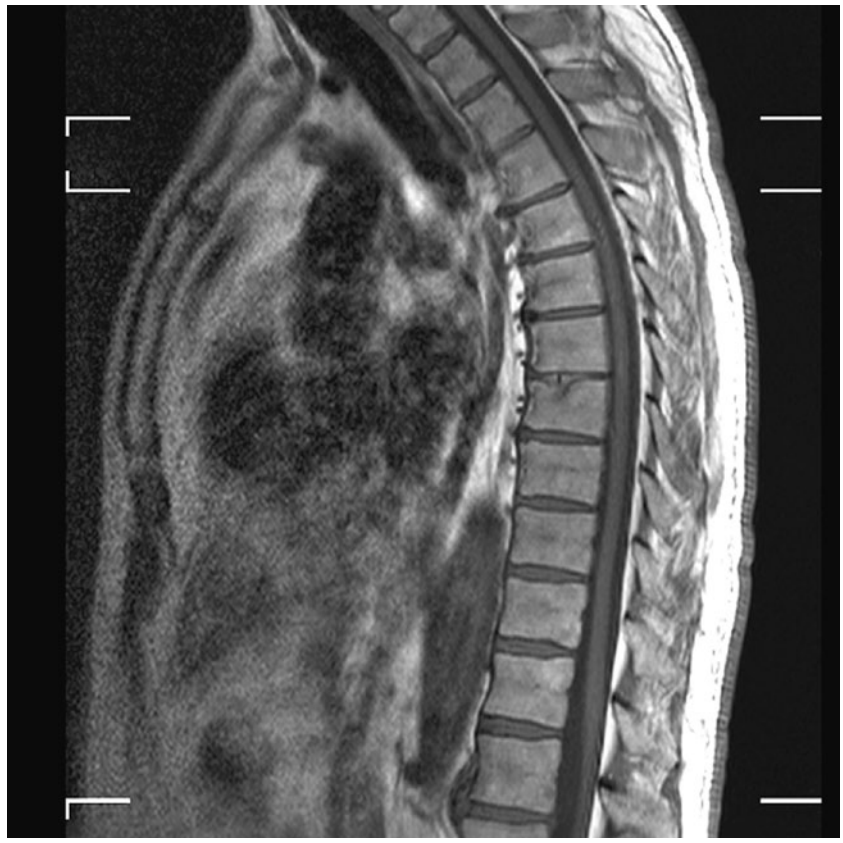

Figure 9.9 Sagittal FSE T1-weighted midline slice through the thoracic spine.

Sagittal SE/FSE T1 (Figure 9.9)

Thin slices/gaps are prescribed on either side of the longitudinal alignment light, from the left to the right lateral borders of the vertebral bodies (unless the paravertebral areas are required). The area from the seventh cervical vertebra to the conus is included in the image.

L 22 mm to R 22 mm

Sagittal SE/FSE T2 or coherent GRE T2* (Figure 9.10)

Slice prescription as for sagittal T1.

Axial/oblique SE/FSE T1 or coherent gradient echo T2* (Figure 9.11)

Thin slices/gaps are angled so that they are parallel to the disc space or perpendicular to the lesion under examination (Figure 9.12). For disc disease, three or four slices per level usually suffice. For larger lesions such as tumour or syrinx, thicker slices covering the lesion and a small area above and below are necessary.

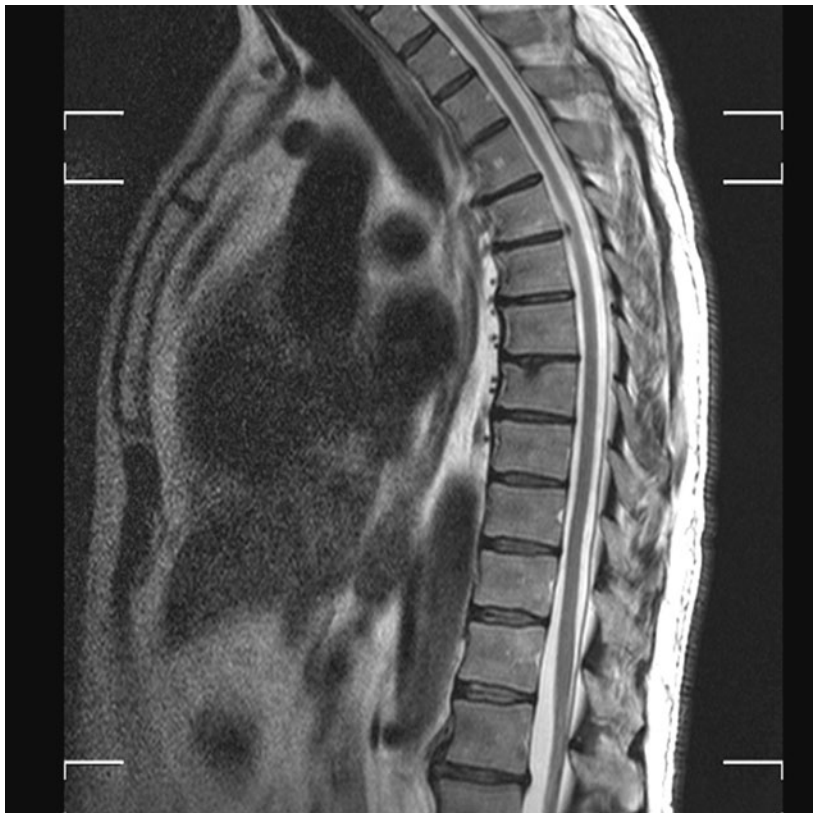

Figure 9.10 Sagittal FSE T2-weighted midline slice through the thoracic cord.

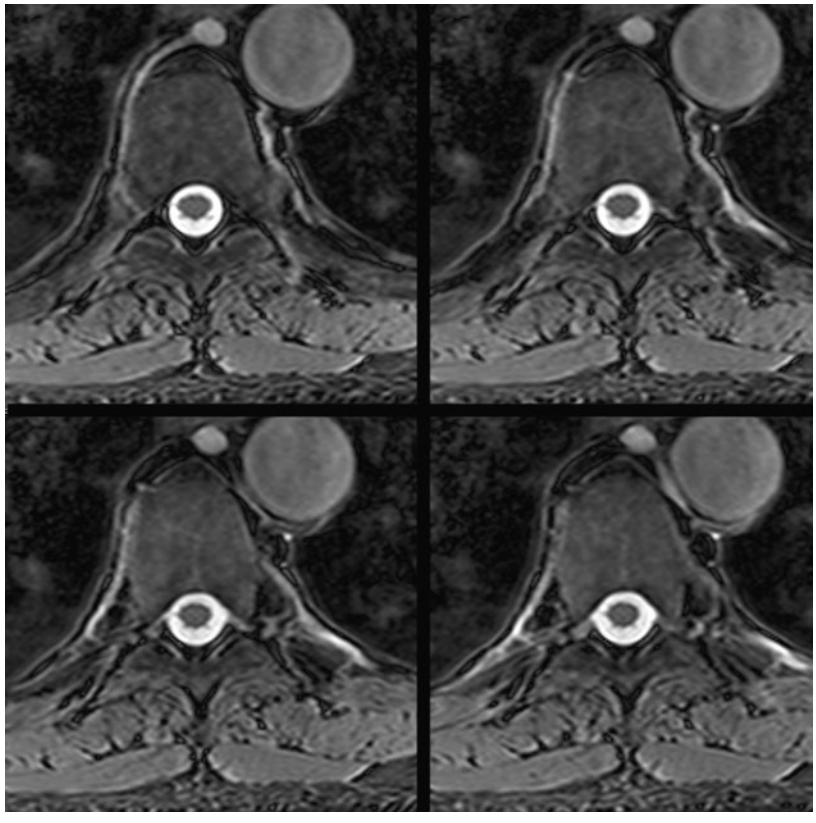

Figure 9.11 Axial/oblique FSE T2-weighted images through the thoracic cord.

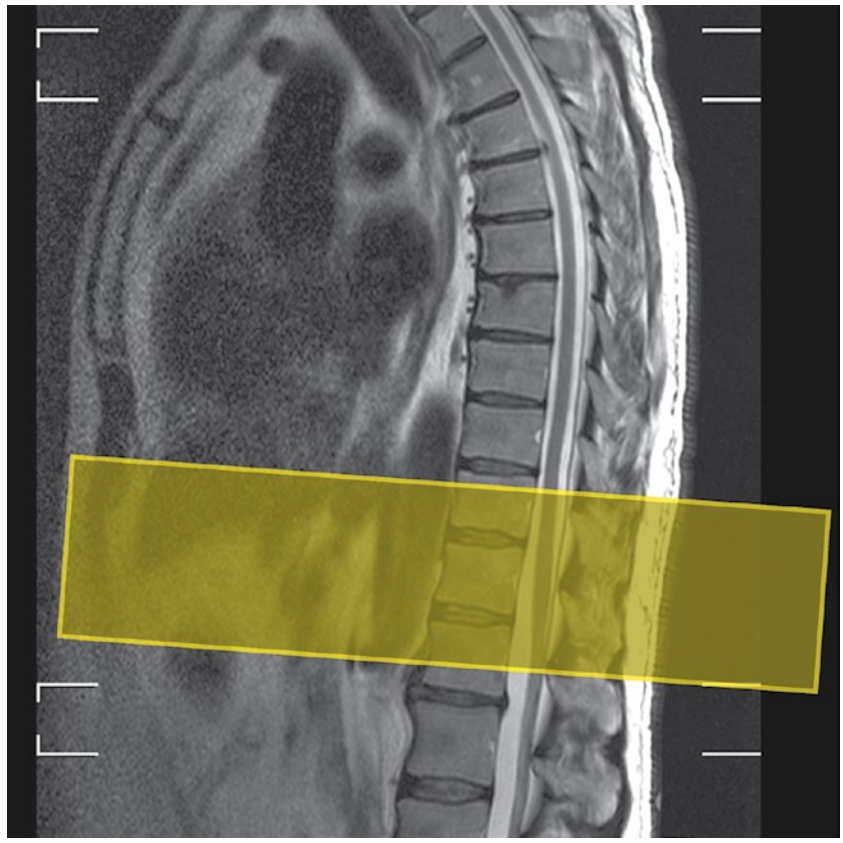

Figure 9.12 Sagittal FSE T2-weighted midline slice through the thoracic spine showing slice prescription boundaries and orientation for axial imaging of the conus.

Additional sequences

Sagittal/axial/oblique SE/FSE T1 +/– contrast

For evaluating the conus and other cord lesions.

Image optimization

Technical issues

The SNR in this region is mainly dependent on the quality of the coil. Flare from the posterior skin surface may be troublesome, especially in sagittal T1 imaging where the fatty tissues posterior to the thoracic spine return a high signal. In addition, there is signal fall-off from the anterior part of the chest due to its distance from the posteriorly situated coil. For this reason, the posterior spinal coil is not utilized to image the thorax, unless the patient is a very small child. Phased array coils are useful to image the whole of the cervical and thoracic cord while maintaining optimum SNR and resolution.

Spatial resolution is important especially in axial/oblique images, as the nerve roots in the thoracic region are commonly difficult to visualize. Thin slices with a small gap and relatively fine matrices are implemented to maintain spatial resolution. Multiple NEX/NSA are also advisable if the inherent SNR is poor. Therefore, unless FSE is utilized, scan times are usually of several minutes duration.

Fortunately, a rectangular/asymmetric FOV is used very effectively in sagittal imaging as the thoracic spine fits into a rectangle with its longitudinal axis running S to I. This facilitates the acquisition of fine matrices in short scan times. With a reduced FOV in the phase direction, aliasing may be a problem. In sagittal imaging, this artefact originates from the anterior chest wrapping into the FOV. Increasing the size of the overall FOV or utilizing oversampling (if available) may eliminate or reduce this artefact. In addition, spatial pre-saturation pulses brought into the FOV are effective (see *Flow phenomena and artefacts* in Part 1). In practice, as a fairly large FOV is used to image the thoracic spine and there is signal fall-off in the anterior part of the chest, aliasing is not usually troublesome.

The multiple 180° RF pulses used in FSE sequences cause lengthening of the T2 decay time of fat so that the signal intensity of fat on T2-weighted FSE images is higher than in CSE. This sometimes makes the detection of marrow abnormalities difficult. Therefore, when imaging the vertebral bodies for metastatic disease, a STIR sequence should be utilized.

Artefact problems

Flow from CSF pulsations commonly causes severe phase ghosting in the thoracic region, although the speed of flow is often less than in the cervical area. Spatial pre-saturation pulses placed S and I to the FOV are necessary to reduce these flow-related problems. GMN also minimizes flow artefact, but as it increases the signal from CSF and the minimum TE available, it is usually reserved for T2- and T2*-weighted sequences. FSE is commonly utilized in this area as the associated scan time reduction enables the implementation of very fine matrices. However, this sequence often demonstrates increased flow artefact compared with SE and GRE sequences. Therefore, if flow artefact is too troublesome, SE or GRE may be substituted.

Phase ghosting from cardiac and respiratory motion is the main source of artefact in the thoracic region. Spatial pre-saturation pulses brought into the FOV and placed over the heart and lung fields are very effective at reducing this. Pe gating minimizes artefact even further but, as the scan time is dependent on the patient's heart rate, it is sometimes time-consuming. The implementation of Pe gating is therefore best reserved for cases of severe flow artefact that cannot be reduced to tolerable levels by other measures.

In sagittal imaging, swapping the phase axis so that it runs from S to I instead of A to P removes the artefact from the cord. However, if there is

significant kyphosis, the artefact may still obscure the cervical and lumbar regions. In addition, if a rectangular/asymmetric FOV is implemented, swapping the phase axis places the longitudinal axis of the rectangle horizontally so that its benefits cannot be utilized. On newer systems, it is possible to use curved spatial pre-saturation pulses so that accurate placement of bands over the thoracic aorta is possible.

Due to the implementation of a small FOV in axial/oblique imaging, aliasing commonly occurs, and therefore, oversampling is necessary. In addition, phase artefact from movement of the lateral walls of the chest during respiration, and some vessel pulsation, often interferes with the images. Careful placement of spatial pre-saturation pulses A, R and L of the FOV is usually effective at reducing this. RC is rarely necessary in the thoracic spine because the posteriorly situated spinal coil causes signal fall-off from the anterior chest wall, and therefore, respiratory artefact is usually less troublesome than when imaging the whole chest in the body coil. Movement of the diaphragm is more significant, however, and RC may be considered if this is a particular problem.

Patient considerations

Patients with cord trauma may be severely disabled and in great pain. The examination should obviously be undertaken as speedily as possible under these circumstances. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely given for disc disease. However, in cases of leptomeningeal spread of certain tumours such as medulloblastoma, contrast is invaluable. Other cord lesions such as ependymomas and pinealoblastomas also enhance well with contrast, as do infectious processes and active MS plaques. Bony tumours, especially those that return a low signal on T1-weighted images, enhance with contrast but this often increases their signal intensity so that they are isointense with the surrounding vertebra. Under these circumstances, tissue suppression or some type of frequency-based fat saturation/suppression technique such as a Dixon-based technique should be implemented to reduce the signal from fatty marrow in the vertebral bodies. STIR should not be used in conjunction with contrast, as its inverting pulse may nullify the signal from the tumour that, as a result of contrast enhancement, now has a similar T1 recovery time to fat.

Lumbar spine

Common indications

- Disc prolapse with cord or nerve root compression
- Spinal dysraphism (to assess cord termination, syrinx, diastematomyelia)
- Discitis
- Evaluation of the conus in patients with appropriate symptoms
- Failed back syndrome
- Arachnoiditis

Equipment

- Posterior spinal coil/multi-coil array spinal coil
- Foam pads to elevate the knees
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with their knees elevated over a foam pad, for comfort and to flatten the lumbar curve so that the spine lies nearer to the coil. The coil should extend from the xiphisternum to the bottom of the sacrum for adequate coverage of the lumbar region. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes just below the lower costal margin, which corresponds to the third lumbar vertebra. Depending on the particular coil configuration, the patient may be placed either head first or feet first. If the patient is anxious or claustrophobic, when/if possible, the feet-first position may be better tolerated.

Suggested protocol

Sagittal/coronal SE/FSE T1 or coherent GRE T2*

Acts as a localizer if three-plane localization is unavailable. The coronal or sagittal planes may be used.

Coronal localizer: Medium slices/gaps are prescribed relative to the vertical alignment light, from the posterior aspect of the spinous processes to the anterior border of the vertebral bodies. The area from the conus to the sacrum is included in the image.

P 20 mm to A 30 mm

Sagittal localizer: Medium slices/gaps are prescribed on either side of the longitudinal alignment light, from the left to the right lateral borders

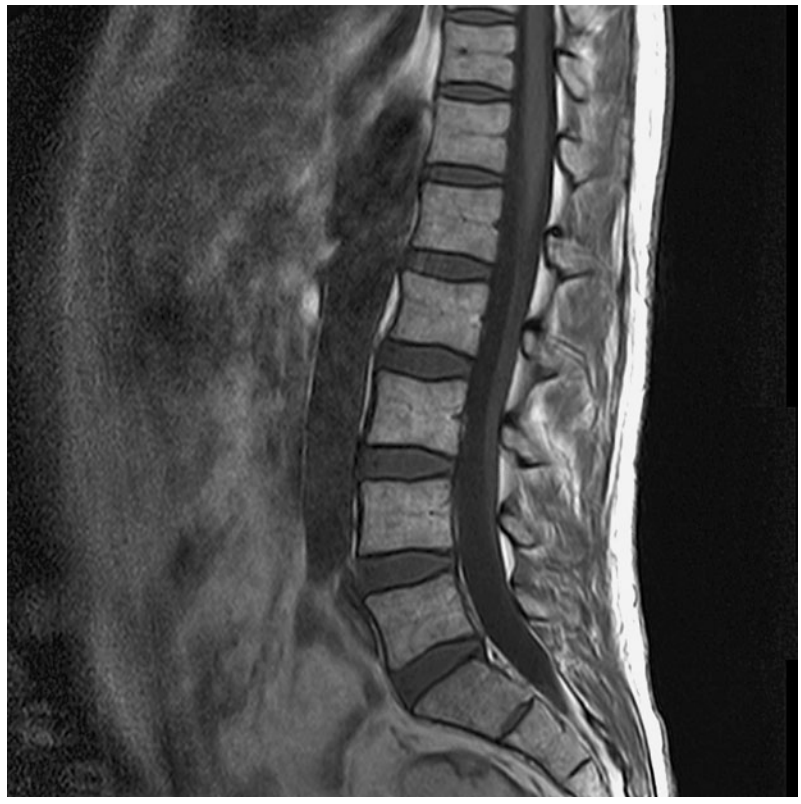

Figure 9.13 Sagittal FSE T1-weighted midline slice through the lumbar spine showing normal appearances.

of the vertebral bodies. The area from the conus to the sacrum is included in the image.

L 7 mm to R 7 mm

Sagittal SE/FSE T1 (Figure 9.13)

Thin slices/gaps are prescribed on either side of the longitudinal alignment light, from the left to the right lateral borders of the vertebral bodies (unless the paravertebral region is required). The area from the conus to the sacrum is included in the image.

L 22 mm to R 22 mm

Sagittal SE/FSE T2 or coherent GRE T2* (Figure 9.14)

Slice prescription as for sagittal T1.

Axial/oblique SE/FSE T1/T2 or coherent GRE T2* (Figure 9.15)

Thin slices/gaps are angled so that they are parallel to each disc space and extend from the lamina below to the lamina above the disc. The lower three lumbar discs are commonly examined (Figure 9.16).

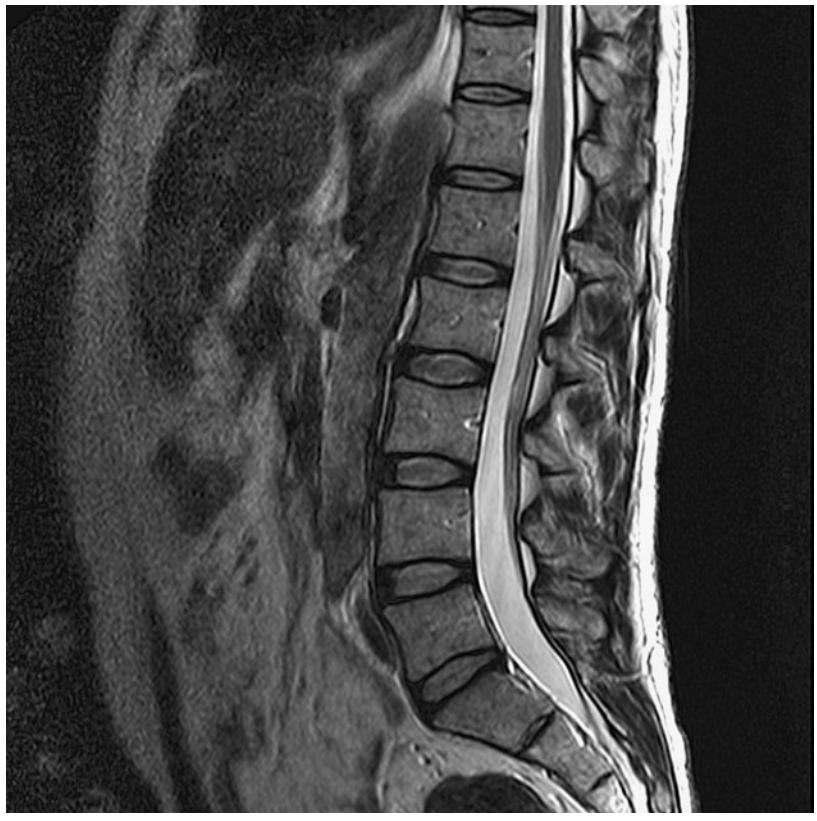

Figure 9.14 Sagittal FSE T2-weighted midline slice through the lumbar spine showing normal appearances.

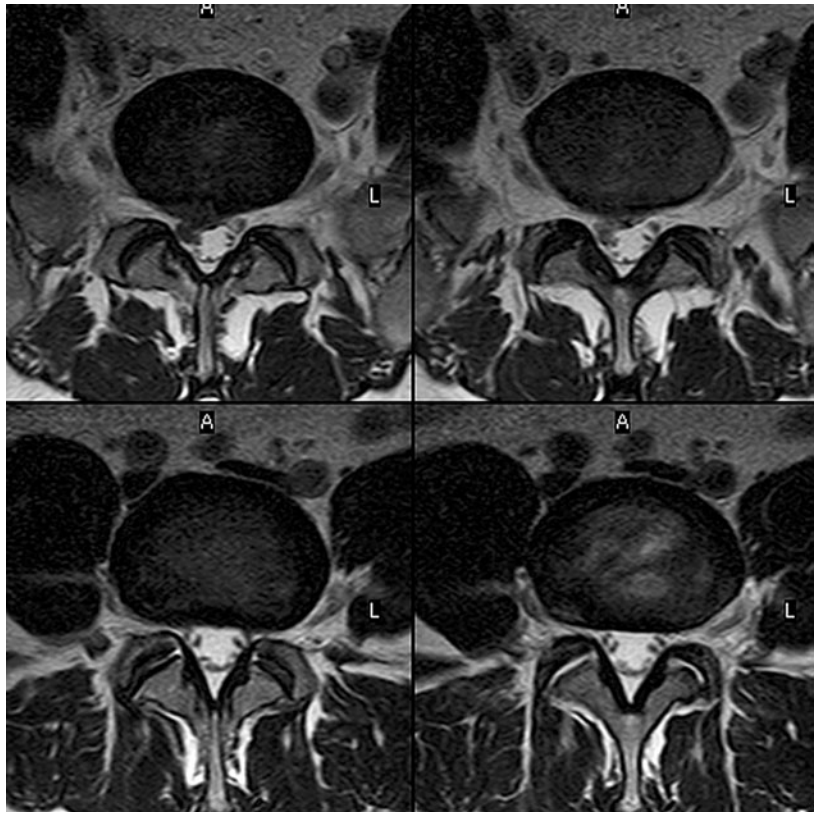

Figure 9.15 Axial/oblique FSE T2-weighted image of the lumbar spine.

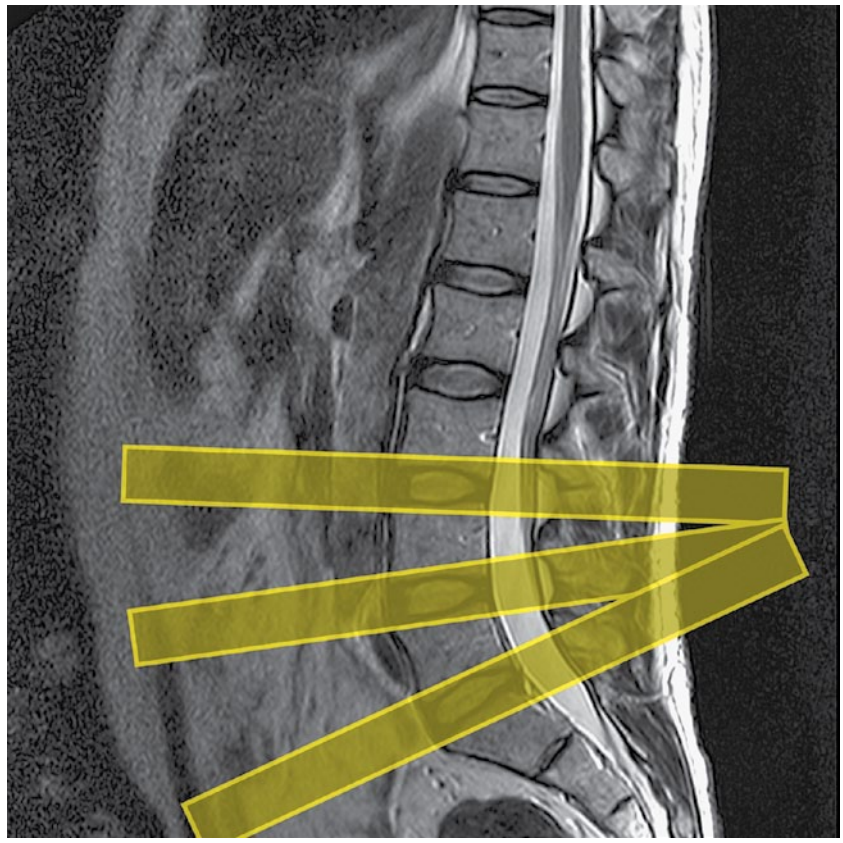

Figure 9.16 Sagittal FSE T2-weighted midline slice showing slice prescription boundaries and orientation for axial/oblique imaging of lumbar discs.

Additional sequences

Axial/oblique or sagittal SE/FSE T1

With contrast for determining disc prolapse versus scar tissue in failed back syndrome, and for some tumours. Without contrast in spinal dysraphism. Tissue suppression is beneficial to differentiate between fat and enhancing pathology.

Coronal SE/FSE T1

For cord tethering or alternative view of conus when sagittals are inconclusive.

Axial/oblique FSE T2

For arachnoiditis. As for axial/obliques, **except** prescribe one slice through, and parallel to, each disc space and vertebral body from the sacrum to the conus (Figure 9.17).

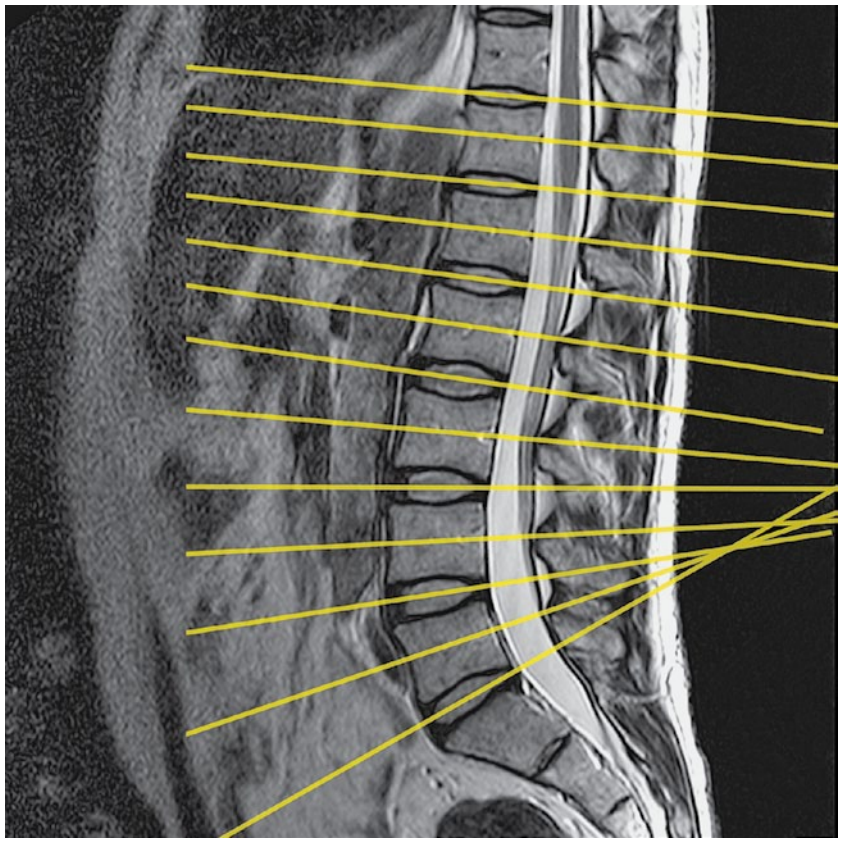

Figure 9.17 Sagittal FSE T2-weighted image of the lumbar spine showing axial/oblique slice prescription for arachnoiditis.

STIR

While FSE sequences provide excellent T2-weighted images of the spine, the signal intensity from the normal fat in the marrow of the vertebral bodies is generally high, even with longer TE times. For that reason, marrow pathology, such as tumours or fractures, may not be adequately visualized on T2-weighted FSE sequences. A STIR sequence can be utilized to visualize bone marrow abnormalities better. This is demonstrated in the images in Figures 9.18, 9.19 and 9.20. The T1-weighted FSE shows an acute fracture of the L1 vertebral body. The T2-weighted FSE also shows the fracture, but the majority of the bone marrow signal in the L1 vertebral body appears similar to the other vertebral bodies. The STIR clearly shows the increased signal within the L1 vertebral body consistent with an acute fracture.

Image optimization

Technical issues

The SNR in the lumbar region depends on the quality of the coil. Posterior spinal coils return high signal in the area of the lumbar canal and vertebral

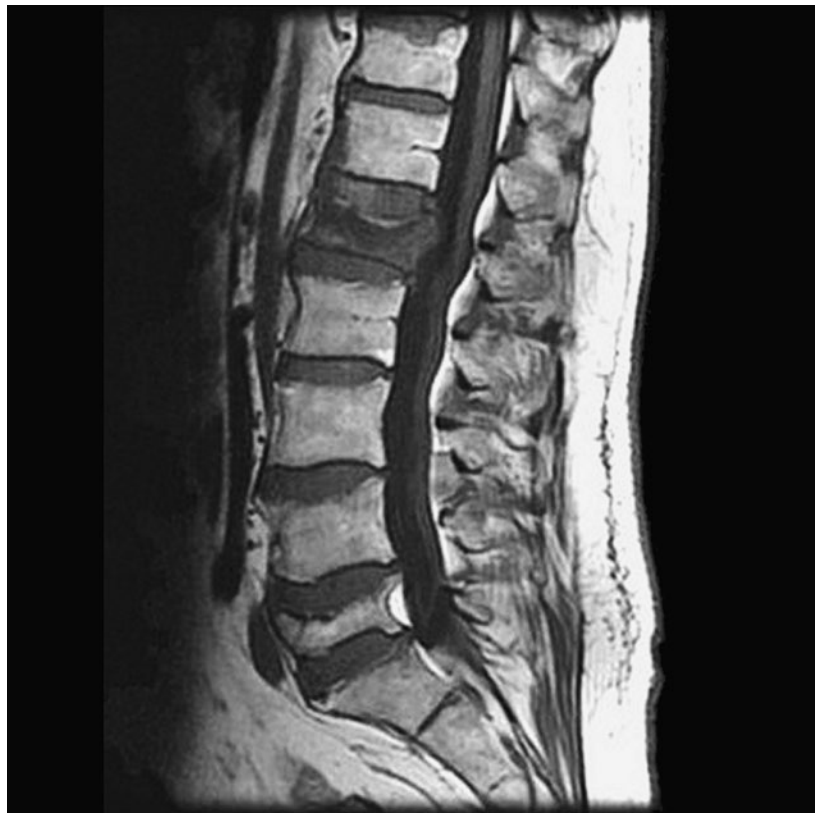

Figure 9.18 Sagittal T1-weighted FSE showing an acute fracture in the body of L1.

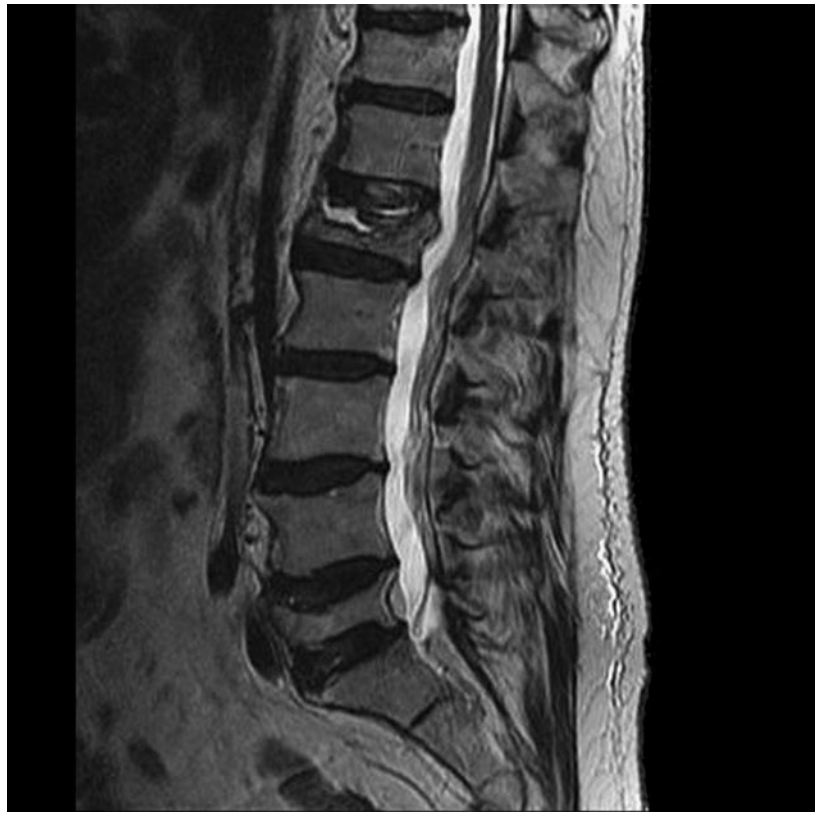

Figure 9.19 Sagittal T2-weighted FSE of the same patient shown in Figure 9.18.

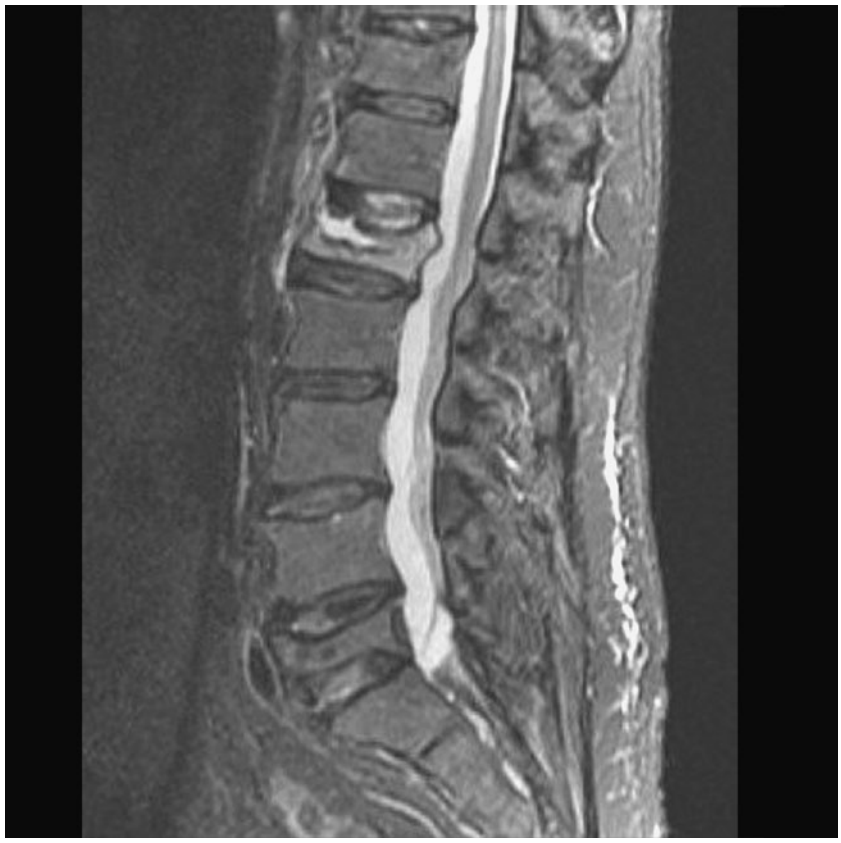

Figure 9.20 Sagittal FSE-STIR of the same patient shown in Figure 9.18.

bodies, but flare from the fatty tissues in the buttocks sometimes interferes with the image. Phased array coils allow for imaging of the thoracic and lumbar spine in conjunction with good SNR and resolution. As CSF flow is reduced in this area, FSE is routinely used. This enables the implementation of very fine matrices so that spatial resolution is significantly increased. Resolution is also maintained by using rectangular/asymmetric FOV in sagittal imaging (with the long axis of the rectangle running from S to I), and a small FOV in axial/oblique imaging. Fine matrices are especially necessary in arachnoiditis to detect nerve root clumping.

Artefact problems

CSF pulsation is not usually troublesome as the speed of flow is relatively slow. However, phase artefact from the aorta and the inferior vena cava (IVC), and lateral flow from the lumbar vessels, sometimes obscures the lumbar canal. Spatial pre-saturation pulses brought into the FOV and placed S, I and A in the sagittal images, and A, R and L in the axial/oblique images, reduce phase ghosting. GMN minimizes flow artefact even further, but as it increases the signal in CSF and the minimum TE available, it is mainly reserved for the T2- and T2*-weighted sequences.

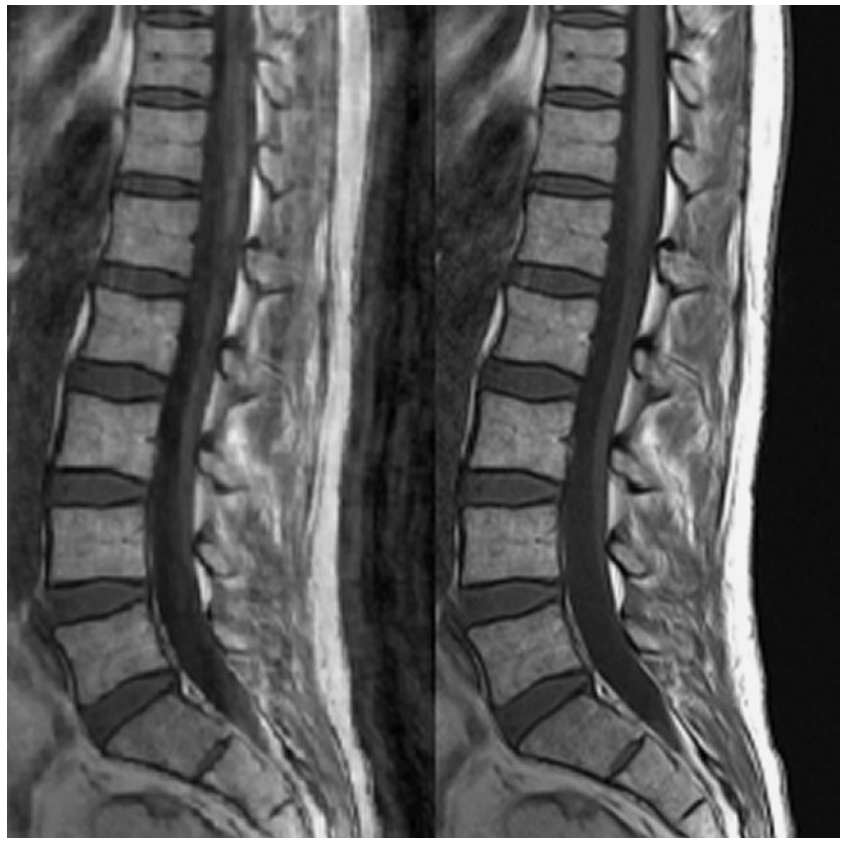

Figure 9.21 Sagittal FSE T1-weighted images of the lumbar spine with phase A to P (left) and S to I (right). The definition of the spinal cord is clearly improved on the right-hand image.

Swapping the phase axis in sagittal imaging so that it runs from S to I instead of A to P is probably the best way of removing this artefact from the cord. However, a rectangular/asymmetric FOV cannot be used under these circumstances as the long axis of the rectangle is placed horizontally (Figure 9.21). A compromise is to swap the phase axis and not use a rectangular/asymmetric FOV in the T1 sagittal image, and keep the phase axis AP and use a rectangular/asymmetric FOV in the T2 sagittal image.

With a reduced FOV in the phase direction, aliasing may be a problem. In sagittal imaging, this artefact originates from the buttocks and abdomen wrapping into the FOV (Figure 9.22). Increasing the size of the overall FOV or utilizing oversampling (if available) may eliminate or reduce this artefact. If the phase axis is swapped, aliasing occurs as the areas superior and inferior to the coil are wrapped into the FOV, and therefore, oversampling is necessary to avoid this. In addition, owing to the implementation of a small FOV in the axial/oblique imaging, aliasing commonly occurs, and therefore, oversampling is also required in this plane. Spatial pre-saturation pulses brought into the FOV are also effective (Figure 9.23).

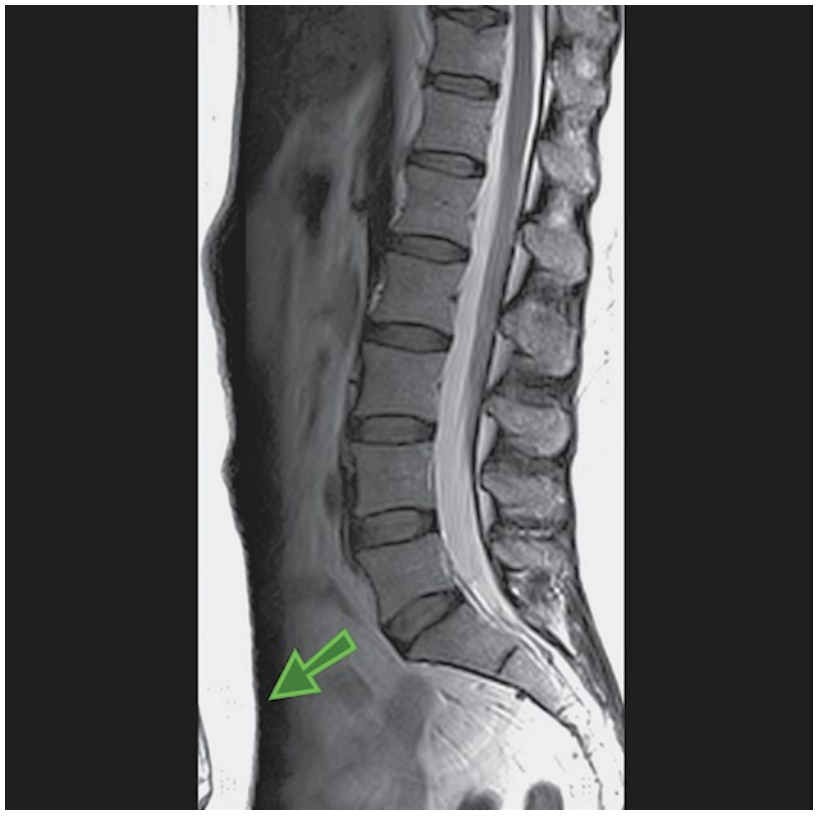

Figure 9.22 Sagittal FSE T2-weighted midline slice through the lumbar spine using rectangular/asymmetric FOV. Note phase aliasing from the buttocks (arrow).

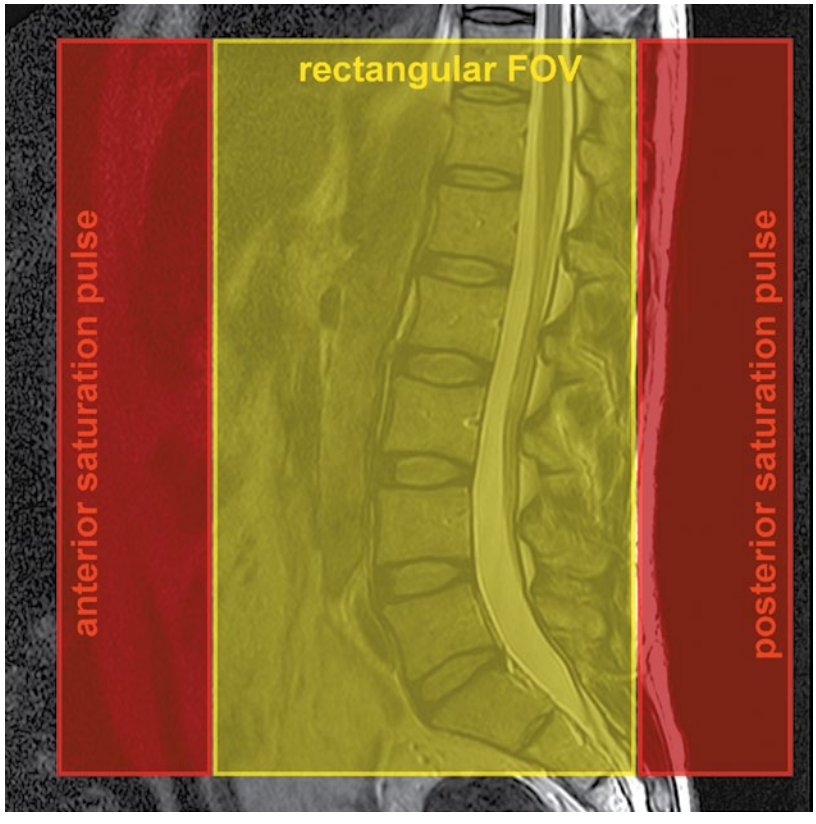

Figure 9.23 Correct placement of spatial pre-saturation bands when using rectangular/asymmetric FOV in the lumbar spine.

The multiple 180° RF pulses used in FSE sequences cause lengthening of the T2 decay time of fat so that the signal intensity of fat on T2-weighted FSE images is higher than in CSE. This sometimes makes the detection of marrow abnormalities difficult. Therefore, when imaging the vertebral bodies for metastatic disease, a STIR sequence should be utilized.

Patient considerations

Many patients are in severe pain especially if they are suffering from a prolapsed lumbar disc. Make the patient as comfortable as possible with pads supporting their knees in a slightly flexed position. Small pads placed in the lumbar curve often help to alleviate sciatica and other types of back pain.

Due to excessively loud gradient noise associated with some sequences, earplugs/headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is used to distinguish disc prolapse from scar tissue post-operatively in failed back syndrome. These images are acquired with or without tissue suppression. STIR should not be used with contrast enhancement, as the contrast reduces the T1 value of damaged tissues so that it is similar to that of fat, and is therefore nullified by the inverting pulse. Scar tissue enhances immediately after the injection, but disc material does not. However, about 20–30 min after the injection, disc material also enhances, and therefore, scanning should not be delayed after the administration of contrast. In addition, the epidural veins and granulation tissue at the periphery of a disc and fibrosis may enhance. Contrast is also invaluable to visualize suspicious lesions in the conus.

Whole spine imaging

Common indications

- Cord compression (level unknown), due to metastatic disease or primary cord tumour
- Bone marrow screening
- Congenital abnormalities of spinal curvature (scoliosis and kyphosis)
- Evaluation of the extent of a syrinx
- Leptomeningeal disease

Equipment

- Body coil/multi-coil array spinal coil
- Pe gating leads if required
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through a point midway between the sacrum and the base of the skull (which corresponds to about 2 cm below the sternal notch). Pe gating leads are attached if required.

Suggested protocol

Sagittal SE/FSE T1 (Figure 9.24a)

Thin slices/gap are prescribed on either side of the longitudinal alignment light, from the left to the right lateral borders of vertebral bodies (or prescribed graphically from a coronal localizer).

L 22 mm to R 22 mm

Include the entire canal from the base of the skull to below the sacrum and use the largest FOV available. Repeat the scan if an area is missed. If severe scoliosis is present, coronal images may be more beneficial than sagittals to assess the direction and extent of the curvature.

Sagittal SE/FSE T2 or coherent GRE T2* (Figure 9.24b)

Slice prescription as for sagittal T1.

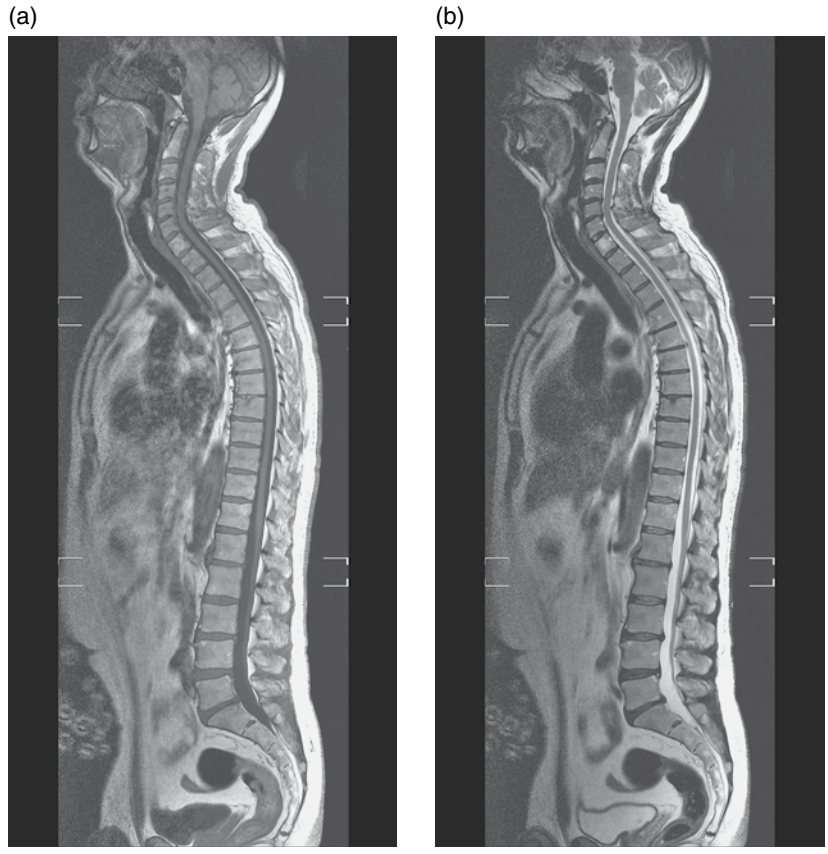

Figure 9.24 Sagittal FSE T1-weighted image (a) and T2-weighted image (b) of the cervical and thoracic cord imaged using a phased array coil.

Axial/oblique SE/FSE T1/T2

Thin slices/gaps are prescribed through the ROI. Use a smaller local coil once the ROI has been established (not necessary with a multi-coil array). In patients with severe spinal curvature, obliques may be performed to achieve orthogonal images.

Additional sequences

Sagittal SE/FSE T2 or STIR

For bone marrow screening, include the sternum in the image and add coronals of the bony pelvis. Use tissue suppression pulses in SE/FSE sequences.

Sagittal/oblique SE/FSE T1

With contrast for tumour infection and leptomeningeal disease.

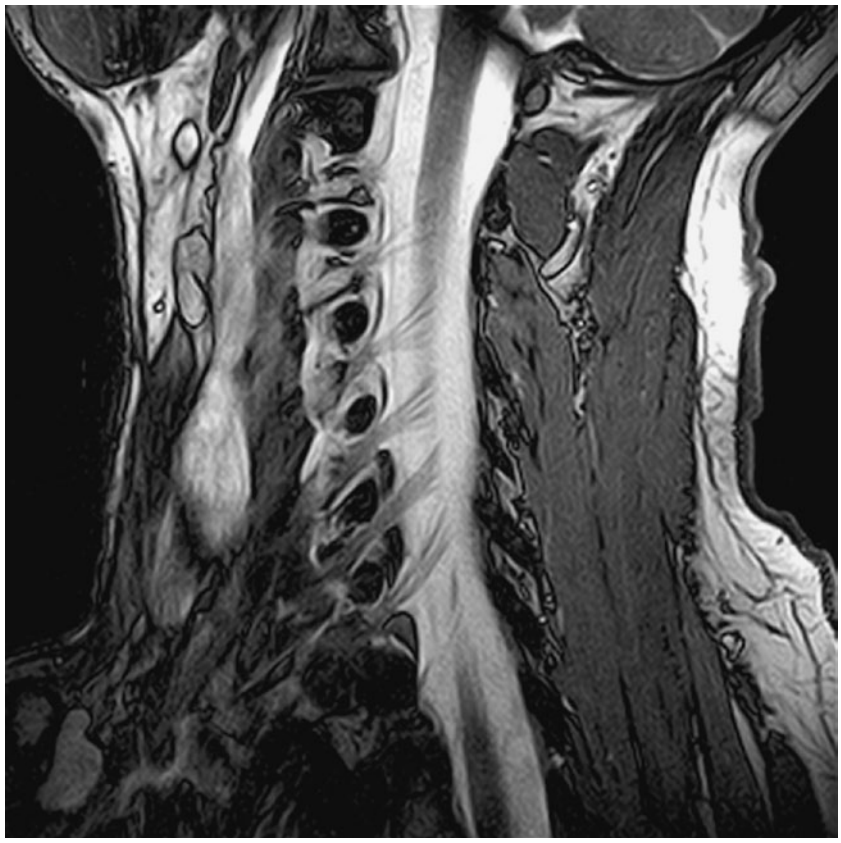

Figure 9.25 Sagittal oblique balanced GRE through the cervical cord showing nerve roots and peripheral nerves.

MR myelography/neurography (Figure 9.25)

Examination of nerve roots and peripheral nerves with high-resolution imaging are useful additional techniques.

Image optimization

Technical issues

These examinations are often carried out to establish the level and cause of a cord compression. Therefore, spatial resolution is not necessarily as important as a quick diagnosis. The level of the compression may be unknown, and therefore, coverage of the whole spinal canal is the most important consideration. In the past, this could only be achieved with the body coil, as surface coils did not cover the entire spine. However, phased array coils have now been introduced that give the benefits of maximum coverage and optimum SNR. If phased array coils are unavailable, the body coil is implemented. This results in a loss of overall SNR and poor local spatial resolution, as a large FOV is utilized to cover the whole spine. Once a level has been established, the body coil may be substituted

for a surface coil and higher-quality images obtained. This strategy is unnecessary when using a multi-array as the increase in SNR enables acquisition of images with adequate resolution. With both coil types, a rectangular/asymmetric FOV is used in the sagittal images to improve spatial resolution with the long axis of the rectangle S to I.

Artefact problems

When imaging the entire spine with the body coil, artefacts are caused by CSF flow, heart and great vessel motion, and respiration. Spatial pre-saturation pulses placed S and I to the FOV reduce CSF artefact. They are often also placed over the heart and great vessels but can obscure some of the spine if there is spinal curvature. However, on newer systems, it is possible to use curved spatial pre-saturation pulses that enable accurate placement of the bands over the aorta. Spatial pre-saturation pulses are commonly less effective over a large FOV, and therefore, phase ghosting may still be evident. In addition, if tissue suppression is employed, it may be less effective than with a small FOV. This is because the energy of the pre-saturation pulse is now delivered to a greater volume of tissue, thereby reducing its effectiveness. Additional shimming may be required before tissue suppression sequences.

GMN also minimizes flow artefact, but as it increases signal in CSF and the minimum TE available, it is usually only beneficial in T2- and T2*-weighted sequences. Pe gating minimizes artefact even further but, as the scan time is dependent on the patient's heart rate, it is sometimes time-consuming. The implementation of Pe gating is therefore best reserved for cases of severe flow artefact that cannot be reduced to tolerable levels by other measures.

The multiple 180° RF pulses used in FSE sequences cause lengthening of the T2 decay time of fat so that the signal intensity of fat on T2-weighted FSE images is higher than in CSE. This sometimes makes the detection of marrow abnormalities difficult. Therefore, when imaging the vertebral bodies for metastatic disease, a STIR sequence should be utilized.

Patient considerations

Patients with cord compression are sometimes severely disabled and in extreme pain. A swift examination is often necessary to avoid patient movement. An analgesic administered prior to the examination may be beneficial. Patients with severe curvature of the spine often find it impossible to lie flat on the examination couch. Patient comfort is very important as these examinations are sometimes lengthy due to the extra sequences needed to achieve orthogonal images. It is wise to let the patient assume the most comfortable position and use foam pads to support them. The plane of the images is then adjusted to their position. Sometimes the lung field area of these patients is compromised and respiration may become an effort when they lie supine. Oxygen can be

administered to the patient during the examination, but reducing the scan time as much as possible is probably the best remedy for this problem.

Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is often necessary especially for leptomeningeal disease, intradural or extra-medullary lesions and metastases. It may also be useful for spinal osteomyelitis and almost always in the post-operative patient.

Key points

- T2W FSE sequences may not be the most sensitive to cord lesions. Whatever sequence chosen, good contrast between the grey and white matter must be demonstrated.
- GRE (T2*-weighted) sequences demonstrate osteophytes in the cervical spine better than T2W FSE sequences.
- A fat suppression technique based on the Dixon technique often is the best choice for acquiring fat-suppressed images in the cervical spine.
- A gadolinium-based contrast agent is most often utilized when a lesion within the cord is suspected.
- STIR sequences are very useful for demonstrating lesions and/or fractures of the vertebral bodies.

10 Chest

Handbook of MRI Technique, Fourth Edition. Catherine Westbrook.

Companion website: www.wiley.com/go/westbrook/mritechnique

Table 10.1 Summary of parameters

1.5T		3T	
SE		**SE**	
Short TE	Min–30 ms	Short TE	Min–15 ms
Long TE	70 ms+	Long TE	70 ms+
Short TR	600–800 ms	Short TR	600–900 ms
Long TR	2000 ms+	Long TR	2000 ms+
FSE		**FSE**	
Short TE	Min–20 ms	Short TE	Min–15 ms
Long TE	90 +	Long TE	90 ms+
Short TR	400–600 ms	Short TR	600–900 ms
Long TR	4000 ms+	Long TR	4000 ms+
Short TEL	2–6	Short TEL	2–6
Long ETL	16+	Long ETL	16+
IR T1		**IR T1**	
Short TE	Min–20 ms	Short TE	Min–20 ms
Long TR	3000 ms+	Long TR	300 ms+
TI	200–600 ms	TI	Short or null time of tissue
Short ETL	2–6	Short ETL	2–6
STIR		**STIR**	
Long TE	60 ms+	Long TE	60 ms+
Long TR	3000 ms+	Long TR	3000 ms+
Short TI	100–175 ms	Short TI	210 ms
Long ETL	16+	Long ETL	16+
FLAIR		**FLAIR**	
Long TE	80 ms+	Long TE	80 ms+
Long TR	9000 ms+	Long TR	9000 ms +(TR at least 4 × TI)
Long TI	1700–2500 ms (depending on TR)	Long TI	1700–2500 ms (depending on TR)
Long ETL	16+	Long ETL	16+
Coherent GRE		**Coherent GRE**	
Long TE	15 ms+	Long TE	15 ms+
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Incoherent GRE		**Incoherent GRE**	
Short TE	Minimum	Short TE	Minimum
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Balanced GRE		**Balanced GRE**	
TE	Minimum	TE	Minimum
TR	Minimum	TR	Minimum
Flip angle	>40°	Flip angle	>40°
SSFP		**SSFP**	
TE	10–15 ms	TE	10–15 ms
TR	<50 ms	TR	<50 ms
Flip angle	20–40°	Flip angle	20–40°

(*Continued*)

Table 10.1 (*Contd.*)

1.5T and 3T			
Slice thickness 2D		**Slice thickness 3D**	
Thin	2–4 mm	Thin	<1 mm
Medium	5–6 mm	Thick	>3 mm
Thick	8 mm		
FOV		**Matrix**	
Small	<18 cm	Coarse	256×128/256×192
Medium	18–30 cm	Medium	256×256/512×256
Large	>30 cm	Fine	512×512
		Very fine	>1024×1024
NEX/NSA		**Slice number 3D**	
Short	1	Small	<32
Medium	2–3	Medium	64
Multiple	>4	Large	>128
PC-MRA 2D and 3D		**TOF-MRA 2D**	
TE	Minimum	TE	Minimum
TR	25–33 ms	TR	28–45 ms
Flip angle	30°	Flip angle	40–60°
VENC venous	20–40 cm/s	**TOF-MRA 3D**	
VENC arterial	60 cm/s	TE	Minimum
		TR	25–50 ms
		Flip angle	20–30°

The figures given are for 1.5T and 3T systems. Parameters are dependent on field strength and may need adjustment for very low or very high field systems.

Lungs and mediastinum

Basic anatomy (Figure 10.1)

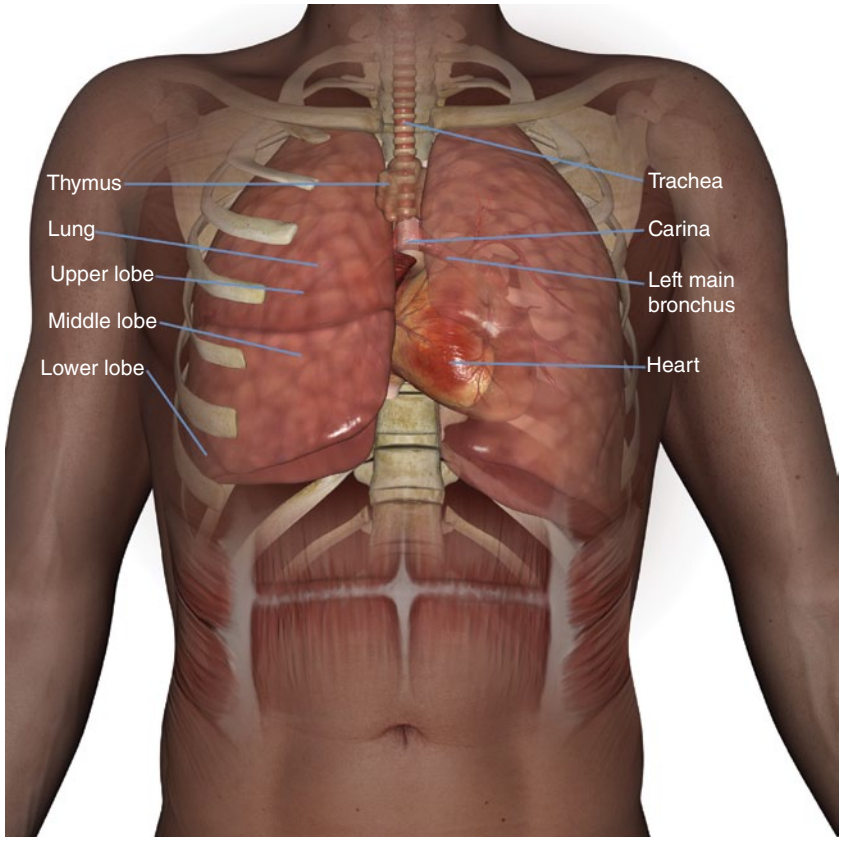

Figure 10.1 Anterior view of the components of the chest cavity.

Common indications

- Mediastinal lymphadenopathy
- Central and superior sulcus bronchial tumours
- Distinction between neoplasm and consolidated lung
- Alternative to CT of the mediastinum and chest wall when the patient is hypersensitive to contrast medium
- Vascular evaluation of aortic dissection, pulmonary embolus, aortic aneurysm or vascular stenosis
- Lung perfusion studies
- Assessment of diaphragmatic motion
- Chest wall infections
- Pleural disease
- Rib lesions or metastases

Equipment

- Body coil/volume torso multi-coil array
- RC bellows
- ECG or peripheral gating leads
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with the RC bellows (if required) and ECG gating leads attached. Pads can be placed under the patient's knees (for comfort) and beside the patient's elbows (for optimal MR imaging). In some cases, if the patient is not comfortable supine and/or if the patient has trouble in confined spaces, prone positioning may be a suitable alternative.

The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the fourth thoracic vertebra, or the nipples. The patient can be placed feet first into the magnet if the ECG trace is unsatisfactory as this changes the patient's polarity relative to the main field (see *Gating and respiratory compensation techniques* in Part 1).

Suggested protocol

Coronal breath-hold fast incoherent (spoiled) GRE/SE T1 (Figure 10.2)

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Medium slices/gaps are prescribed relative to the vertical alignment light, from the posterior chest muscles to the sternum. The entire lung fields from apex to base are included in the image. As the chest anatomy is generally located more anteriorly than posteriorly, slices are offset in the anterior direction.

P 60 mm to A 80 mm

Axial FSE T1/incoherent (spoiled) GRE T1 (Figures 10.3, 10.4 and 10.5)

As for the coronal T1, **except** slice thickness/gap is adjusted to fit the ROI. Prescribe slices from the diaphragm to the apex of the lung or through the ROI.

Axial FSE PD/T2/SS-FSE T2/GRE T2* (Figure 10.6)

Slice prescription as for axial T1.

Useful to characterize active tissue such as distinguishing tumour from consolidated lung and to evaluate fluid pneumonia or pleural effusion.

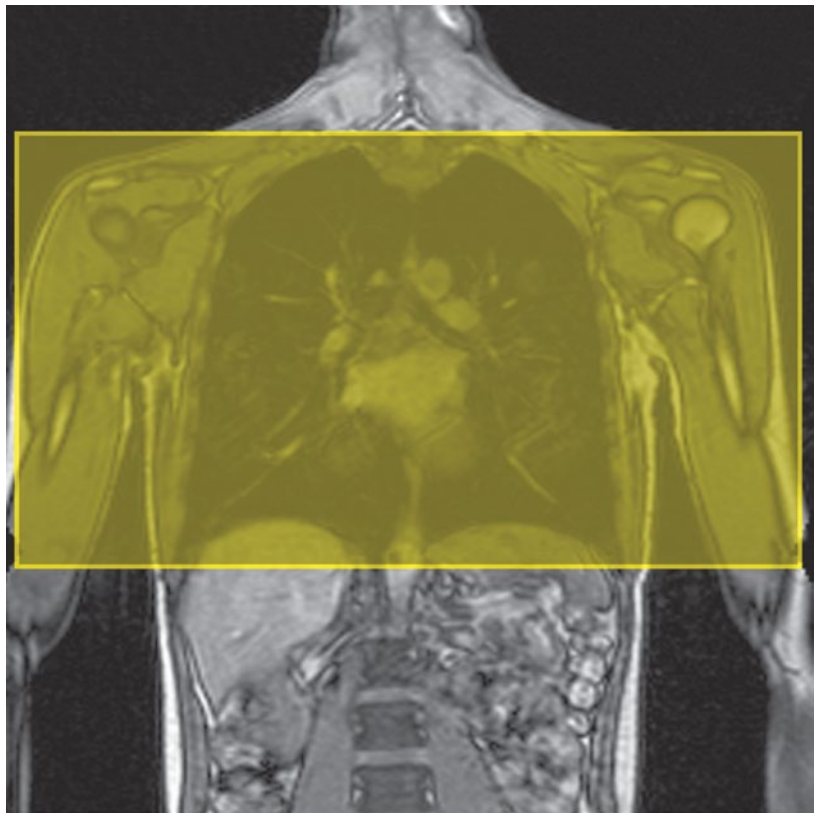

Figure 10.2 Coronal breath-hold incoherent (spoiled) GRE T1 of the chest showing prescription of axial slices.

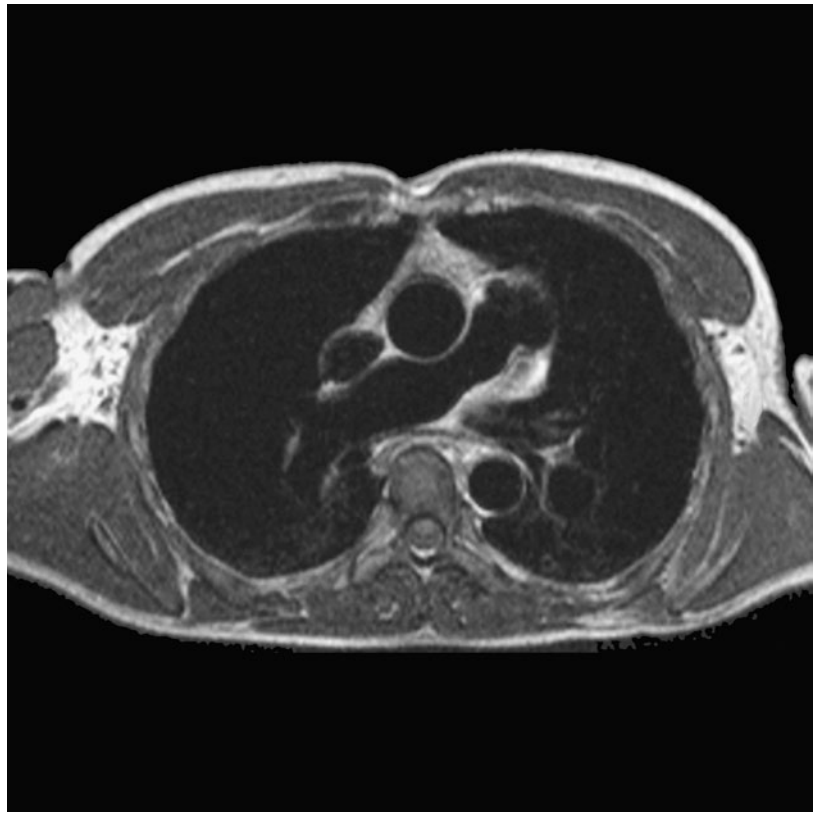

Figure 10.3 Axial SE T1-weighted gated image of the chest or axial imaging.

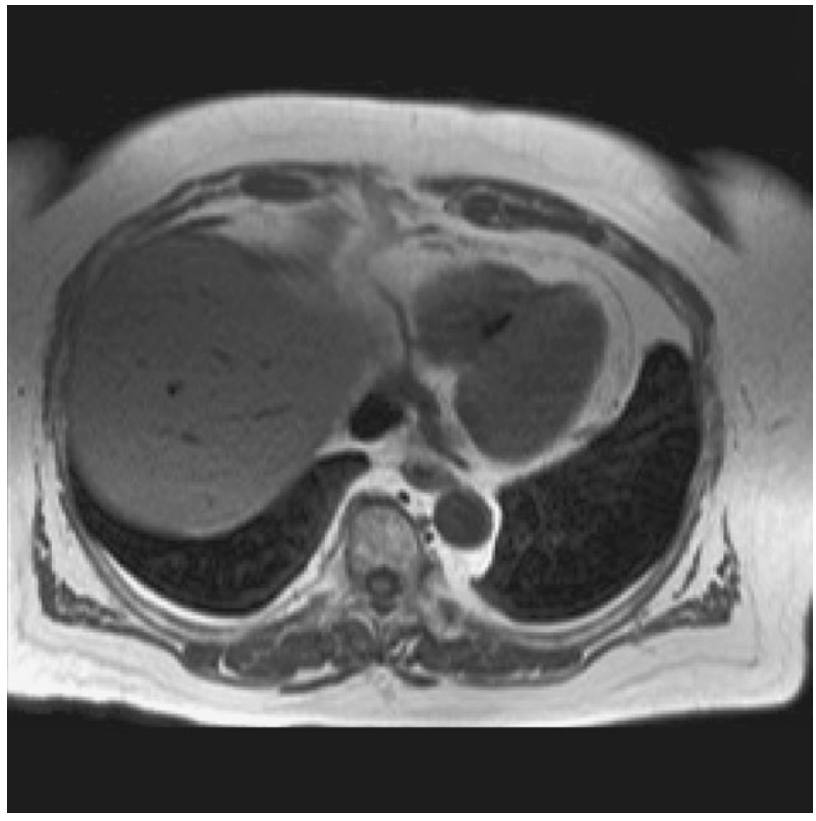

Figure 10.4 Axial FSE T1-weighted image through the chest showing a large lesion in the left lung.

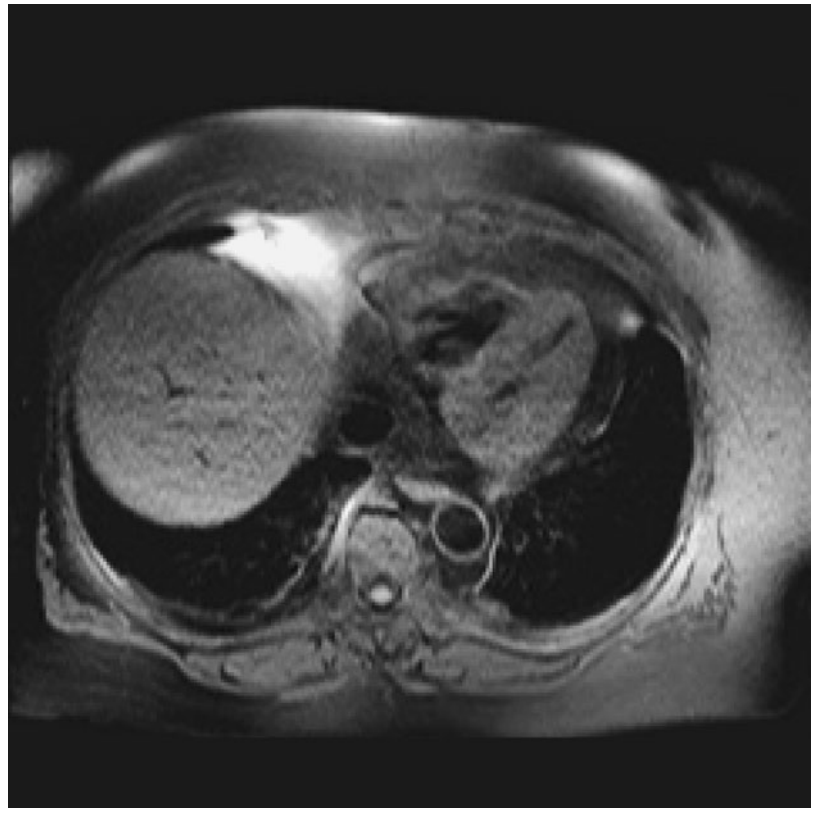

Figure 10.5 Axial incoherent GRE T1. Same slice as Figure 10.4.

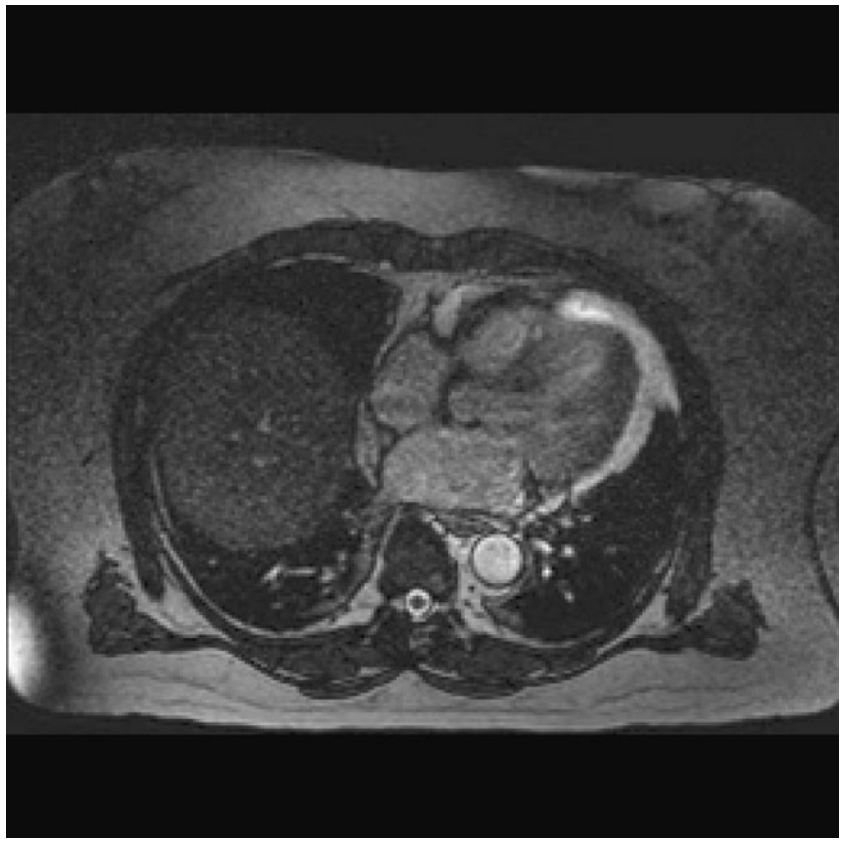

Figure 10.6 Axial SS-FSE. Same slice as shown in Figure 10.4.

Additional sequences

Perfusion studies

Lung perfusion can be evaluated by either administering contrast or with 'spin tagged perfusion' techniques. In these cases, contrast is 'tagged' with either contrast or arterial spin tagging applied in the midline of the patient in an attempt to saturate blood flowing from the heart and into the lungs by way of the pulmonary arteries.

Ventilation studies

This study is analogous to the VQ scan offered in Nuclear Medicine. The patient breathes in hyper-polarized helium gas and holds their breath while images are acquired.

Coronal fast incoherent (spoiled) GRE T1/SS-FSE T2

These sequences can be used during respiration to assess motion of the diaphragm. In this case, slices are acquired during normal respiration and replayed as a movie or cine loop.

Image optimization

Technical issues

The chest has a relatively poor SNR as the proton density of the lung fields is low. In addition, there is little fat to give good contrast. The implementation of a volume array coil helps maintain SNR. This is especially useful when thinner slices and a finer matrix are required. Chest imaging can be performed with a number of RF coil designs. Although the body coil is notorious for lower SNR, it can be utilized for large areas of coverage. Also, the body coil is acceptable in cases where contrast is the main determining factor in image contrast, such as MRA of the aorta or the pulmonary arteries. For the most part therefore, the body coil will produce optimum images for chest imaging. For higher SNR, higher resolution torso array coils should be used (see *Heart and great vessels*).

The use of multiple NEX/NSA not only reduces some respiratory and cardiac artefact because of signal averaging, but also improves the SNR due to increased data collection. The disadvantage of this strategy is the associated increase in scan time, although this can be compensated for, to some degree, by the implementation of a coarser matrix or a rectangular/asymmetric FOV. SE T1-weighted sequences are traditionally used to show anatomy and black blood. Dark-blood images can be acquired by using the double inversion recovery (DIR) technique to null the signal from blood. DIR sequences can be FSE, in which case each image is acquired in a separate breath-hold, or single shot, in which case multiple images are acquired in one breath-hold. DIR images are always gated to the ECG so that cardiac motion artefact is reduced from the images. GRE sequences are useful for the evaluation of flow, and T2-weighted sequences demonstrate pathology and free fluid. On some systems, FSE is not compatible with RC techniques that use phase reordering. Under these circumstances, SE sequences can be substituted. Fast imaging employing T2 steady-state acquisition sequences should also be considered instead of SS-FSE to image fluid-filled structures in very short acquisition times.

Artefact problems

Respiratory, cardiac and flow motion are the most obvious artefacts in the chest. Image quality can be compromised by physiologic motion from the lungs and heart, from flowing blood within vessels and, in some cases, from the oesophagus and stomach. Compensation for physiologic motion artefacts in the chest can be reduced by a number of imaging options including respiratory compensation, breath-hold techniques, cardiac gating, cardiac triggering or other imaging options (saturation pulses or gradient moment nulling). Breath-hold techniques are achieved by the acquisition of rapid imaging sequences (20 s or less) and instructing the patient to hold their breath during the image acquisition.

Motion artefact will always occur along the phase encoding axis, and the degree to which they interfere with the image is mostly due to the proficiency of the respiratory compensation techniques used and ECG gating. For respiratory gating and/or respiratory triggering, a respiratory monitoring device, known as a bellows, is placed around the patient's chest or abdomen. Placement can be determined by the patient's breathing style. If, for example, patient respiratory motion is generated by motion in the chest, then the bellows should be placed there. However, if the patient's motion occurs more within the abdomen, the bellows should be located in the abdominal region. (For more information about bellows placement, see *Respiratory compensation techniques* in Part 1.) Alternatively, breath-hold techniques may be used to suspend respiration. Check that the ECG leads are correctly attached and that the ECG trace has good amplitude and is triggering correctly (see *Gating and respiratory compensation techniques* in Part 1). When implemented properly, ECG gating effectively reduces cardiac motion artefact. However, if ECG gating is inefficient, image quality is compromised.

The phase encoding direction is generally prescribed by the system and thus defaults along a given direction. For the most part, the phase direction defaults along the short axis of the anatomy. Therefore, the phase encoding axis usually lies A to P on axial images and R to L on coronals. Swapping the phase axis to R to L on the axial scans and S to I on coronals is occasionally beneficial to remove artefact from the area of interest. For example, the phase direction for axial chest imaging generally defaults to a position anterior to posterior direction. However, if the motion artefact 'streaks' across anatomy or pathology of interest, swapping phase and frequency directions can be selected to 'relocate' the motion artefact to a position right to left across the image (Figures 10.7 and 10.8). As this strategy positions the long axis of the anatomy along the phase axis, oversampling is necessary to avoid aliasing. Furthermore, caution should be used if rectangular FOV has also been selected as the short axis of the rectangle is located along the phase direction. Therefore, as the phase direction is swapped, so is the direction of the rectangle.

Spatial pre-saturation pulses are also important to reduce flow artefact further. They are placed S and I to the FOV to decrease artefact from the aorta and IVC. R and L spatial pre-saturation pulses are beneficial in coronal images to decrease artefact from venous flow entering the chest from the subclavian vessels. In addition, when used in conjunction with SE or FSE sequences, spatial pre-saturation pulses produce black blood (see Figure 10.19). If signal persists in a vessel, it may indicate either slow flow or occlusion. GMN reduces flow artefact further, but as it also increases the signal in vessels and the minimum TE available, it is not usually beneficial in T1-weighted sequences unless contrast agents have been administered. When used in conjunction with GRE sequences, GMN produces bright blood (see Figure 10.18). If low signal is seen within the vessel, it may indicate

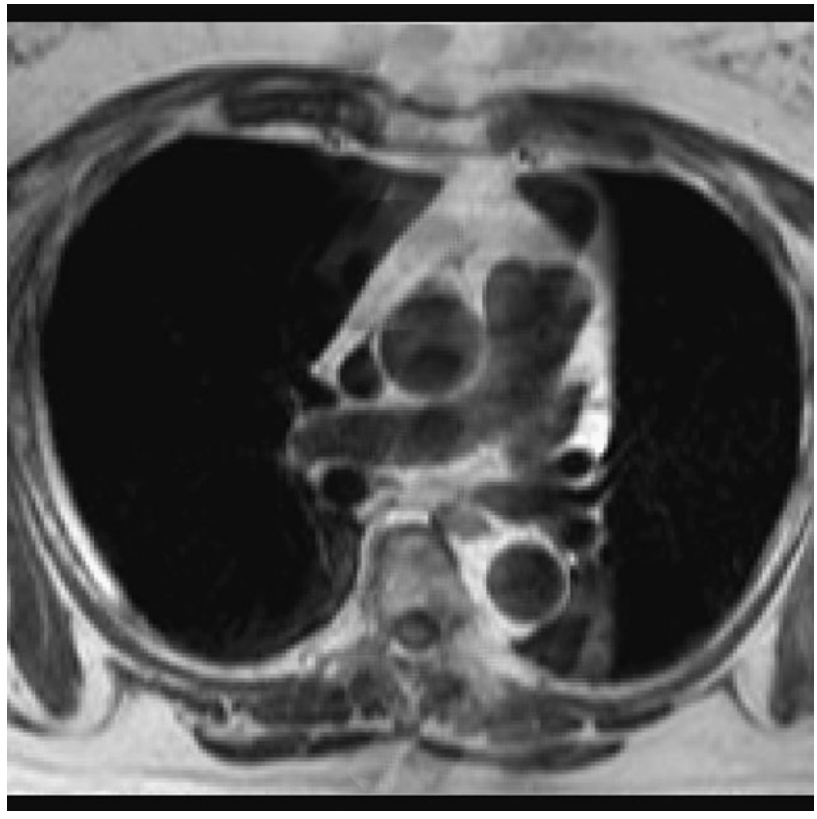

Figure 10.7 Axial FSE T1-weighted image of the chest with phase anterior to posterior.

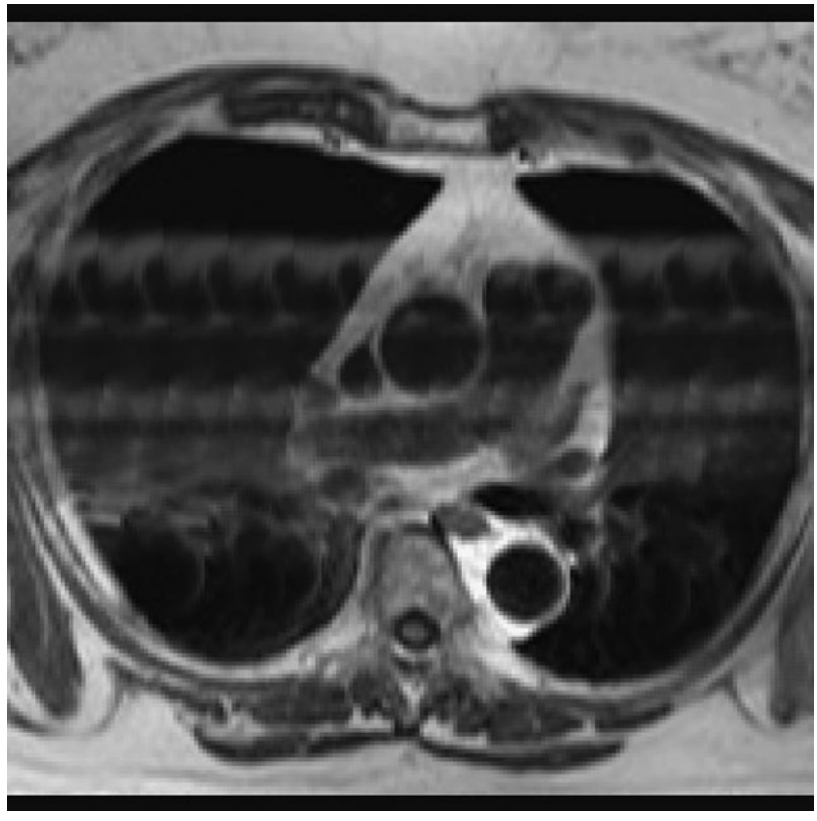

Figure 10.8 Axial FSE T1-weighted image of the chest with phase left to right.

either slow flow or occlusion. In addition, consideration should be given to the fact that when a structure is bright and it moves during MR image acquisition, it can 'streak' across the MR image in the phase direction.

Patient considerations

Patients having this kind of investigation are often breathless; therefore, minimizing the scan time is important. However, if the patient has a slow heart rate or a poor cardiac output, the system cannot always trigger off every R wave, thereby lengthening the scan time considerably. Under these circumstances, limiting the number of sequences is beneficial, and continuous reassurance of the patient may steady their heart rate and respiration. In addition, patient monitoring is recommended for patients who are short of breath and the administration of oxygen may be required. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast can be given to enhance lung, mediastinal or hilar masses. This may be helpful to increase the conspicuity of pathology in an area with low inherent contrast and to visualize pleural inflammation. Contrast can also be useful for visualizing chest vessels. Gaseous agents such as hyper-polarized helium gas ^{3}He are being used in MRI research settings to visualize and evaluate regional ventilation in chronic obstructive pulmonary disease (COPD).

Heart and great vessels

Basic anatomy (Figures 10.9 and 10.10)

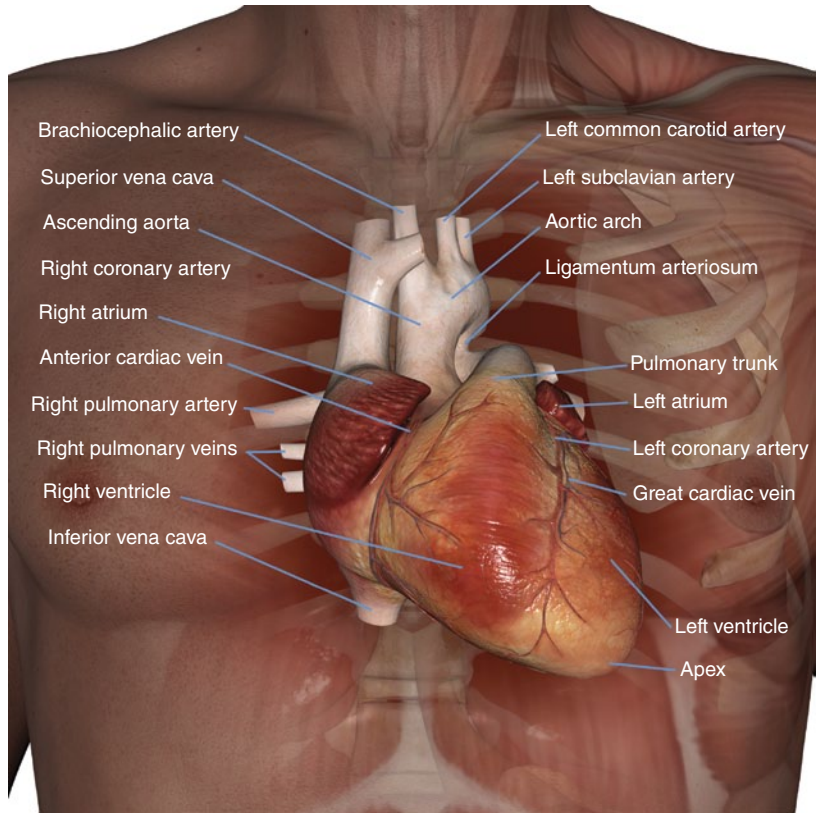

Figure 10.9 The great vessels and chambers of the heart.

Common indications

- Thoracic aortic aneurysm, dissection and coarctation
- Complex congenital abnormalities of the heart and great vessels
- Atrial or ventricular septal defect
- Assessment of ventricular function
- Assessment of ventricular muscle mass
- Vessel patency and thrombus
- Valvular dysfunction

Equipment

- Body coil/volume torso array coil
- RC bellows
- ECG gating leads
- Earplugs/headphones

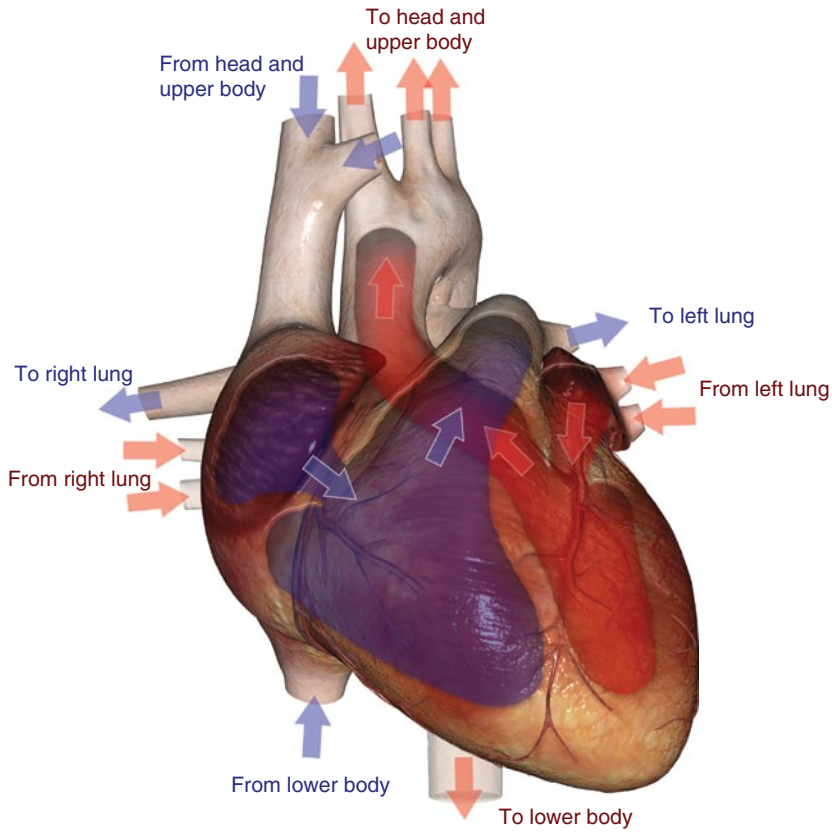

Figure 10.10 The cardiac circulation.

Patient positioning

The patient lies supine on the examination couch with the RC bellows (if required) and ECG gating leads attached. If breath-hold technique is not possible, respiratory gating or triggering is recommended to reduce the respiratory artefacts. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the fourth thoracic vertebra, or the nipples. The patient can be placed feet first into the magnet if the ECG trace is unsatisfactory to change the polarity of the patient relative to the main field of the magnet (see *Gating and respiratory compensation techniques* in Part 1).

Suggested protocol

A three-plane localizer is optimal as the heart and vascular structures of the chest lie obliquely within the cavity of the chest. The images provided in three orthogonal planes provide a localizer so that oblique views of the heart and great vessels can be prescribed.

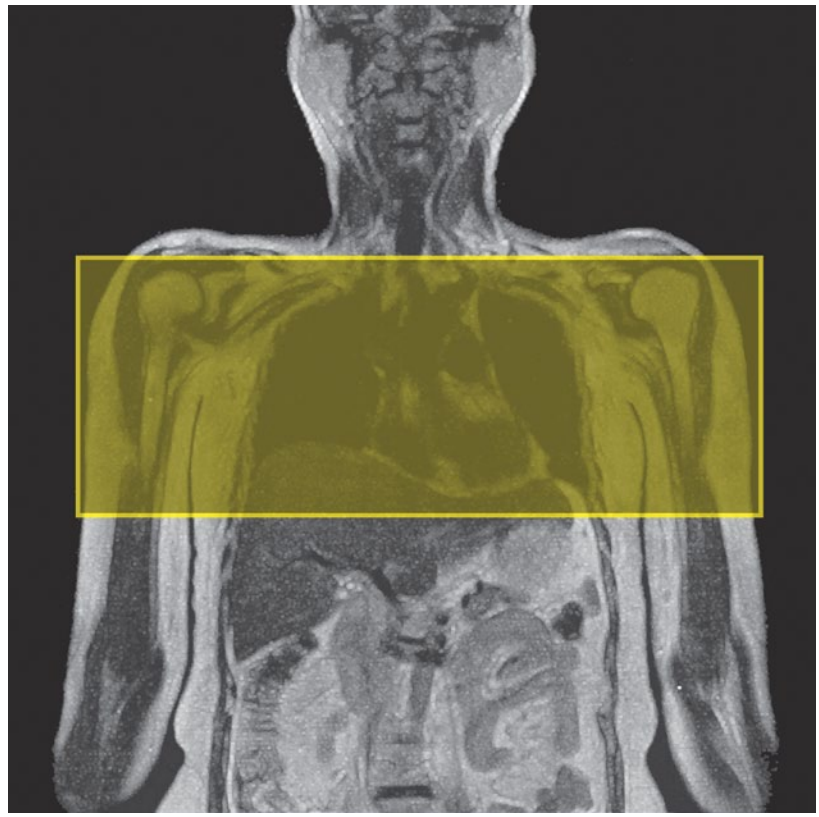

Figure 10.11 Coronal SE T1-weighted image through the chest cavity demonstrating slice prescription boundaries and orientation for axial imaging of the heart.

Coronal breath-hold fast incoherent (spoiled) GRE/SE T1 (Figure 10.11)

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Medium slices/gaps are prescribed relative to the vertical alignment light, from the posterior chest muscles to the sternum. The area from the top of the sternum to the diaphragm is included in the image.

P 60 mm to A 80 mm

Axial SE/FSE T1 (Figure 10.12)

As for the coronal T1, except slice thickness/gap is altered to fit the ROI. Prescribe slices from the inferior border of the heart to the superior aspect of the arch of the aorta (see Figure 10.11).

Specific cardiac views

Long-axis view (two chambers): From the axial T1 projection, using a slice through the left ventricle, align the slice slab parallel to the intraventricular septum and ensure the slab covers the whole of the left ventricle (Figures 10.13 and 10.14).

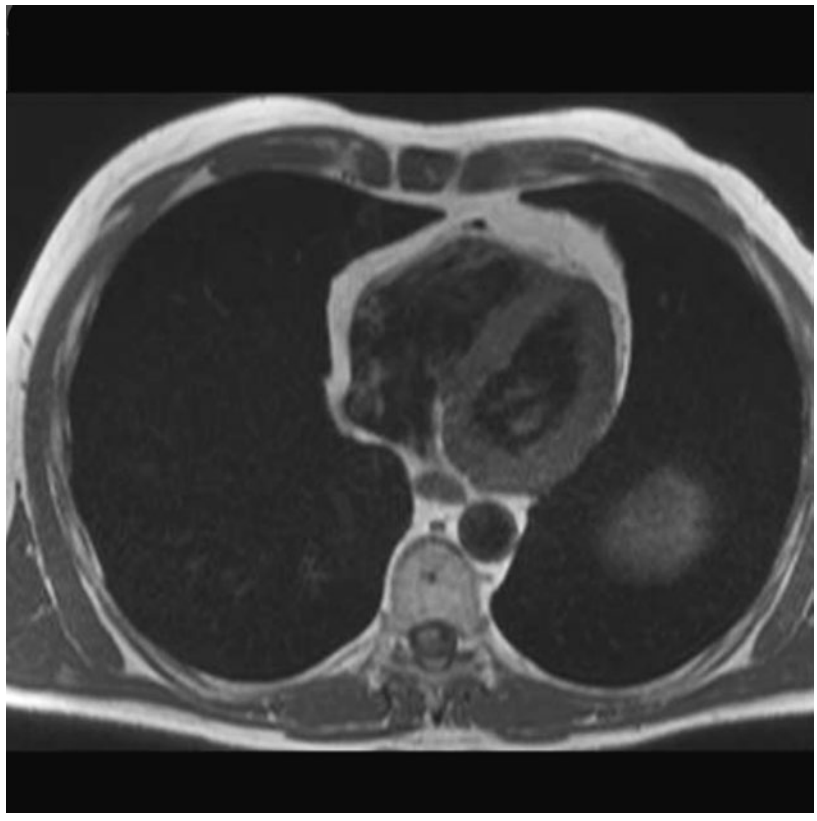

Figure 10.12 Axial T1-weighted FSE image of the chest using cardiac gating.

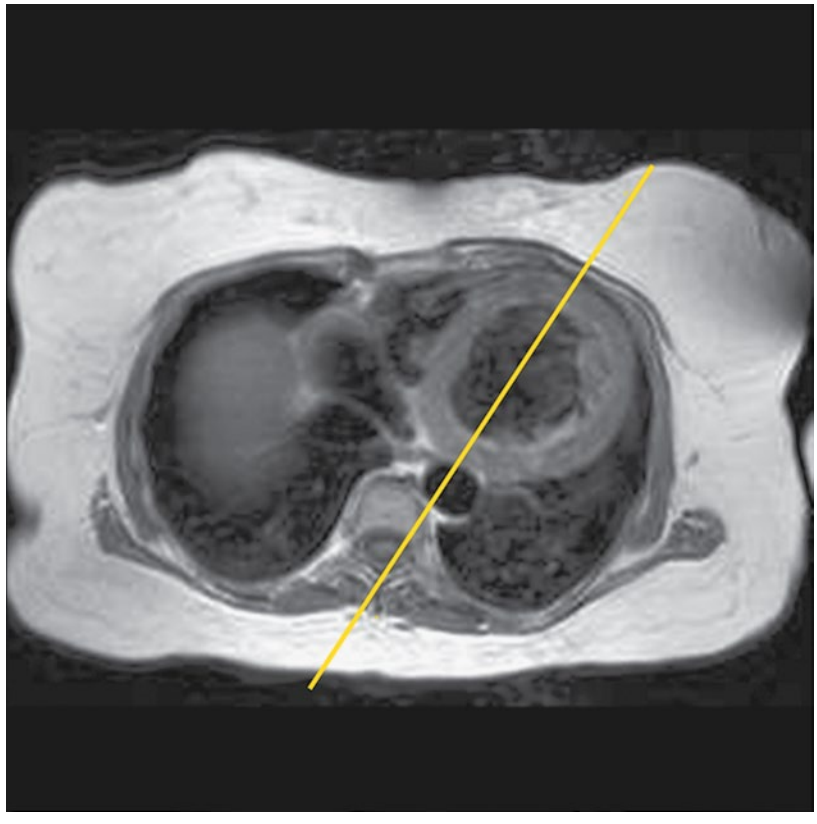

Figure 10.13 Axial FSE T1-weighted image showing slice orientation for the long-axis view.

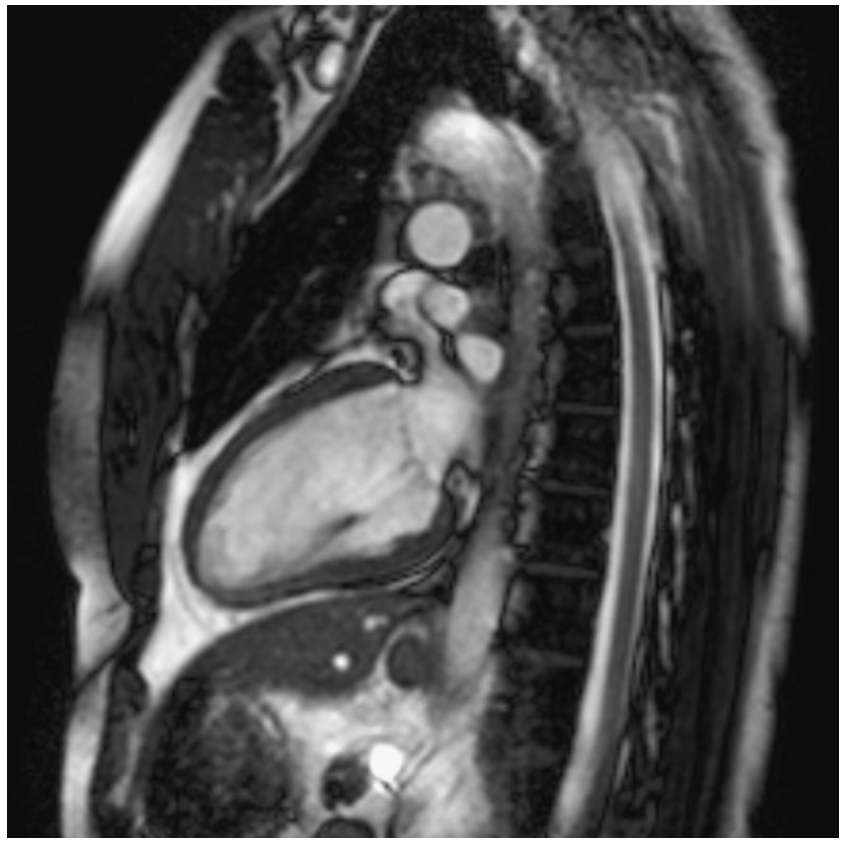

Figure 10.14 Two-chamber long-axis view.

Four-chamber view: From the long-axis view, align through the apex of the left ventricle and the mitral valve. Ensure the slice slab covers the whole of the left ventricle. This plane can also be acquired from the short-axis view (Figures 10.15 and 10.16).

Short-axis view: From the long-axis view, align perpendicular to the long-axis view imaging plane so that the alignment is parallel to the mitral valve. Ensure the slice slab covers the whole of the left ventricle (Figures 10.17 and 10.18). The short-axis plane can also be prescribed from the coronal localizer. A location can be identified on the coronal localizer, posterior at the aortic root, and another on the coronal by paging the slices anteriorly to the apex of the heart. Once these locations are known, the short axis can be prescribed by explicitly identifying the locations. The scanner will essentially draw an imaginary line between the points and scan perpendicular to that imaginary line. The four-chamber view can also be acquired from the short-axis view by orientating the slice prescription through the left and right ventricles angled parallel to the diaphragm.

Sagittal/oblique SE T1

As for axial SE T1, except slices are angled through the ascending and descending aorta and prescribed from one lateral edge of the vessel wall to the other.

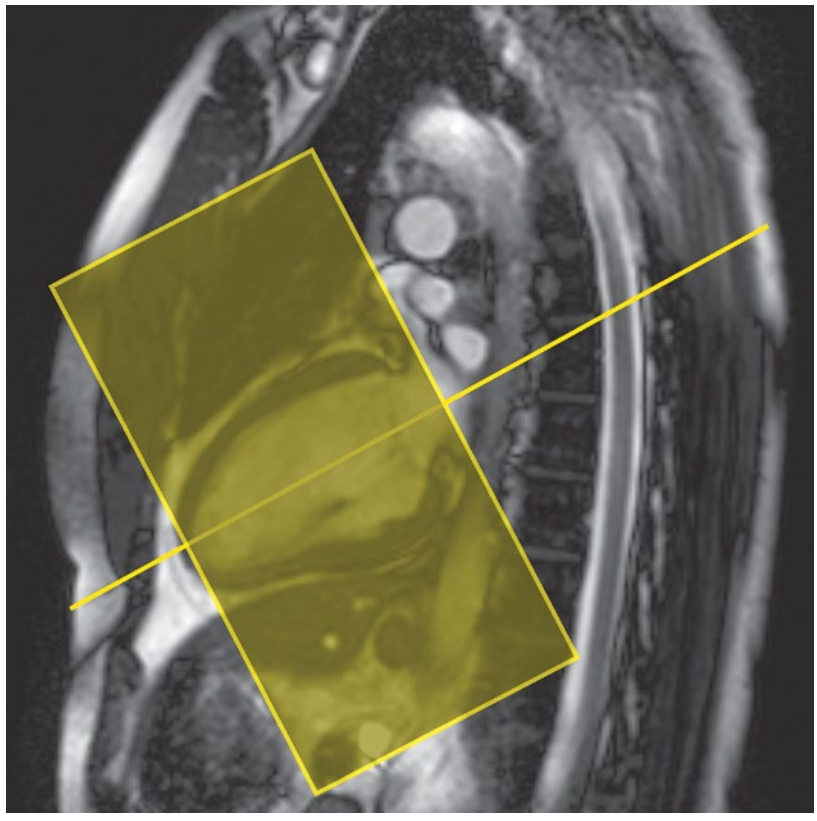

Figure 10.15 Long axis with slice orientation and slice boundaries for the four-chamber view.

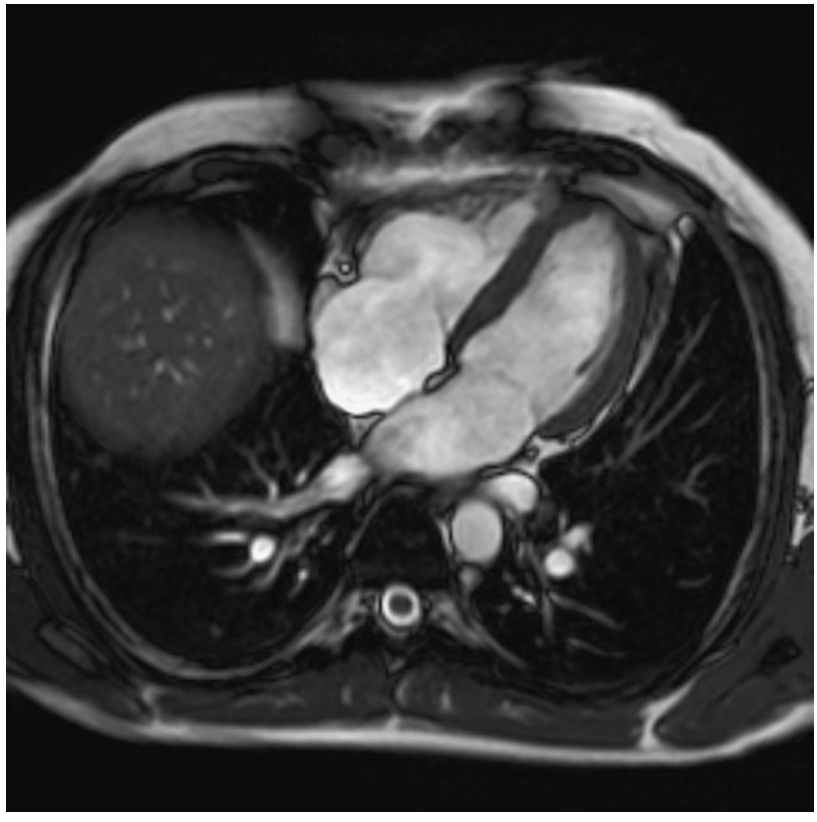

Figure 10.16 Four-chamber view.

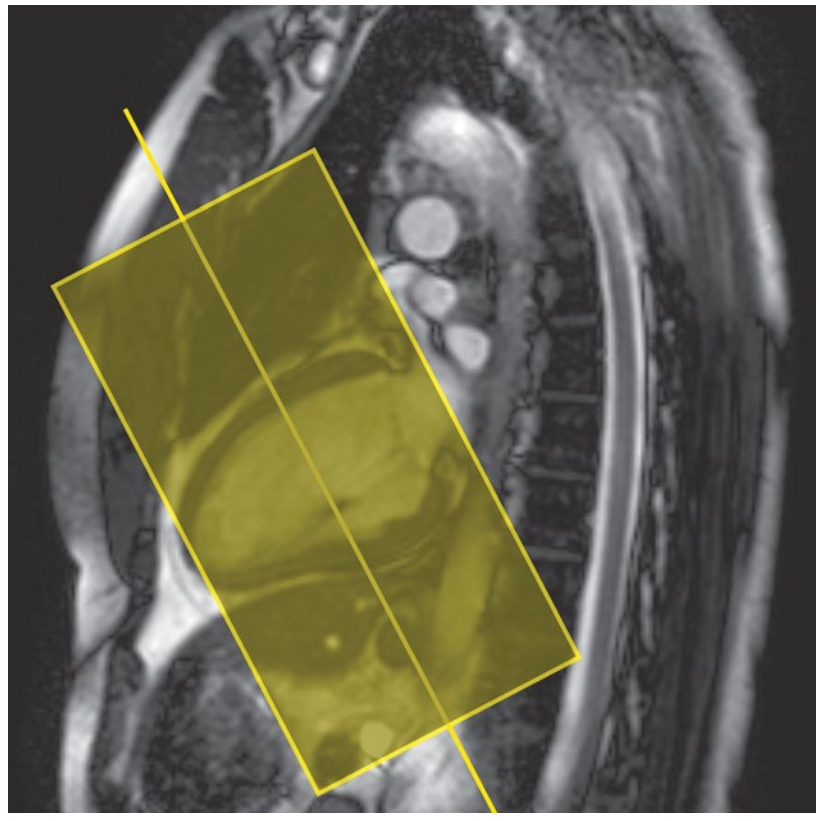

Figure 10.17 Long axis with slice orientation and slice boundaries for the short-axis view.

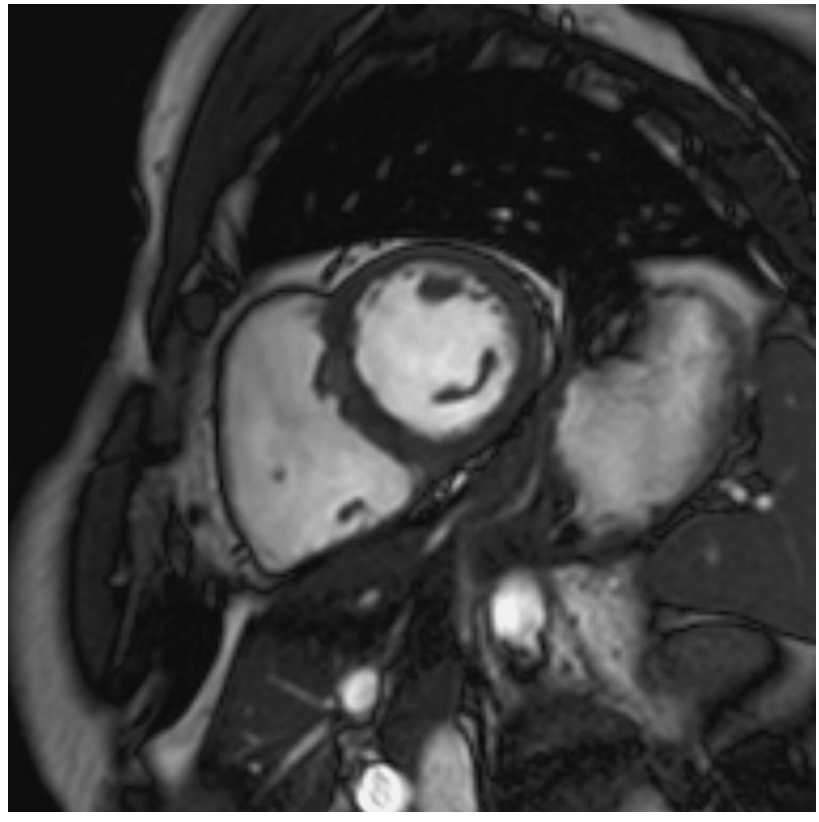

Figure 10.18 Short-axis view.

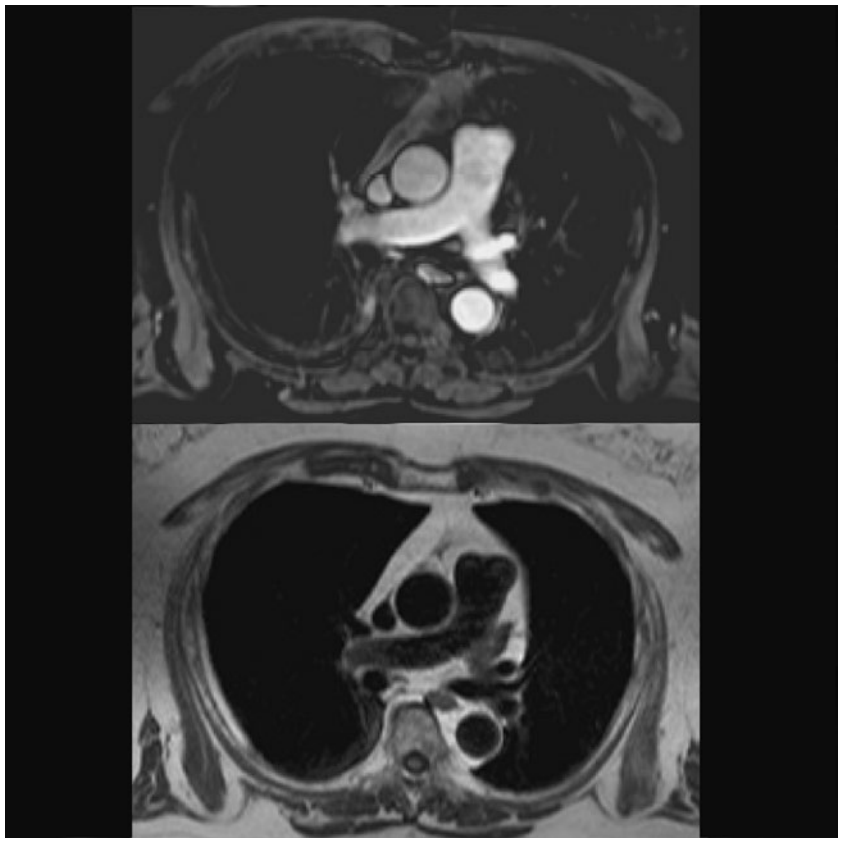

Figure 10.19 Axial images showing bright-blood imaging (above) and black-blood imaging (below) of the great vessels.

This sequence is used to visualize the ascending and descending aorta in one view (candy cane or walking stick view). Select an image from the axial series that demonstrates both portions of the aorta. Check slice position on a more superior slice that demonstrates the arch.

Black-blood imaging versus bright-blood imaging (Figure 10.19)

SE or FSE images are generally acquired with saturation pulses for the evaluation of black blood. Gradient echo, PC or EPI imaging sequences can be acquired with GMN for the evaluation of bright blood. Other black-blood imaging techniques utilize a modified inversion recovery sequence, known as DIR or triple IR. Although the various vendors have unique acronyms for these sequences, the premise is the same. In each case, the sequence begins with one 180° RF pulse followed by another 180° RF (DIR). In this case, the sequence has essentially been driven to equilibrium. Since flowing blood does not stay within the slice for enough time to experience both 180° RF pulses, flowing blood appears black. In triple IR sequences, the DIR sequence has an additional 180° pulse at the frequency of fat for spectral pre-saturation. In this case, the suppression of epicardial fat combined with black flow within the cavity of the heart allows for better visualization of the myocardium.

Oblique incoherent (spoiled) GRE T1 or coherent GRE T2* multiphase (cine)

Images of the heart, acquired during multiple phases of the cardiac cycle, provide cardiac images during the beating of the heart. This technique is known as multiphase imaging. The more slices acquired within each cardiac cycle, the better the temporal resolution (resolution over time). For cardiac imaging, temporal resolution, particularly in multiphase imaging, is limited by scan time. For example, if 16 phases of the cardiac cycle are to be acquired during one phase of the cardiac cycle, this means that these images are acquired at the same slice location, but at different times during the cardiac cycle R–R interval.

Cardiac cine (like multiphase imaging) is used to assess cardiac function. The most common views for cardiac cine images are the short-axis view or the straight axial view of the chest. This view is generally used to evaluate the left ventricle. For other areas of the heart, two-chamber or four-chamber views may be utilized. Two chambers are best demonstrated on a sagittal/oblique view, and four chambers in the coronal/oblique plane. Additional views such as the left ventricular outflow technique may also be useful.

Medium slices/gaps are prescribed in the plane relevant to the ROI (often axial or oblique). Select the cine functions as appropriate to the system, that is, the number of slices and phases per acquisition (see *Gating and respiratory compensation techniques* in Part 1).

Additional sequences

SPAMM tagging

SPAMM (spatial modulation of magnetization) essentially modulates or varies the magnetic field in the region of the heart, like waves. Since the RF pulse is dependent upon the magnetic field, RF excitation pulses only excite tissues with the same frequency. Therefore, the RF pulses match, for example, the peaks of the waves but not the valleys. The effect is a signal in the location of the RF match (resonance) and no signal in the areas where the RF pulse does not match the frequency. Modulation can be applied along several directions. If one direction is used, stripes appear across the images. If modulation is applied along two perpendicular axes, then the resultant image has a grid-like appearance. The choice between stripes and grids is generally at the discretion of the radiologist.

This technique is used in conjunction with multiphase or fast cardiac SE or GRE sequences to assess myocardial wall function post-myocardial infarction. The SPAMM technique used with multiphase imaging enables visualization of the SPAMM stripes or grid that appears to move with the myocardium. In fact, the stripes or grids not only move but tend to fade away over time during the cardiac motion in normal myocardium (or heart wall muscle). However, in areas of myocardial infarction, the heart wall muscle does not move normally. SPAMM images therefore yield

stripes or grids that persist rather than fade. This provides information about heart function.

SPAMM sequences, used in conjunction with cine PC, show promise for real-time imaging of the heart. In addition, PC images can be reconstructed as magnitude images or phase images. Magnitude images are reconstructed like MR images, where phase data are utilized to produce phase images. Phase images provide directional information about heart wall motion and flow direction.

EPI

This sequence, used in conjunction with cine PC, shows promise for real-time imaging of the heart and coronary vessels. In addition, EPI imaging is acquired with rapid imaging times for the reduction in motion artefacts. However, EPI is plagued with image artefacts such as chemical shift and susceptibility.

Contrast-enhanced cardiac and vascular studies (Figure 10.20)

Gadolinium-enhanced GRE sequences of the heart can be used to demonstrate masses or infarcts of the heart as well as vasculature of the chest and heart. GRE, with contrast enhancement, provide images with

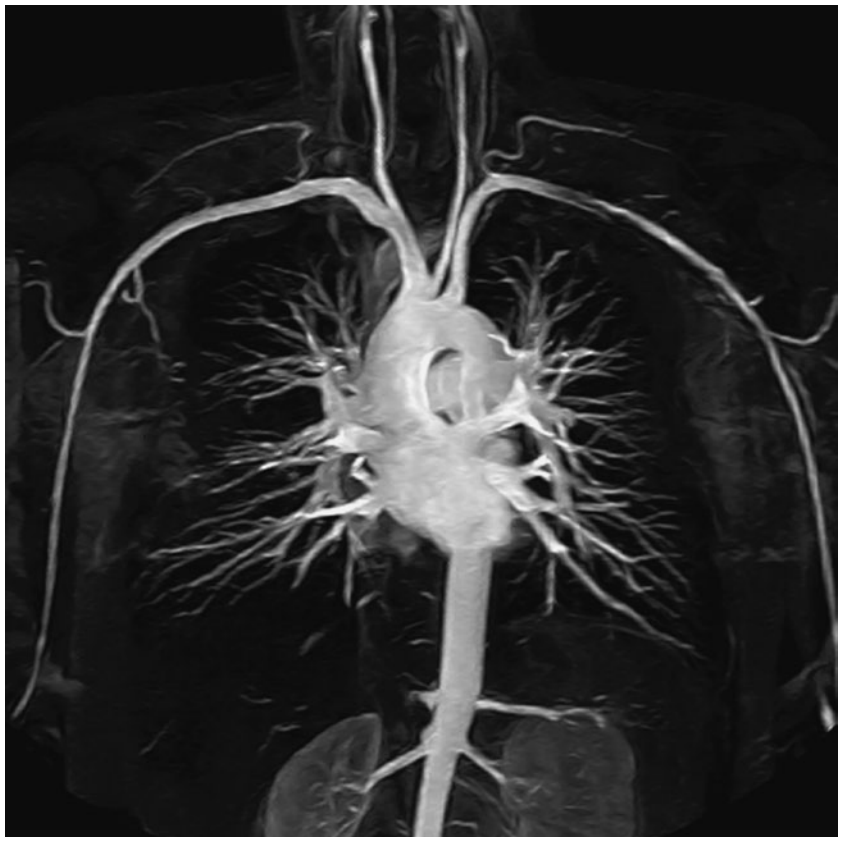

Figure 10.20 Coronal fast incoherent (spoiled) GRE T1-weighted image acquired after contrast enhancement.

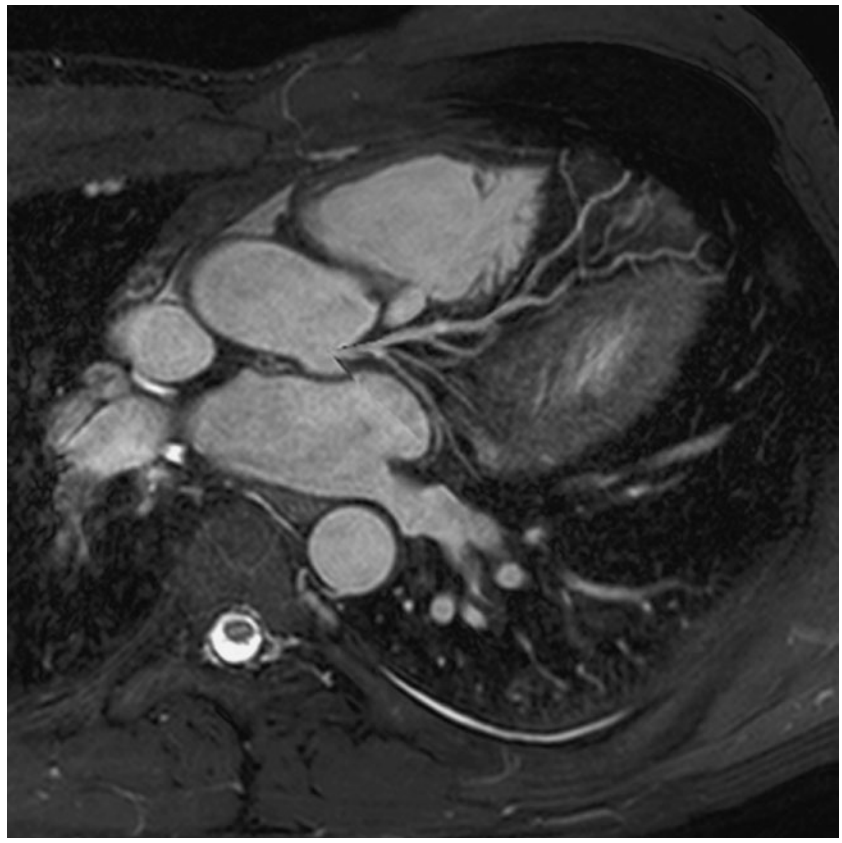

Figure 10.21 Coronary artery imaging after contrast enhancement.

high signal in areas of flowing blood. MRA sequences, acquired with a sagittal oblique or the 'candy cane shot' of the aortic arch, can demonstrate comparison views of the aortic dissection.

Typically, for the evaluation of the aortic arch, sagittal or sagittal oblique sequences are acquired. However, for the evaluation of the pulmonary arteries, the coronal plane is optimal. Pulmonary MRA sequences are acquired with dynamic contrast enhancement. For coronary artery imaging, high-resolution, multiple oblique images with dynamic contrast enhancement are required for bright-blood imaging (Figure 10.21).

Cardiac perfusion studies

In some cases, cardiac perfusion studies are used with, and without, pharmacologic (stress inducing) agents for the evaluation of cardiac function.

One such agent is known as Dobutamine™. This agent produces cardiac stress, and therefore, imaging can be acquired during pharmacologically induced stress and while the heart is at rest. Such agents, however, may not be approved for use in MRI. For this reason, caution should be taken in performing MR cardiac imaging during pharmacologically induced stress.

Diffusion imaging

Recent studies using diffusion tensor imaging to visualize the myocardium show some promise but require very strong and fast gradients.

Image optimization

Technical issues

As the chest has a relatively poor SNR, the implementation of a volume array coil helps maintain SNR. This is especially useful because thinner slices and a finer matrix are required for high-resolution imaging of the heart. Remember however that the FOV is limited to the size of the coil. For smaller structures such as the heart and coronary arteries, multichannel coils or phased array coils for improved SNR are recommended as they permit smaller voxels and therefore higher resolution. The use of multiple NEX/NSA not only reduces some respiratory and cardiac artefact, but also improves the SNR. The disadvantage of this strategy is the associated increase in scan time. This can be compensated for, to some degree, by the implementation of a coarser matrix.

Artefact problems

Respiratory, cardiac and flow motion are the most obvious artefacts in the chest. They occur along the phase encoding axis, and the degree to which they interfere with the image is mostly due to the proficiency of RC and ECG gating. Ensure the RC bellows are properly connected and are working efficiently. Alternatively, breath-hold techniques may be used to suspend respiration. Check that the ECG leads are correctly attached and that the ECG trace has good amplitude and is triggering correctly (see *Gating and respiratory compensation techniques* in Part 1) (Figure 10.22).

Spatial pre-saturation pulses are also important to further decrease flow artefact. They are placed S and I to the FOV to reduce flow artefact from the aorta and IVC. R and L pre-saturation pulses are beneficial in coronal images to decrease artefact from venous flow entering the chest from the subclavian vessels. When used in conjunction with SE sequences, spatial pre-saturation pulses produce black blood. If signal is seen within a vessel, it may indicate either slow flow or occlusion. GMN reduces flow artefact further and is mainly used in cine imaging (see *Gating and respiratory compensation techniques* in Part 1). It is not commonly utilized in T1-weighted SE sequences as it increases signal in vessels and the minimum TE available. When used in conjunction with coherent GRE sequences, GMN produces bright blood. If a signal void is seen within a vessel, it may indicate either slow flow or occlusion.

Patient considerations

Patients who undergo MRI of the heart generally have cardiac problems. These patients should be closely monitored for cardiac function with pulse oximetry.

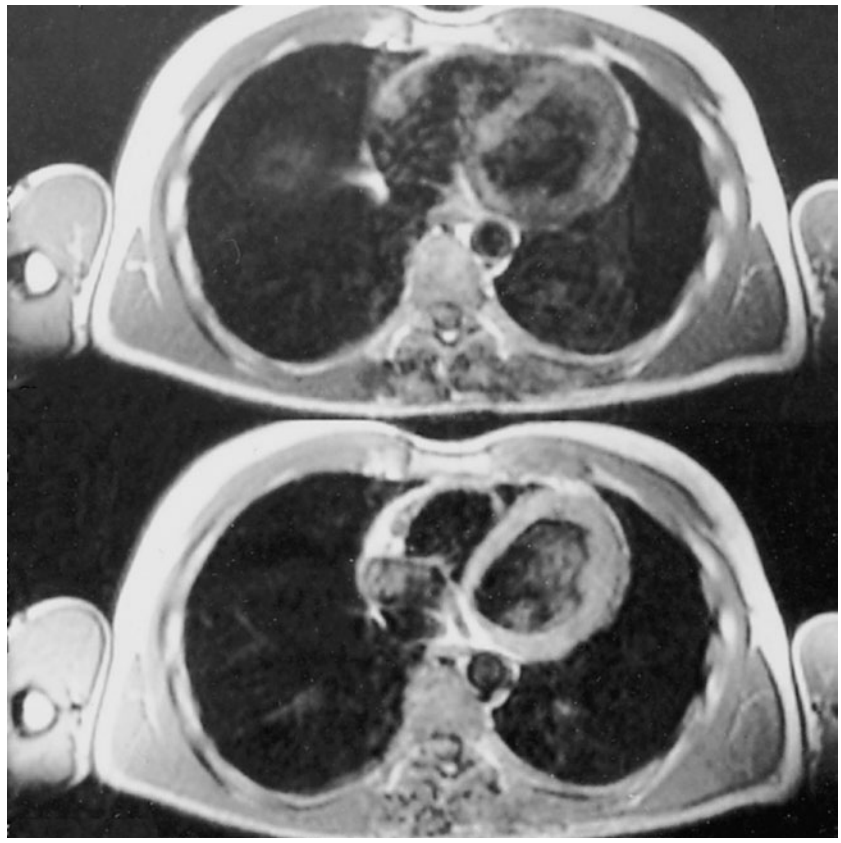

Figure 10.22 Axial images through the heart without cardiac gating (above) and with cardiac gating (below).

Also the cardiac gating leads, and hence the ECG tracing that is detected from these leads, may have been altered by the manufacturer to reduce the effect of the elevated 'T' wave caused by the magnetic field. This effect is known as the magnet–haemodynamic effect or the magnet–hydrodynamic effect. If the patient has a slow heart rate or a poor cardiac output, the system cannot always trigger off every R wave, thereby lengthening the scan time considerably. Under these circumstances, limiting the number of sequences is beneficial, and continuous reassurance of the patient may steady their heart rate and respiration. Vector cardiac triggering methods have demonstrated potential for depicting the cardiac cycle more accurately. In this type of gating, a trigger is produced that depends on heart motion, and thus, many of the deficiencies associated with the traditional ECG gating are now overcome even in problematic patient suffering from cardiac arrhythmias. Oxygen can also be administered for patients who are, or who become, short of breath. Due to excessively loud gradient noise associated with some sequences, hearing protection in the form of headphones or earplugs is recommended to prevent hearing impairment.

Contrast usage

Contrast is routinely given for imaging the heart and great vessels in conjunction with fast GRE sequences and dynamic imaging of the heart, aortic arch, great vessels, pulmonary arteries and coronary arteries (Figures 10.20 and 10.21). Double or triple doses may improve vascular visualization. In addition, cardiac masses can be sometimes well visualized after contrast enhancement.

Thymus

Common indications

- Thymic evaluation of myasthenia gravis
- Evaluation of thymic masses in general
- Evaluation of the post-operative mediastinum

Equipment

- Body coil/volume torso array coil
- RC bellows
- ECG gating leads
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with the RC bellows (if required) and ECG gating leads attached. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the sternum. The patient can be placed feet first into the magnet if the ECG trace is unsatisfactory (see *Gating and respiratory compensation techniques* in Part 1).

Suggested protocol

Sagittal breath-hold fast incoherent (spoiled) GRE/SE T1

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Medium slices/gaps are prescribed on either side of the longitudinal alignment light. The area from the diaphragm to the apex of the lung is included in the image.

L 15 mm to R 15 mm

Axial SE T1

Medium slices/gap are prescribed through the thymus

Axial SE T1 contrast

As for axial SE T1, **except** use tissue suppression to distinguish enhancing pathology from fat.

Additional sequences

Axial SE/FSE T2

Slice prescription as for axial T1.

Chemical shift imaging (in-phase/out-of-phase GRE)

In out-of-phase and in-phase images, the chemical shift ratio (CSR) may be used to compare relative changes in the signal intensity received from the thymic tissue relative to the paraspinal muscles. This method is useful in differentiating thymic hyperplasia from a neoplasm when encountering a mass in the anterior mediastinum.

Image optimization

Technical issues

The chest has a relatively poor SNR as the proton density of the lung fields is low. In addition, there is little fat to give good contrast. The implementation of a volume array coil helps maintain SNR. This is especially useful when thinner slices and a finer matrix are required. The use of multiple NEX/NSA not only reduces some respiratory and cardiac artefact because of signal averaging, but also improves the SNR due to increased data collection. The disadvantage of this strategy is the associated increase in scan time, although this can be compensated for, to some degree, by the implementation of a coarser matrix. On some systems, FSE is not compatible with RC techniques that use phase reordering. However, in conjunction with multiple NEX/NSA and a rectangular/asymmetric FOV, its implementation often increases both the resolution and SNR, and can be beneficial in examinations of the thymus.

Artefact problems

Respiratory, cardiac and flow motion are the most obvious artefacts in the chest. They occur along the phase encoding axis, and the degree to which they interfere with the image is mostly due to the proficiency of RC and ECG gating. Ensure the RC bellows are properly connected and are working efficiently. Alternatively, breath-hold techniques may be used to suspend respiration. Check that the ECG leads are correctly attached and that the ECG trace has good amplitude and is triggering correctly (see *Gating and respiratory compensation techniques* in Part 1). When implemented properly, ECG gating effectively reduces cardiac motion artefact. However, if ECG gating is inefficient, image quality is compromised.

The phase encoding axis usually lies A to P on axial images so that any phase ghosting interferes with the anteriorly situated thymus. It is therefore necessary to swap the phase axis to R to L to remove artefact

from the thymus gland. This strategy positions the long axis of the anatomy along the phase axis; therefore, oversampling is necessary to avoid aliasing, especially if the FOV is small (see *Flow phenomena and artefacts* in Part 1).

Spatial pre-saturation pulses are also important to reduce flow artefact further. They are placed S and I to the FOV to decrease flow artefact from the aorta and IVC. GMN reduces flow artefact further, but as it also increases signal in vessels and the minimum TE available, it is not usually beneficial in T1-weighted sequences. Additional shimming may be required before tissue suppression sequences.

Patient considerations

Thymus imaging is generally acquired on paediatric patients as the thymus gland shrinks as the child matures. For this reason, sedation may be considered, depending upon the age of the child.

Patients are made as comfortable as possible, and a careful explanation of the examination is important. If the patient is nervous, their ECG trace is often affected, thereby reducing the effectiveness of ECG gating. Under these circumstances, continuous reassurance of the patient may steady their heart rate and respiration and improve the efficiency of gating. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is often administered to improve the visualization of the thymus gland. This strategy is especially useful in conjunction with tissue suppression techniques.

Breast

Basic anatomy (Figure 10.23)

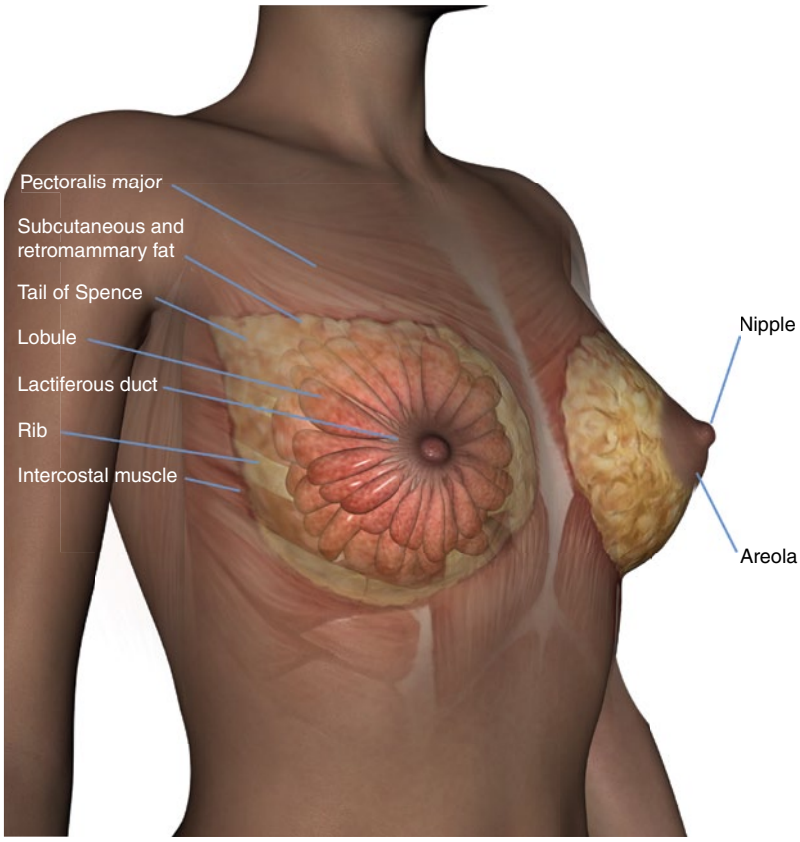

Figure 10.23 Sagittal section through the breast.

Common indications

For breast lesions

- Screening for high risk patients
- Staging of benign and malignant disease
- Characterization of abnormalities in patients with breast implants
- When conventional or digital is not optimal
- Characterization of abnormalities in patients with very fatty or dense breasts

For breast implants

- Implant rupture (linguine sign)
- Known rupture (intra-capsular vs. extra-capsular)
- Implanted patients with lesions

Equipment

- Breast coil(s) either single, double or phased array
- Extension tubing, needle and contrast (MR-compatible biopsy needles if MR interventional procedure is planned)
- A magnetically safe automatic injector if available
- Earplugs/headphones

Patient positioning

Patient positioning includes the patient lying prone, with breasts positioned within the breast coil. Exact patient position generally depends upon the method used for breast imaging. Some imaging centres choose to utilize the so-called European method, whereas others choose to do the so-called U.S. method (see later in *Technical considerations*). When evaluating lesions with the U.S. method, images are acquired in the sagittal plane, one breast at a time. The European method acquires images in the axial plane imaging both breasts simultaneously.

The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the centre of the coil(s). For vertical field systems, breasts should be raised to isocentre in the anterior/posterior direction. This ensures that the breast is in the most homogeneous portion of the magnetic field, and therefore optimizes fat suppression on post-contrast images.

If contrast is given during the examination (for evaluation of breast lesions), a needle is inserted into the ante-cubital fossa prior to the examination. The contrast can then be administered through extension tubing so that patient movement is minimized during the injection. A magnetically safe automatic injector can be used if available. Power injectors are capable of delivering injections of consistent timing and dose. This becomes particularly useful for the evaluation of breast lesions when followed up. Furthermore, since the haemodynamics of the breast lesion is one determining factor for benign versus malignant lesions, consistent timing and dose of gadolinium contrast injection is important (see *Dynamic imaging* under *Pulse sequences* in Part 1).

A note on compression: Many breast lesions are associated with a large vascular supply that results in thick blood vessels known as neovascularity and angiogenesis. This neovascularity and angiogenesis result in high blood flow to the lesions known as hypervascularity. The hypervascularity of breast cancers causes rapidly enhancing lesions of the breast. Over-compression of the breast may result in reduction in the visualization of some breast lesions. This occurs because the vascularity of some lesions is reduced upon compression and therefore will not enhance. Some coils have a compression device built into their design. When evaluating implants compression is not required. When using the U.S. method or the European method, the breast is reshaped (gently compressed) to reduce the number of slices required to cover the whole breast in a single acquisition. This provides dynamic images of the breast in acceptable imaging times.

Suggested protocol for the U.S. method

Three-plane localizer/incoherent (spoiled) GRE T1

Three-plane localization is optimal for the evaluation of the breast in three orthogonal planes. For optimal breast imaging, it is important to include all of the breast tissue from the superior axillary tail to the nipple and posteriorly to include pectoralis muscle and chest wall.

Axial SE/FSE/incoherent (spoiled) GRE T1

If three-plane localization is unavailable, an axial localizer can be acquired. Thick slices/gaps are prescribed through one or both breasts on either side of the horizontal alignment light.

I 25 mm to S 25 mm

Sagittal SE/FSE T1

High-resolution images of the breast are acquired in the sagittal scan plane.

Small FOV (sufficient to include the entire breast) are selected for high in-plane resolution. Thin slices/gaps are prescribed through the breast(s) to include medially from the sternum to laterally the axilla. Fat suppression should **not** be used on this acquisition, as lesions are generally dark relative to high signal intensity of fat within the breast.

Sagittal SE/FSE T2 +/– tissue suppression

Slice prescription as for sagittal T1 acquisition for comparative slice locations and in-plane resolution. Fat suppression could be used on this acquisition, as lesions are generally bright relative to low signal intensity of suppressed fat within the breast.

Sagittal fast incoherent (spoiled) GRE T1 tissue suppression (pre-contrast)

Slice prescription as for sagittal T1 and T2 acquisitions for comparative slice locations and in-plane resolution. High-resolution acquisitions provide information about lesion architecture. In many cases, lesions that have speculated margins are likely to be malignant, and lesions that have smooth edges are likely to be benign.

Sagittal 3D fast incoherent (spoiled) GRE T1 tissue suppression (post-contrast) (Figure 10.24)

Slice prescription as for sagittal T1 and T2 acquisitions for comparative slice locations and in-plane resolution. Images are acquired before and for several minutes after the injection. Scan times should not exceed 1.5 min per acquisition and should be repeated three to five

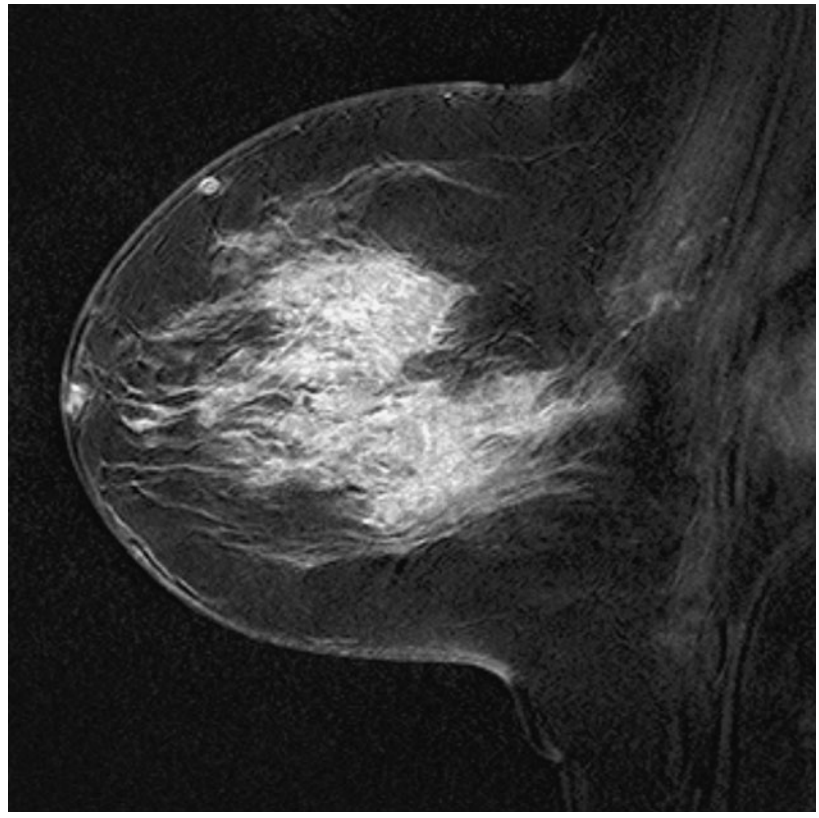

Figure 10.24 Sagittal incoherent (spoiled) GRE image post-contrast with tissue suppression.

times post-injection. Timing the beginning of each acquisition after the commencement of the injection is necessary for image interpretation. Fat suppression is useful as enhancing lesions have a high signal relative to low signal intensity of suppressed fat within the breast.

Sagittal fast incoherent (spoiled) GRE T1 (post-processing)

Subtraction techniques remove additional signal from fat. In this technique, the pre-contrast images are subtracted from the post-gadolinium images. The resultant images demonstrate enhanced structures only. In addition, maximum intensity projection (MIP) processing permits evaluation of breast vasculature. Hypervascularity may indicate malignant disease of the breast. Breast workstations are increasing in popularity as they provide colourization and reformatting opportunities for further evaluation of breast lesions.

Suggested protocol for the European method

Three-plane localizer or axial localizer/incoherent (spoiled) GRE T1

The localizer for this method is the same as that for the U.S. method described earlier. However, if this is not available on the system, an axial localizer is adequate.

Axial SE/FSE/incoherent (spoiled) GRE T1

If three-plane localization is unavailable, an axial localizer can be acquired. Thick slices/gaps are prescribed through one or both breasts on either side of the horizontal alignment light.

I 25 mm to S 25 mm

Axial SE/FSE T1 (Figure 10.25)

High-resolution images of the breast are acquired in the axial scan plane. A FOV large enough to include both breasts is selected. Thin slices/gaps are prescribed through the breast(s) to include all of the breast tissue from the superior axillary tail to the nipple and posteriorly to include pectoralis muscle and chest wall.

Fat suppression should not be used on this acquisition, as lesions are generally dark relative to high signal intensity of fat within the breast.

Axial SE/FSE T2 +/– tissue suppression (Figure 10.26)

Slice prescription as for axial T1 acquisition for comparative slice locations and in-plane resolution. Fat suppression could be used on this acquisition, as lesions are generally bright relative to low signal intensity of suppressed fat within the breast.

Axial 3D fast incoherent (spoiled) GRE T1 (pre-contrast) (Figure 10.27)

Slice prescription as for axial T1 and T2 acquisitions for comparative slice locations and in-plane resolution. As for the U.S. method but images are acquired in the axial plane. Fat suppression should not be used on this acquisition.

Axial 3D fast incoherent (spoiled) GRE T1 (post-contrast)

As for the U.S. method but images acquired in the axial plane. Fat suppression should not be used on this acquisition. Subtracted images using post-processing software show the enhancing vessels and lesions.

Suggested protocol for the evaluation of silicone implants

Three-plane localizer or axial localizer/incoherent (spoiled) GRE T1

As for U.S. and European methods described earlier.

Sagittal T1 and T2 FSE (high resolution)

Slice location and resolution as that for the U.S. method.

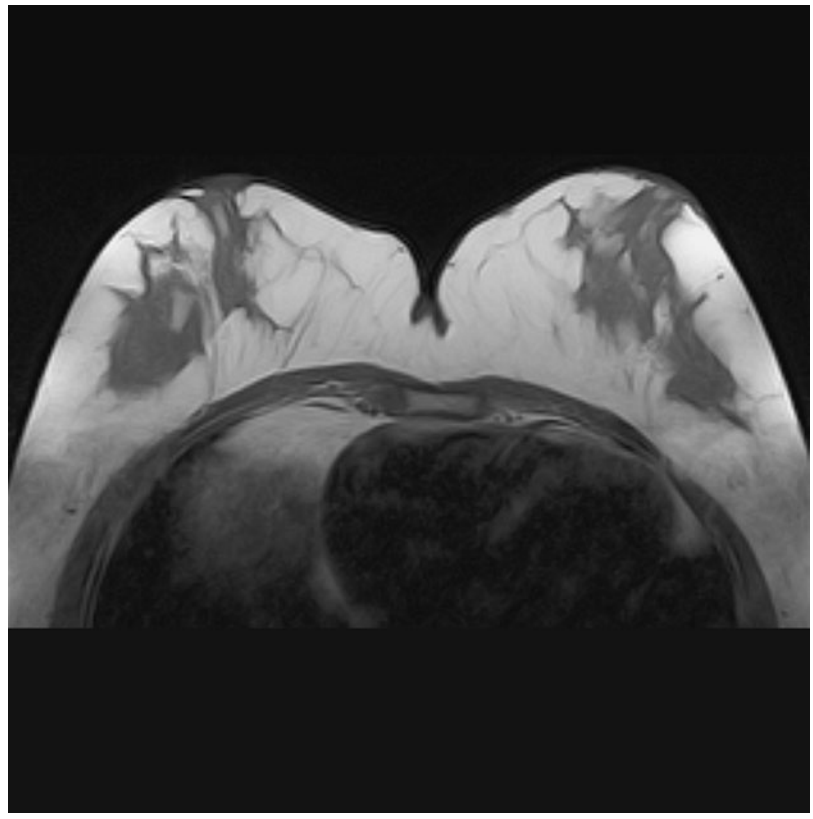

Figure 10.25 Axial SE T1-weighted image through both breasts.

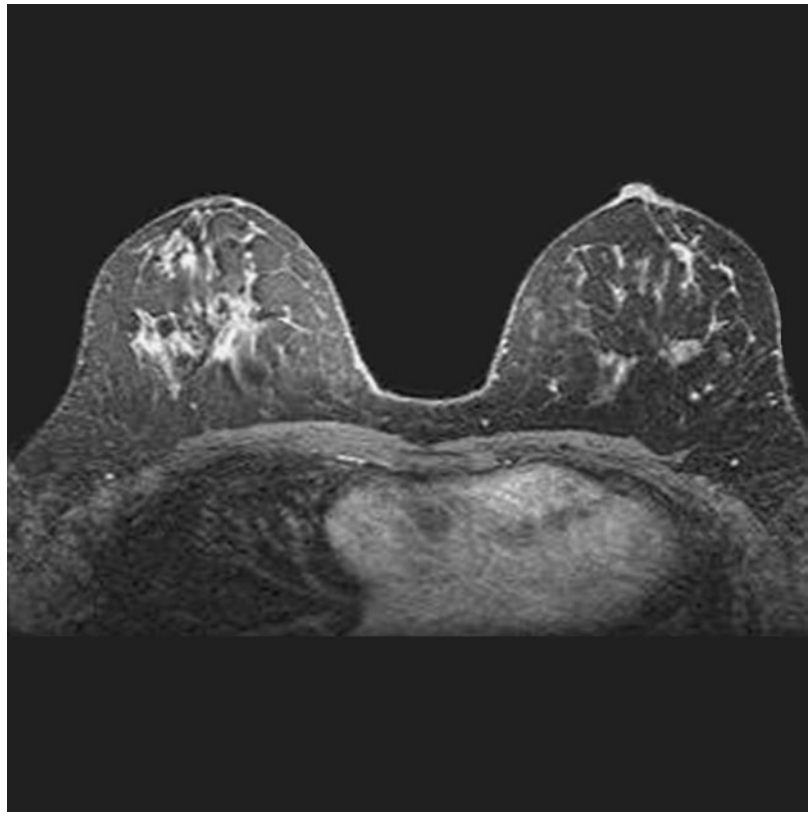

Figure 10.26 Axial T2-weighted image through both breasts.

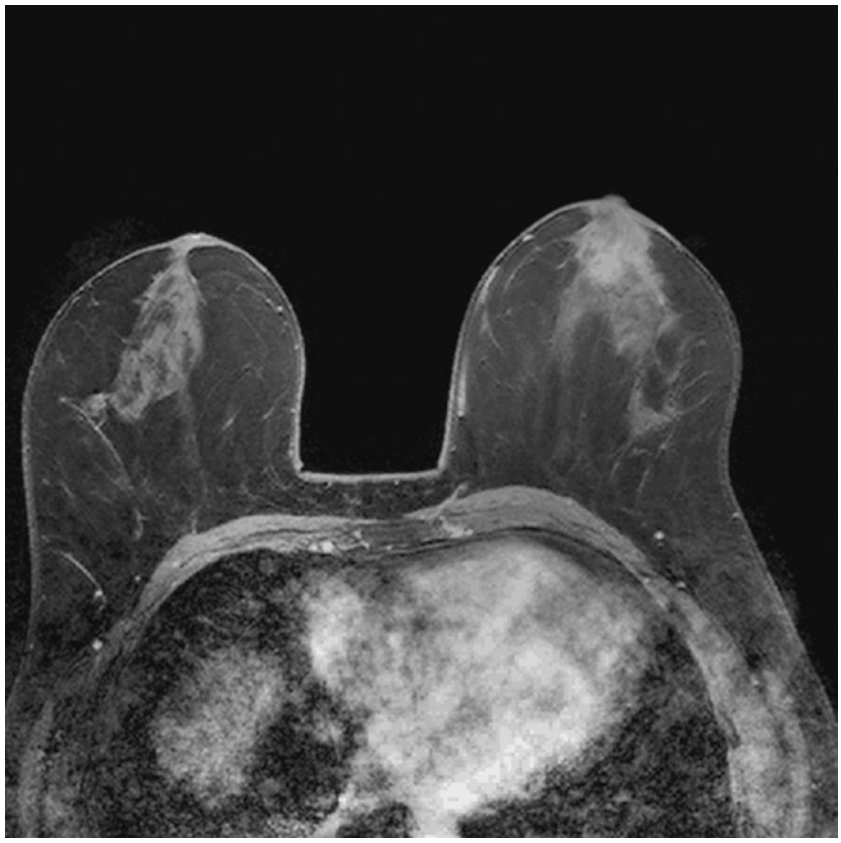

Figure 10.27 Axial incoherent (spoiled) GRE image with tissue suppression.

Sagittal spectral IR or IR-FSE tissue suppression contrast

In order to evaluate implants, ruptured or intact, sequences that suppress either silicone or fat and water together are necessary. These suppression techniques involve either the suppression of water (using water pre-saturation pulses) and fat within the breast using STIR to visualize silicone (known as silicone imaging) or the suppression of silicone itself for the visualization of the other breast anatomy (known as silicone suppression). The choice between silicone imaging and silicone suppression is generally the responsibility of the radiologist. Slice prescription as for sagittal T1 in the U.S. method or axial prescriptions in the European method.

Additional sequences

Axial SE/FSE T1/T2 or STIR

Useful to visualize implants. Tissue suppression can be implemented in conjunction with SE/FSE sequences instead of STIR. Note: STIR should not be used after contrast enhancement (see *Pulse sequences* in Part 1). STIR with water suppression produces images that show only silicone.

SS-FSE/SE-EPI/GRE-EPI/diffusion imaging

The use of real-time imaging has applications in the breast. These include biopsies and thermal or focused RF ablations of lesions under real-time MR control. DWI of the breast may have potential uses in the differentiation of benign from malignant lesions, and it may enable evaluation of the response of metastases to chemotherapy.

Image optimization

Technical issues

Developments in coil technology have greatly increased the SNR characteristics of breast coils. Phased array coils return the highest and most uniform signal, whereas some others can give glare at the nipple, and signal fall-off nearer the chest. There is usually good tissue contrast and, as the SNR is relatively high, spatial resolution can be maximized. FSE is a great advantage in breast examinations as it facilitates the acquisition of very fine matrices in relatively short scan times. Parallel imaging can also be a useful tool for reducing scan time, without reducing resolution. Multichannel coils are required.

Some imaging centres choose to utilize the so-called European method, whereas others choose to use the so-called U.S. method. Each method includes high-resolution images acquired with a rapid scan time, during dynamic contrast enhancement.

The **European method** acquires the breast images using an axial scan plane. In this method, axial images are acquired to include both breasts on the same axial image. This requires a FOV that is relatively large and, although high imaging matrices are generally selected to provide improved in-plane resolution, this lengthens the scan time, which is not optimal for dynamic imaging. Thin slices may be used depending upon the coverage required and through-plane resolution desired, but coverage may be a problem.

The **U.S. method** acquires images in the sagittal scan plane, one breast at a time, either unilaterally or bilaterally. As this plane covers the breast in fewer slices, acquisition times are shorter (ideal for dynamic imaging). In addition, as a smaller FOV is required, very high in-plane and through-plane resolution is achieved. Unilateral breast imaging opts to image the breast in question and then, on another date, the contralateral side (because another dose of gadolinium to image the contralateral side cannot be given on the same day). Bilateral acquisition can be achieved however by imaging one breast then the other within the same acquisition. A more optimal bilateral acquisition produces 3D scans, acquired with interleaved acquisition, dynamically during contrast enhancement.

The caveat for the U.S. method is that the breast images are generally acquired one breast at a time, whereas the European method acquires both images simultaneously.

The caveat for the European method is that many facilities, in an attempt to see more anatomy (of the chest and surrounding structures), tend to use less than optimal in-plane resolution (large FOV and/or low matrix) compared with the U.S. method, which uses high in-plane resolution (small FOV and/or high matrix) sagittal images.

Tissue suppression techniques are useful in breast imaging to distinguish a lesion from the surrounding fatty breast tissue. Conventional fat suppression is not always optimal, particularly on axial bilateral European acquisitions that use a large FOV, resulting in shading on breast images. Unfortunately, STIR (albeit a homogenous fat suppression technique) cannot be used after gadolinium as it suppresses gadolinium-enhancing lesions. Spectral suppression techniques, which improve the homogeneity of fat suppression, often produce more uniform suppression across a large FOV.

Local magnetic field homogeneity can also improve the quality of fat suppression with these techniques. For this reason, shimming may be required before tissue suppression sequences. Shimming for the breast can be troublesome however. Breasts can be shimmed unilaterally or bilaterally. Bilateral shim generally includes both breasts, the air between the breasts and the anterior chest wall and therefore a number of different tissue types. With a unilateral shim, the suppression is more optimal, as the shim volume includes tissues of similar composition. However, the contralateral breast will have a suboptimal shim (Figures 10.28 and 10.29).

Artefact problems

Respiratory artefact is somewhat reduced by laying the patient prone rather than supine. Also the coil(s) do not move during respiration when the patient is prone. Cardiac motion and flow within the mammillary vessels can also be troublesome. Swapping the phase encoding axis to S to I on sagittal images and R to L on axials moves the artefact posterior to the breast, but it can then interfere with the axilla. Therefore, repeat scans with the phase axis returned to its original direction are usually required if the axillae are also under investigation. Oversampling is necessary when the phase axis is swapped if signal is returned by tissue that lies within the coil, but outside the FOV in the phase direction. Spatial pre-saturation pulses brought into the FOV and placed posteriorly over the heart are useful in reducing cardiac motion artefact.

Patient considerations

Many patients are very anxious, as some have already had an abnormal mammogram and/or previous disease. Reassurance and a careful explanation of the procedure are therefore more important than usual. The rather complicated and time-consuming nature of this examination can be daunting to the patient. It is vital that she does not move during or

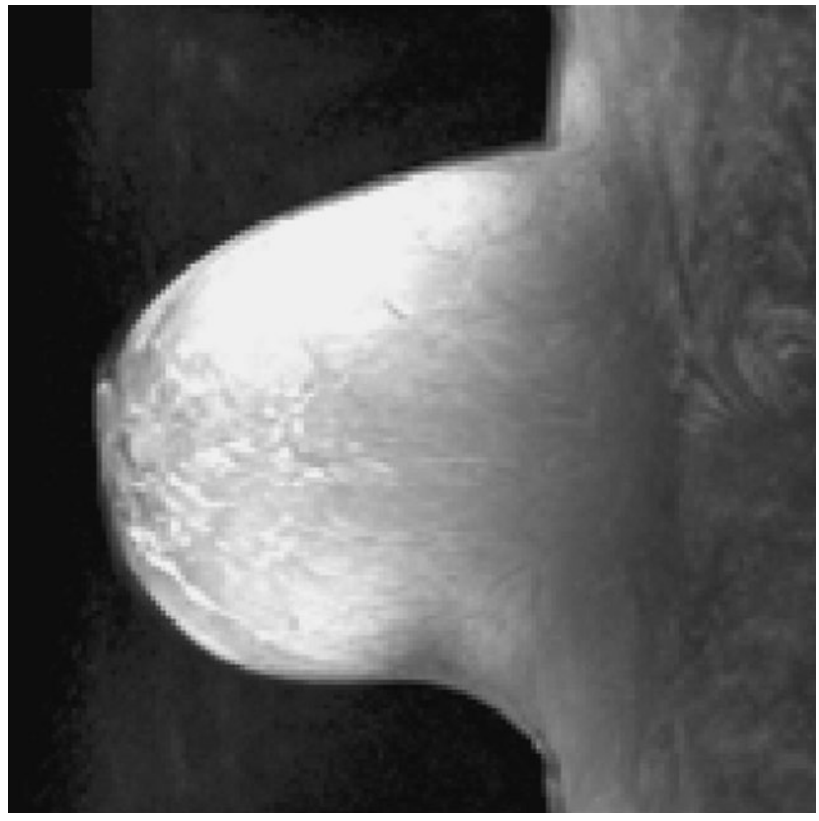

Figure 10.28 Sagittal image of the breast after bad shimming.

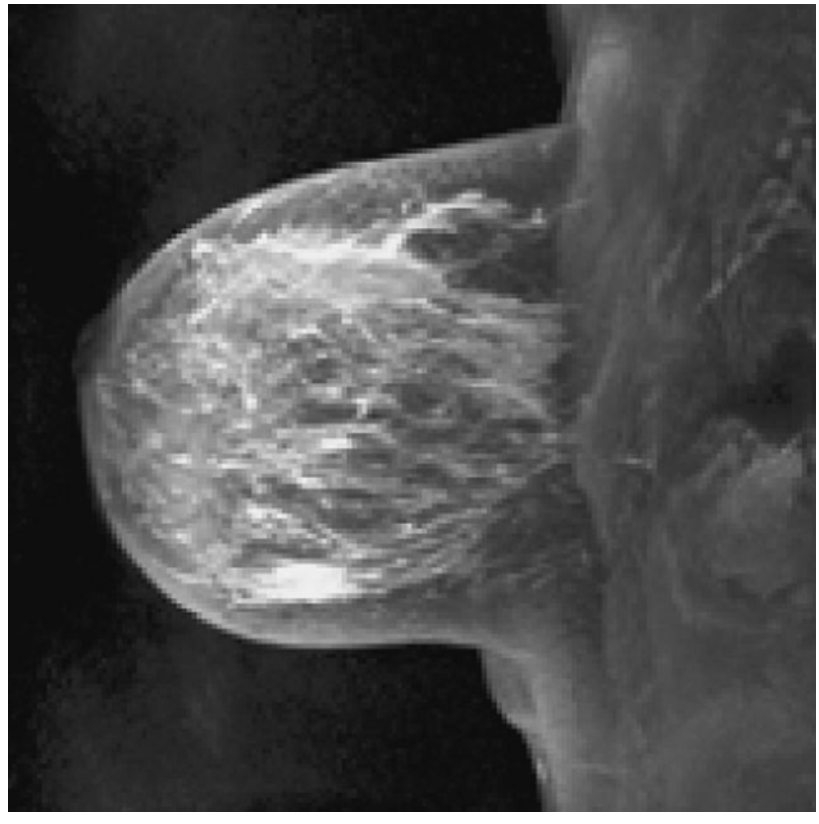

Figure 10.29 Sagittal image of the breast after good shimming.

after the injection, because the dynamic sequence is planned from the previous axials, and comparisons are made between the pre- and post-contrast images.

As the patient has to lie in a rather unnatural position (prone with arms back or forward), and the examination is fairly lengthy, it is important to ensure that the patient is comfortable before the examination begins. Some studies show that due to hormonally influenced tissue changes in the breast, this examination should be performed 10–15 days into the menstrual cycle. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is used in conjunction with rapid imaging to evaluate the temporal resolution of a lesion (see *Dynamic imaging* under *Pulse sequences* in Part 1). This dynamic acquisition allows for the evaluation of the haemodynamics of the breast lesion. In many cases, lesions that wash in and out quickly are likely to be malignant. Lesions that wash in/out slowly are likely to be benign.

The optimal imaging window for the evaluation of breast cancer is approximately 10 days post-menses. At other times during the menstrual cycle, there can be hormonal variability, and normal breast parenchyma can enhance, obscuring small lesions. Unfortunately, patients are generally anxious to have the investigation as soon as possible rather than waiting for time to evolve between their menstrual cycles. If this is the case and the patient cannot wait, care should be taken to make the radiologist aware of this as unexplained enhancement may occur in normal breast tissue. This is somewhat inefficient, however, as these patients may need to have their examination repeated at the correct time during their menstrual cycle. Repeated examinations should wait at least 24 h to allow gadolinium to be excreted.

Unilateral breast imaging opts to image the breast in question and then, on another date, the contralateral side. For unilateral imaging, the breast in question should be imaged dynamically. A look at the post-contrast image of the contralateral side is **not** recommended as many breast lesions wash out before the delayed image is acquired and may produce false results. Remember, repeat examinations should wait at least 24 h to allow gadolinium to be excreted.

Bilateral scans image one breast then the other within the same acquisition. An optimal bilateral acquisition produces interleaved 3D scans dynamically during contrast enhancement. In this example, a 3D acquisition would acquire, nearly simultaneously, the right breast, then the left breast and then the right again during the injection and for several minutes post-injection.

Axilla

Common indications

- Diagnosis and characterization of metastatic disease of the axillary lymph nodes especially, but not exclusively, in patients with carcinoma of the breast
- Diagnosis and characterization of axillary masses

Equipment

- Body coil/surface coils/phased array/multi-array coils
- RC bellows
- Pe gating leads
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with their arms at rest by their sides, or over their heads, with the coil placed over the axilla. The RC bellows (if required) and Pe gating leads are securely attached. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the axillae. Both axillae can be examined together.

Suggested protocol

Coronal SE/FSE/breath-hold fast incoherent (spoiled) GRE T1

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Thick slices/gaps are prescribed relative to the vertical alignment light, from the posterior chest muscles to the sternum. Both axillae and supraclavicular areas are included in the image.

P 60 mm to A 80 mm

Axial SE/FSE T1

Medium slices/gaps are prescribed through both axillae and supraclavicular fossae.

Axial SE/FSE PD/T2 or STIR

Slice prescription as for axial T1, **except** use tissue suppression on SE/FSE sequences.

Additional sequences

Sagittal SE/FSE T1 and T2

Provides an additional plane to visualize the brachial plexus. Prescribe slices from the sterno-clavicular joint medially to the humerus laterally.

Image optimization

Technical issues

There is usually relatively good inherent SNR and contrast in the axilla. This can be further improved if surface coils are placed near the axillae, or phased array breast coils are used instead of the body coil. Good resolution is obtained by using medium to fine matrices, the smallest FOV possible and medium slices, without jeopardizing the SNR. SE sequences are traditionally used to demonstrate anatomy and pathology, but FSE is also beneficial despite some respiratory and flow motion. This is especially true on T2 images as the associated scan time reduction enables the implementation of finer matrices, and therefore, greater resolution is obtained. Image quality is further optimized by the selection of multiple NEX/NSA, which effectively reduces flow and respiratory motion artefact due to increased signal averaging. In axial imaging, a rectangular/asymmetric FOV is beneficial (especially in conjunction with FSE) with the long axis of the rectangle placed R to L. However, if a particularly small FOV is selected, aliasing may be a problem. Spatial pre-saturation pulses placed A and P to the FOV are required to reduce this (see *Flow phenomena and artefacts* in Part 1).

Artefact problems

The main source of artefact in this area is from respiratory and flow motion in the subclavian vessels. Using FSE in conjunction with multiple NEX/NSA is often just as effective at reducing respiratory artefact as RC in this area. Phase ghosting occurs along the A to P axis on the axial images, so it does not usually interfere with the axillae. However, on the coronal series, phase artefact in the R to L axis can be troublesome. R and L spatial pre-saturation pulses brought into the FOV reduce flow artefact entering the axillae from the subclavian veins, but care must be taken to ensure that they do not saturate important anatomy. GMN is also useful to reduce artefact further, but as it gives vessels a high signal and increases the minimum TE, it is not usually beneficial in T1-weighted sequences. Additional shimming may be required before tissue suppression sequences.

Patient considerations

The patient's arms are placed either at the sides or over the head, and secured with immobilization pads if required. Inform the patient of the importance of keeping the arms still during the examination. Due to

excessively loud gradient noise associated with some sequences, earplugs/headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast can be given to identify pathology in this area. As the axillae sometimes contain fat, fat suppression techniques are often necessary. This is especially true on FSE T2-weighted images where fat returns a signal similar to pathology.

Brachial plexus

Basic anatomy (Figure 10.30)

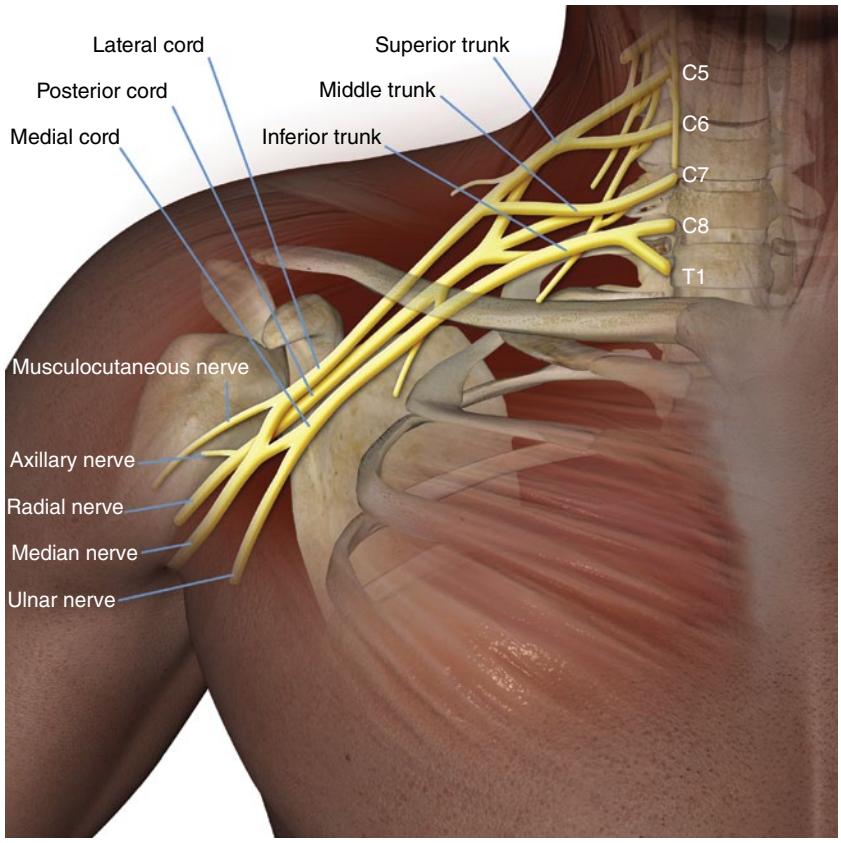

Figure 10.30 The components of the brachial plexus.

Common indications

- Diagnosis and characterization of brachial plexus lesions, especially those secondary to carcinoma of the breast and the bronchus
- Thoracic outlet syndrome
- Evaluation of the brachial plexus following trauma

Equipment

- Body coil/anterior neck coil/volume neck coil/multi-array coils
- RC bellows
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch and the RC bellows are attached if required. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the sterno-clavicular joints.

Suggested protocol

Axial SE/FSE T1

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Thick slices/gaps are prescribed on either side of the horizontal alignment light. The area from the sterno-clavicular joints to the third cervical vertebra is included in the image.

I 25 mm to S 25 mm

Coronal/oblique SE/FSE T1 (Figure 10.31)

Using a sagittal image, thin slices interleaved are prescribed parallel to the long axis of the lower cervical vertebrae (C4 to C7) from the posterior aspect of the cervical cord to the sterno-clavicular joints. The area from the third cervical vertebra to the aortic arch is included in the image. An axial image can be used to adjust the coronal plane such that the brachial plexus is displayed symmetrically.

Axial 3D incoherent (spoiled) GRE T1

Using a sagittal image thin slices and a small or medium number of slice locations are prescribed perpendicular to the lower cervical vertebrae from the arch of the aorta to the third cervical vertebra. Coverage may be extended to allow for slice wrap.

Axial SE/FSE PD/T2

Thin slices/gaps are prescribed from the arch of the aorta to the third cervical vertebra. Tissue suppression pulses are sometimes useful to differentiate tumour from fat.

Sagittal oblique SE/FSE T1

Using a coronal image in which the brachial plexus is displayed, thin slices/gap are prescribed perpendicular to the long axis of the symptomatic brachial plexus covering from the spinal cord to the medial aspect of the humerus. This oblique sagittal displays an accurate cross section of the brachial plexus better than the true sagittal plane.

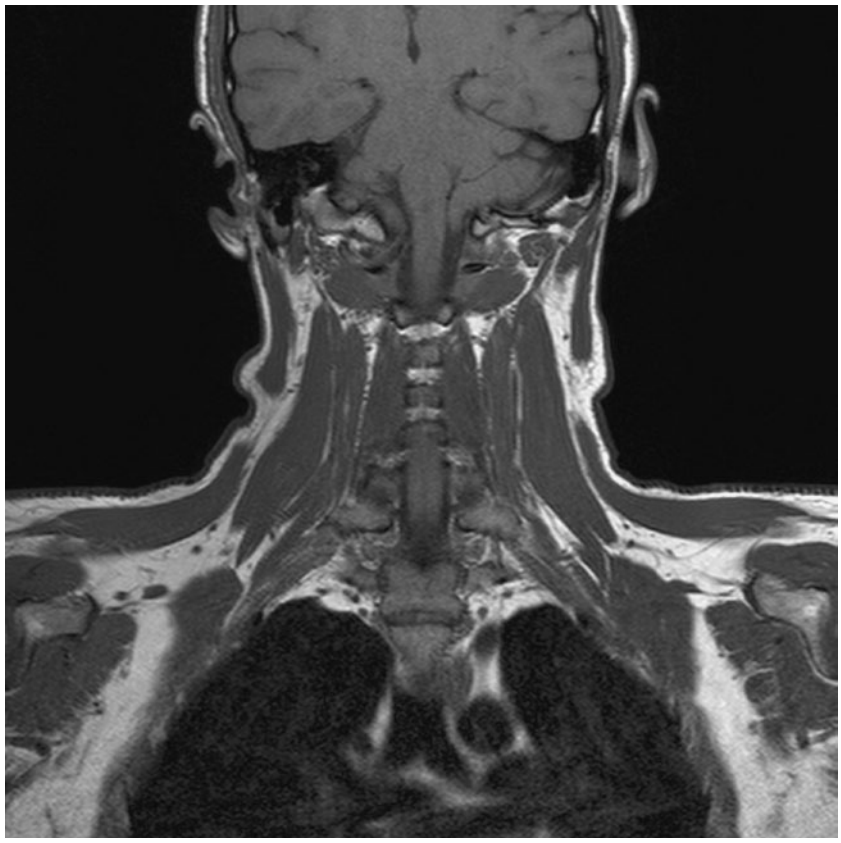

Figure 10.31 Coronal SE T1-weighted image of a normal brachial plexus.

Image optimization

Technical issues

The SNR and CNR characteristics of the brachial plexus are dependent on the type of coil used. Surface coils and specifically designed volume coils return a higher signal than the body coil, and therefore, improved spatial resolution is obtained. SE provides optimum contrast, but FSE can be implemented if required. Spatial resolution is important as it is necessary to demonstrate the nerve pathways within the brachial plexus. The coronal series requires the thinnest slices possible with interleaving. A volume acquisition is also beneficial as very thin slices with no gap are acquired, along with visualization of anatomy in any plane. However, the scan times are quite lengthy, increasing the likelihood of patient movement. As the purpose of the volume acquisition is to demonstrate anatomy, an incoherent (spoiled) GRE T1 is the pulse sequence of choice.

Artefact problems

The main source of artefact is from respiratory motion, and therefore, RC is used if this is especially troublesome. Alternatively, breath-hold techniques may be utilized to suspend respiratory motion. Motion artefact occurs in the phase direction, and therefore, swapping the phase axis to S and I on the coronal series is often beneficial. As a fairly small FOV is selected to optimize spatial resolution, aliasing is a problem if the body coil is used. Oversampling is therefore necessary if anatomy lies within the coil but outside the FOV in the phase direction.

Spatial pre-saturation pulses are important in the S to I direction to reduce flow in the carotid and jugular vessels. In addition, on the coronal series, R and L spatial pre-saturation pulses decrease flow artefact from the subclavian vessels. GMN also reduces flow artefact, but as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences. There is always some slice wrap on the first and last slices of the volume acquisition. Spatial pre-saturation pulses placed over anatomy outside the volume, in the direction of slice acquisition, significantly reduce this. For example, in an axial volume acquisition, spatial pre-saturation pulses placed S and I to the imaging volume nullify signal from slices that may wrap into the volume from above and below (see *Volume imaging* under *Parameters and trade-offs* in Part 1).

Patient considerations

Warn the patient of the length of the volume acquisition and the importance of keeping still. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast may be used to enhance masses in the brachial plexus but is not routinely given.

Key points

- For the most part, the body coil will produce optimum images for chest imaging. For higher SNR, higher resolution torso array coils should be used.
- SE T1-weighted sequences are traditionally used to show anatomy and black blood. Dark-blood images can be acquired by using the DIR technique to null the signal from blood.
- GRE sequences are useful for the evaluation of flow, and T2-weighted sequences demonstrate pathology and free fluid.
- Compensation for physiologic motion artefacts in the chest can be reduced by a number of imaging options including respiratory compensation, breath-hold techniques, cardiac gating, cardiac triggering or other imaging options (saturation pulses or gradient moment nulling). Breath-hold techniques are achieved by the acquisition of rapid imaging sequences (20 seconds or less) and instructing the patient to hold their breath during the image acquisition.
- Cardiac motion is effectively reduced by cardiac gating or swapping the phase encoding direction so that motion artefacts are depicted away from the region of interest.
- Due to the heart's oblique position in the chest, specific cardiac views are necessary to visualize the heart chambers and to perform functional imaging.
- Cardiac specific sequences are also mandatory to assess cardiac anatomy and function.
- Female breast imaging requires attention to protocol detail and expertise from the radiographer carrying out the procedure. Patient anxiety, patient positioning, slice prescription and contrast timing are all required for optimal diagnostic quality.
- Technical expertise and knowledge of MR physics are highly desirable when scanning areas such as the axilla and brachial plexus which are notorious for artefacts arising from different regional body thickness and movement.

11 Abdomen

Handbook of MRI Technique, Fourth Edition. Catherine Westbrook.

Companion website: www.wiley.com/go/westbrook/mritechnique

Table 11.1 Summary of parameters

1.5T		3T	
SE		**SE**	
Short TE	Min–30 ms	Short TE	Min–15 ms
Long TE	70 ms+	Long TE	70 ms+
Short TR	600–800 ms	Short TR	600–900 ms
Long TR	2000 ms+	Long TR	2000 ms+
FSE		**FSE**	
Short TE	Min–20 ms	Short TE	Min–15 ms
Long TE	90 ms+	Long TE	90 ms+
Short TR	400–600 ms	Short TR	600–900 ms
Long TR	4000 ms+	Long TR	4000 ms+
Short TEL	2–6	Short TEL	2–6
Long ETL	16+	Long ETL	16+
IR T1		**IR T1**	
Short TE	Min–20 ms	Short TE	Min–20 ms
Long TR	3000 ms+	Long TR	300 ms+
TI	200–600 ms	TI	Short or null time of tissue
Short ETL	2–6	Short ETL	2–6
STIR		**STIR**	
Long TE	60 ms+	Long TE	60 ms+
Long TR	3000 ms+	Long TR	3000 ms+
Short TI	100–175 ms	Short TI	210 ms
Long ETL	16+	Long ETL	16+
FLAIR		**FLAIR**	
Long TE	80 ms+	Long TE	80 ms+
Long TR	9000 ms+	Long TR	9000 ms + (TR at least 4 × TI)
Long TI	1700–2500 ms (depending on TR)	Long TI	1700–2500 ms (depending on TR)
Long ETL	16+	Long ETL	16+
Coherent GRE		**Coherent GRE**	
Long TE	15 ms+	Long TE	15 ms+
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Incoherent GRE		**Incoherent GRE**	
Short TE	Minimum	Short TE	Minimum
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Balanced GRE		**Balanced GRE**	
TE	Minimum	TE	Minimum
TR	Minimum	TR	Minimum
Flip angle	>40°	Flip angle	>40°
SSFP		**SSFP**	
TE	10–15 ms	TE	10–15 ms
TR	<50 ms	TR	<50 ms
Flip angle	20–40°	Flip angle	20–40°

(*Continued*)

Table 11.1 (*Contd.*)

1.5T and 3T			
Slice thickness 2D		**Slice thickness 3D**	
Thin	2–4 mm	Thin	<1 mm
Medium	5–6 mm	Thick	>3 mm
Thick	8 mm		
FOV		**Matrix**	
Small	<18 cm	Coarse	256×128/256×192
Medium	18–30 cm	Medium	256×256/512×256
Large	>30 cm	Fine	512×512
		Very fine	>1024×1024
NEX/NSA		**Slice number 3D**	
Short	1	Small	<32
Medium	2–3	Medium	64
Multiple	>4	Large	>128
PC-MRA 2D and 3D		**TOF-MRA 2D**	
TE	Minimum	TE	Minimum
TR	25–33 ms	TR	28–45 ms
Flip angle	30°	Flip angle	40–60°
VENC venous	20–40 cm/s	**TOF-MRA 3D**	
VENC arterial	60 cm/s	TE	Minimum
		TR	25–50 ms
		Flip angle	20–30°

The figures given are for 1.5T and 3T systems. Parameters are dependent on field strength and may need adjustment for very low or very high field systems.

Liver and biliary system

Basic anatomy (Figure 11.1)

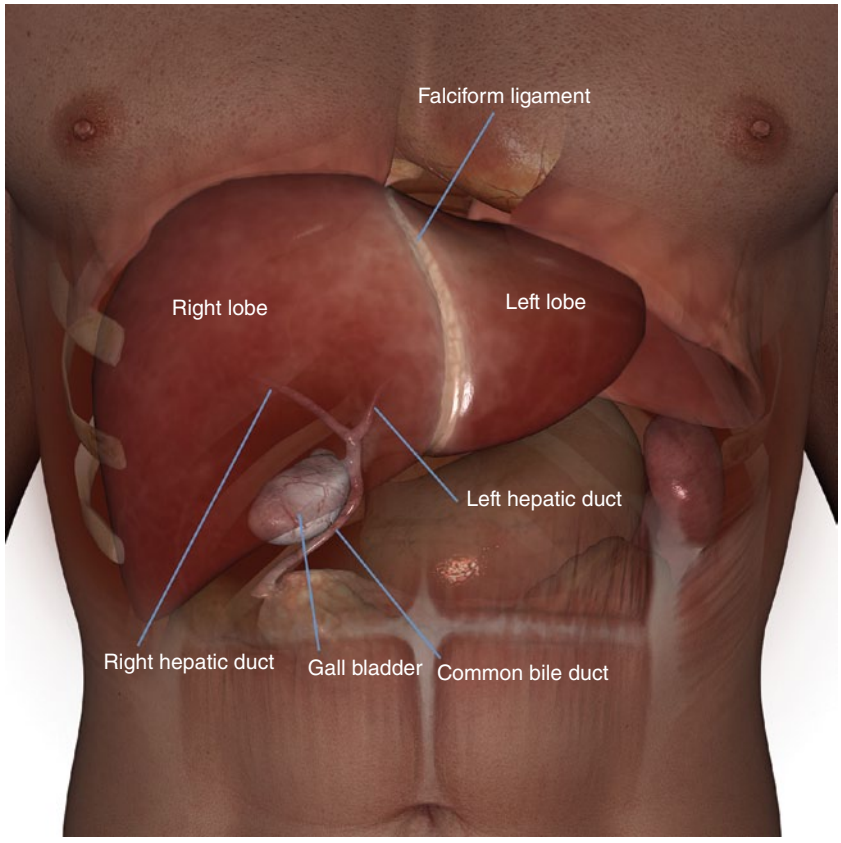

Figure 11.1 The components of the liver and biliary system.

Common indications

- Focal lesions and staging of neoplasms
- Benign hepatic disease, especially haemangioma and focal nodular hyperplasia
- Haemochromatosis
- Gallbladder disease
- Biliary duct obstruction
- Evaluation of liver infiltrants such as iron or fat

Equipment

- Body coil/volume torso array or multi-coil
- RC bellows
- Earplugs/headphones
- Pe gating leads if required

Patient positioning

The patient lies supine on the examination couch with the RC bellows (if required) securely attached. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the third lumbar vertebra, or the lower costal margin.

Suggested protocol

Coronal breath-hold incoherent (spoiled) (Figure 11.2)

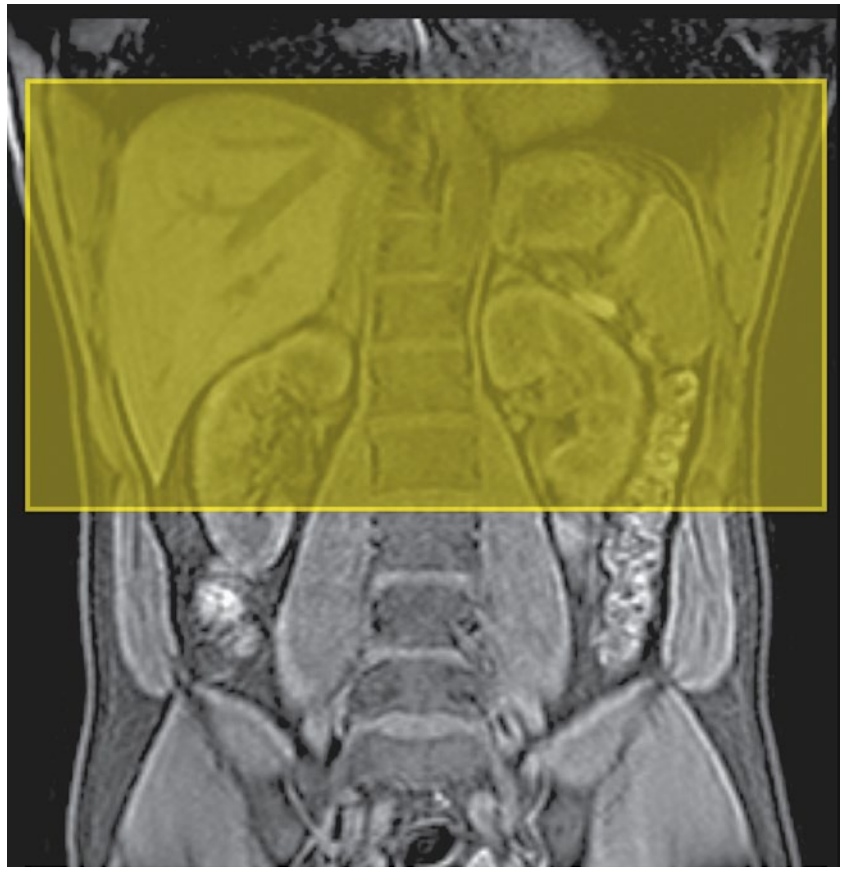

Figure 11.2 Coronal incoherent (spoiled) T1-weighted image through the abdomen demonstrating slice prescription boundaries and orientation for axial imaging of the liver.

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Thick slices/gaps are prescribed relative to the vertical alignment light, from the posterior abdominal muscles to the anterior abdominal wall. The area from the pubis symphysis to the diaphragm is included in the image.

P 60 mm to A 40 mm

Coronal breath-hold SS-FSE

Slice prescription as for coronal T1

P 60 mm to A 40 mm

Axial SE/FSE/incoherent (spoiled) GRE T1 /– in and out of phase (Figures 11.3 and 11.4)

As for coronal T1, **except** prescribe slices from the diaphragm to inferior margin of the liver.

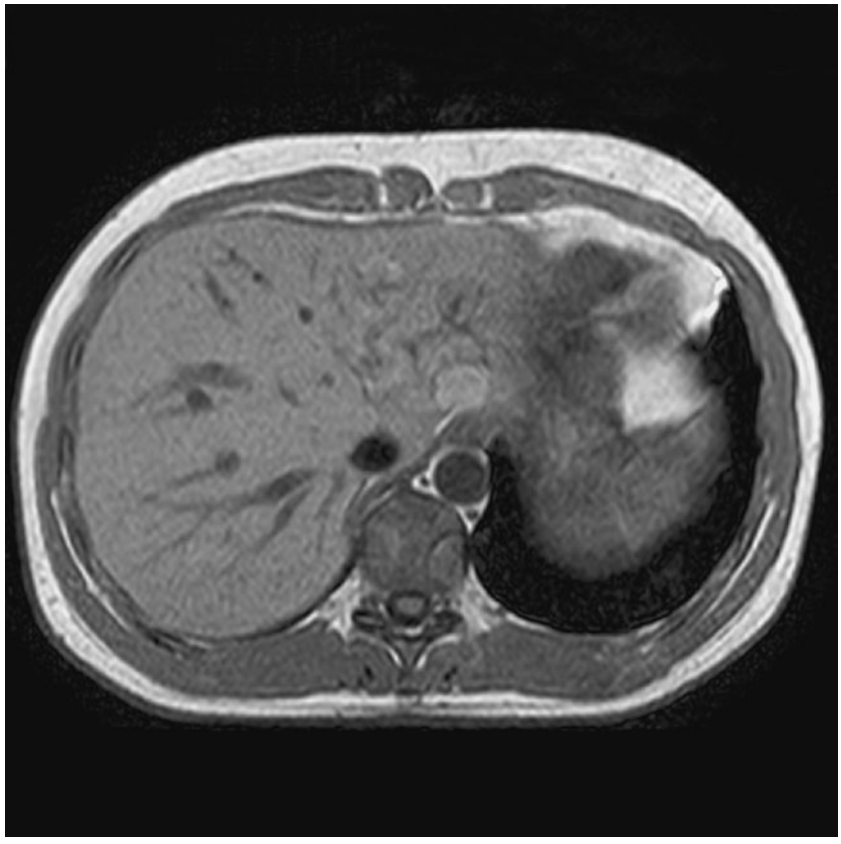

Figure 11.3 Axial FSE T1-weighted image through the liver.

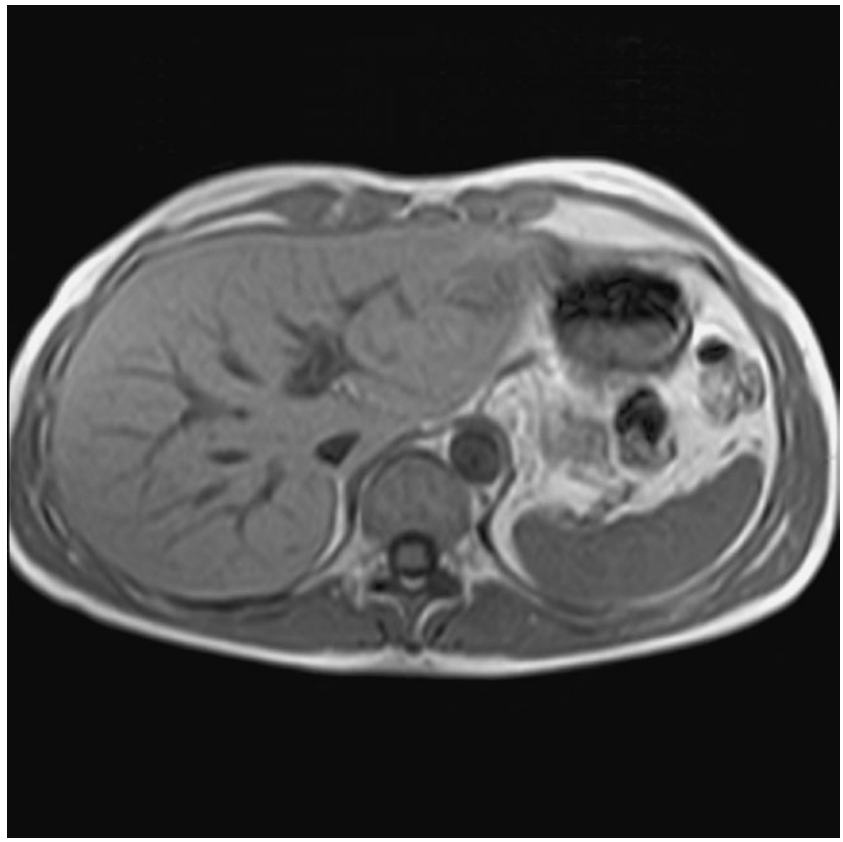

Figure 11.4 Axial incoherent (spoiled) T1-weighted breath-hold image of the liver.

Delayed scans after contrast enhancement using tissue suppression techniques are sometimes necessary to evaluate arterial, venous and equilibrium phases.

Axial SE/FSE T2 or GRE T2* (Figures 11.5 and 11.6)

Slice prescription as for axial T1.

Axial BGRE T2*

Slice prescription as for axial T1.

Axial SE/FSE/breath-hold incoherent (spoiled) GRE T1 contrast

Slice prescription as for axial T1.

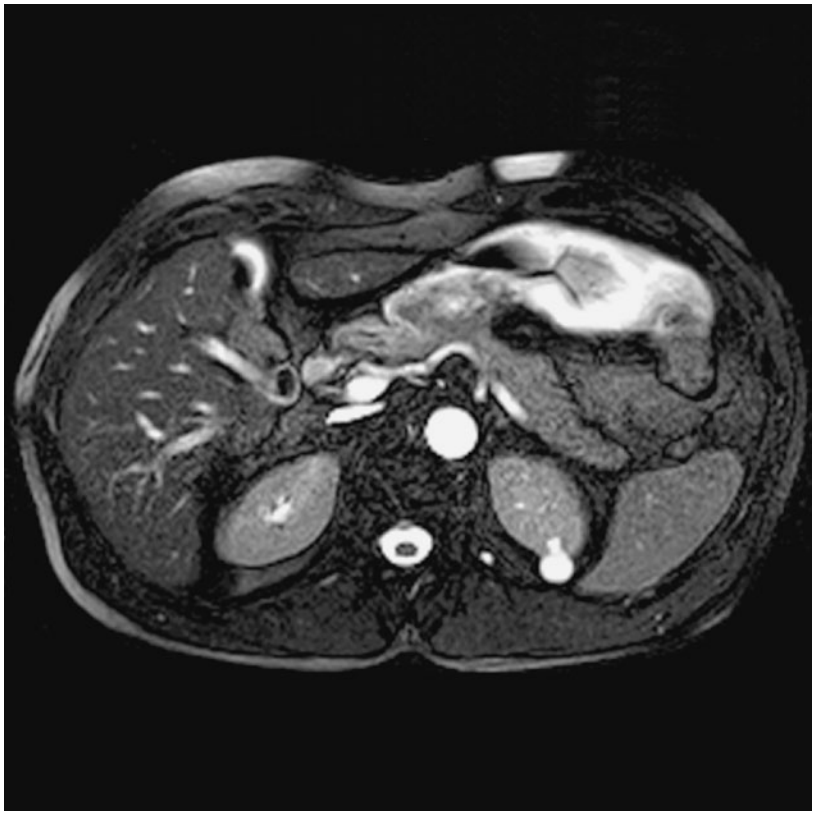

Figure 11.5 Axial fast GRE T2* through the liver.

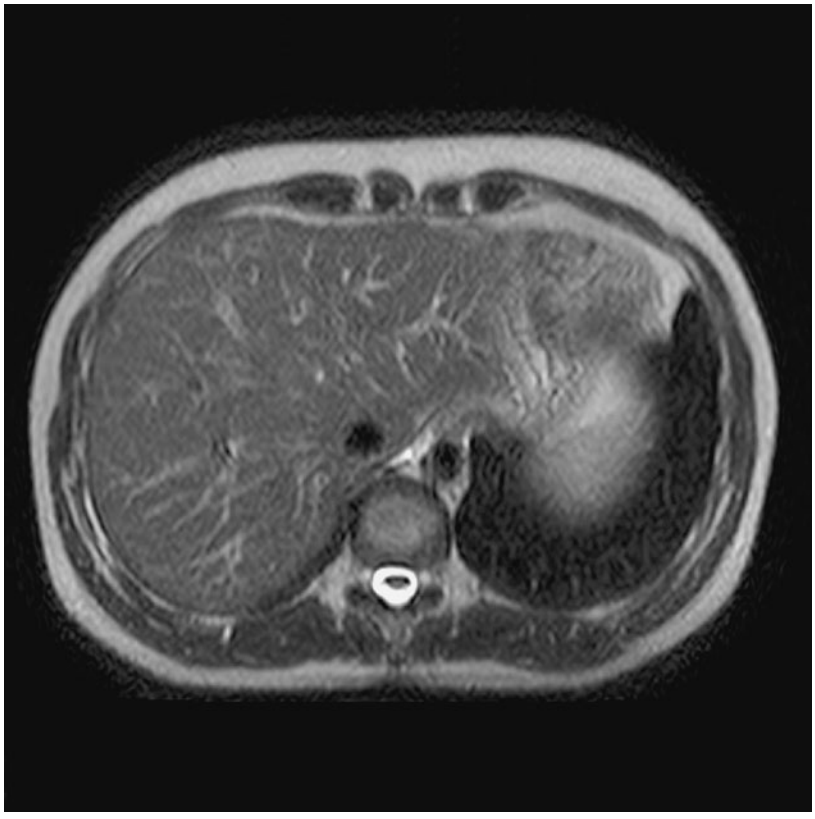

Figure 11.6 Axial SS-FSE T2 through the liver.

Additional sequences

SS-FSE MRCP (Figure 11.7)

Figure 11.7 Coronal SS-FSE image of the gallbladder (MRCP). Very long values of TR and TE were used to acquire images in which only fluid is seen.

This sequence provides images in which only fluid-filled spaces such as the gall bladder and biliary ducts return signal. It is necessary to use very long TEs and TRs to effectively nullify the signal from all tissues except those that have long T2 decay times. TEs in excess of 200 ms and TRs of more than 10 s are required (see also *Pancreas* and *Salivary glands*). If SS-FSE is unavailable then an FSE sequence may be substituted.

SS-FSE/GRE-EPI/SE-EPI/diffusion imaging

The use of real-time imaging has applications in the liver and biliary system. This includes biopsies and thermal ablations of liver lesions under real-time MR control. In addition, diffusion and perfusion techniques of

the liver have been developed that may negate the use of contrast agents in the future. DWI images are overlaid onto T1-weighted acquisitions. The DWI image set provides pathology information, whereas the T1-weighted acquisition provides anatomical data. The images produced are not dissimilar to a PET/CT scan. In addition, diffusion tensor imaging used in conjunction with parallel imaging techniques enables differentiation of benign from malignant hepatic lesions and may also assist in the quantification of hepatic fibrosis.

Image optimization

Technical issues

The inherent SNR and CNR of the abdominal contents are usually excellent due to their high proton density, and the use of a torso array coil increases this even further. In addition, parallel imaging techniques using multi-array coils reduce scan time significantly. Due to respiratory artefact, RC or respiratory triggering may be necessary. Alternatively, breath-hold techniques may be used to suspend respiratory motion. In axial T1 sequences, it is necessary to shorten the TR to less than 400 ms in SE sequences as this is considered the optimum value for demonstrating liver contrast. As the slice number available per acquisition is reduced with a short TR, two or three acquisitions may be required to cover the whole liver. Two FSE sequences using TEs of 80 and 160 ms are required to characterize haemangiomas, which retain a high signal intensity on late-echo images.

Artefact problems

The main source of artefact in the liver is motion caused by respiration, flow and peristalsis. RC or respiratory triggering is often required, especially on the superior axial slices, due to the proximity of the diaphragm. However, breath-hold techniques may also be utilized. Pe gating is sometimes used, but it often increases the scan time, especially if the patient's heart rate is slow or cardiac output poor, so that the system cannot trigger efficiently off each R wave. Commonly, Pe gating does not significantly increase image quality and only serves to lengthen the scan time. Under these circumstances, it is advisable to dispense with it. Spatial pre-saturation pulses placed S and I to the FOV are necessary to decrease flow motion artefact in the aorta and IVC. GMN also minimizes flow artefact, but as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences. Bowel motion is often a problem on the lower axial slices of the liver, whereas gastric motion artefact is sometimes evident on the more superior slices. Antispasmodic agents, given IV, IM or subcutaneously prior to the examination, effectively reduce this.

Patient considerations

Careful explanation of the procedure is important. Ensure that the patient is as comfortable as possible. Some antispasmodic agents given IM may cause nausea, but fruit juice given after the study can alleviate this.

Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is often beneficial to demonstrate liver metastases. Weighting depends on the type of contrast media used. T1 shortening agents such as gadolinium require T1-weighted post-contrast scans. These can be acquired in conjunction with tissue suppression pulses and acquired in multiple phases to evaluate the dynamic contrast enhancement characteristics of hepatic lesions. T2 weighting is necessary after injection of superparamagnetic T2 shortening (liver specific) agents (see *Contrast agents* in Part 1). Scans should be delayed for approximately 1 h after injection to allow time for uptake of contrast by the liver. The use of contrast and dynamic imaging to visualize liver vasculature and the biliary system is gaining in popularity. Oral and rectal contrast agents, for evaluation of gastrointestinal disease, are also used (see *Contrast agents* in Part 1).

Kidneys and adrenal glands

Basic anatomy (Figure 11.8)

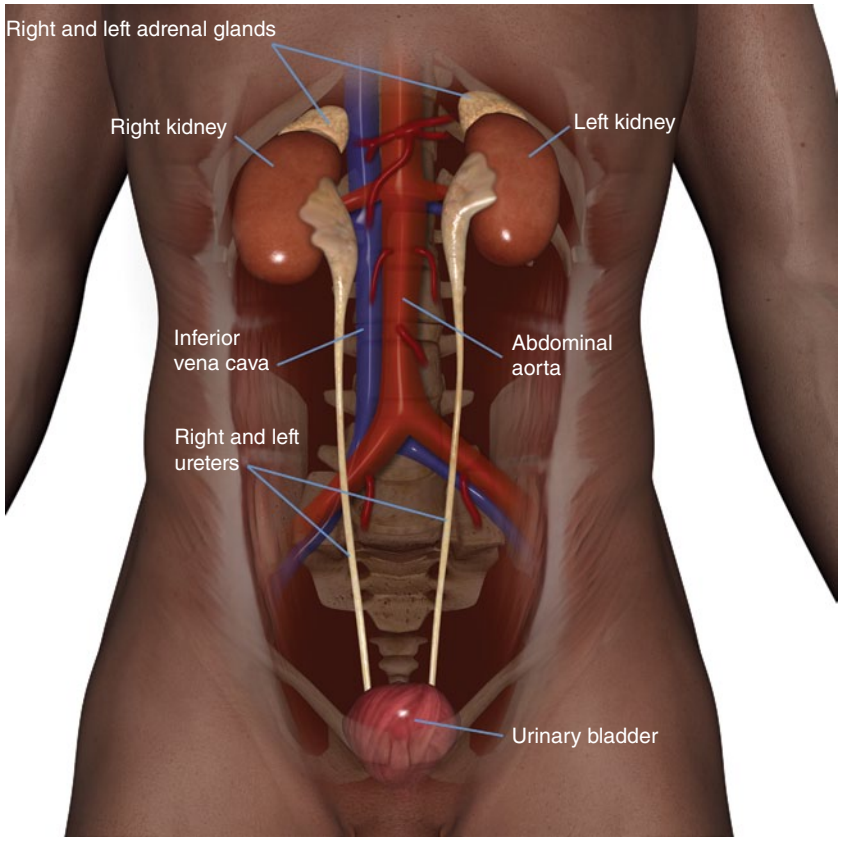

Figure 11.8 The urinary system and its vascular supply.

Common indications

- Adrenal masses and haemorrhage
- Renal masses and haemorrhage
- Renal cell carcinoma
- Renal transplant rejection
- Ureteric obstruction

Equipment

- Body coil/multi-phased array or multi-coil array
- RC bellows
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with the RC bellows securely attached (if required). The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the third lumbar vertebra, or the lower costal margin. The kidneys are generally located about four fingers inferior to the xiphoid.

Suggested protocol

Coronal breath-hold fast incoherent (spoiled) GRE/SE/FSE T1 (Figure 11.9)

Acts as a localizer if three-plane localization is unavailable. Alternatively, it can be used as a diagnostic sequence. Medium slices/gaps are prescribed on either side of the vertical alignment light, from the posterior abdominal

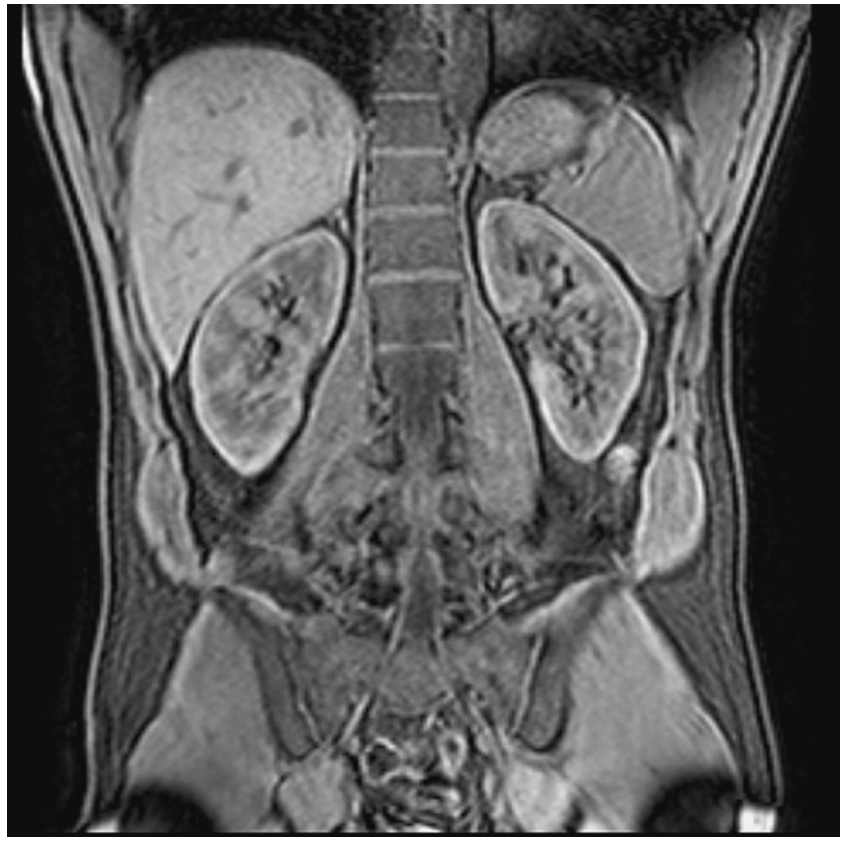

Figure 11.9 Coronal incoherent (spoiled) GRE T1-weighted image through the abdomen demonstrating the kidneys.

muscles to the anterior abdominal wall. The area from the pubis symphysis to the diaphragm is included in the image.

P 60 mm to A 40 mm

Coronal breath-hold SS-FSE T2

Acts as a localizer, but also valuable as a diagnostic sequence providing T2-weighted information. The limitation of this sequence is a relatively low SNR.

Axial breath-hold BGRE T2

Prescribe slices as for axial T1.

This sequence is ideal to show fluid-filled lesions, the status of vessels and detecting solid lesions.

Axial incoherent (spoiled) GRE T1 in and out of phase +/– contrast +/– tissue suppression (Figures 11.10 11.11 and 11.12)

As for coronal SE/FSE T1, **except** medium slices/gap are prescribed from the inferior margin of the kidneys to the superior aspect of the adrenals (Figure 11.13). The coronal plane may also be useful depending on lesion location. Slices may also be offset to specifically image the adrenals (Figure 11.14).

Additional sequences

MR urography

Either FSE or SS-FSE sequences may be used with very long TEs and TRs to produce heavily T2-weighted images in which only fluid that has a very long T2 decay time is seen. It has applications in the biliary system (see also *Liver and biliary system* earlier in this chapter) and in the salivary gland. It may also be of use in the urinary system to visualize the renal collecting system, the ureters and the bladder.

Diffusion imaging

DWI using SS-EPI acquisition in conjunction with parallel imaging techniques may be useful in the differentiation of malignant adrenal lesions from hyperplasia or adenomas and renal cysts from renal cell carcinomas.

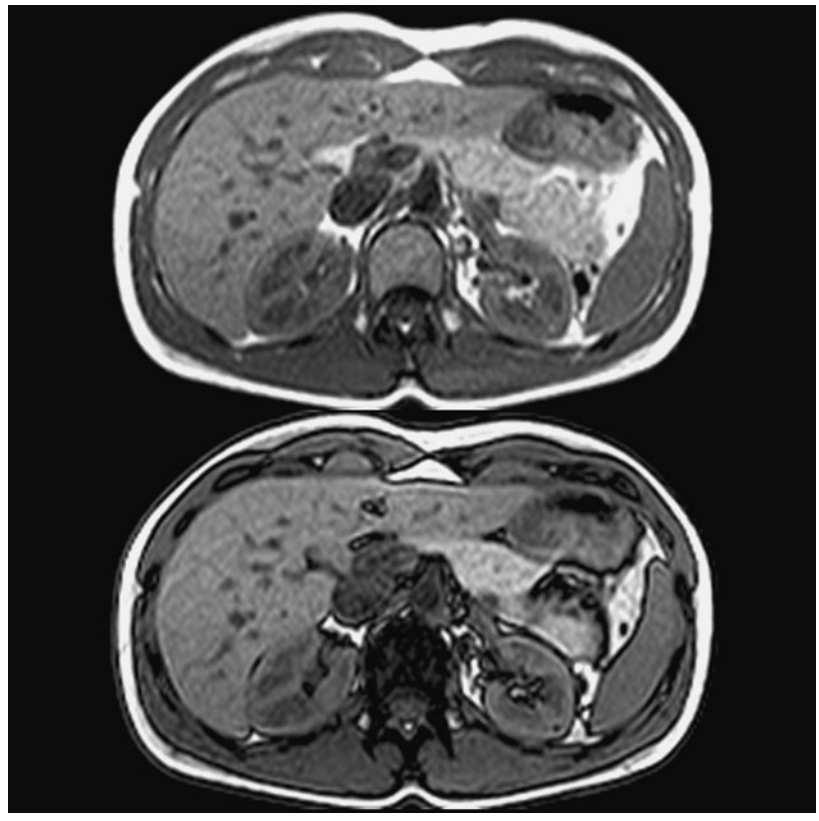

Figure 11.10 Axial incoherent (spoiled) GRE T1-weighted image acquired with a TE when fat and water are in phase (above) and out of phase (below).

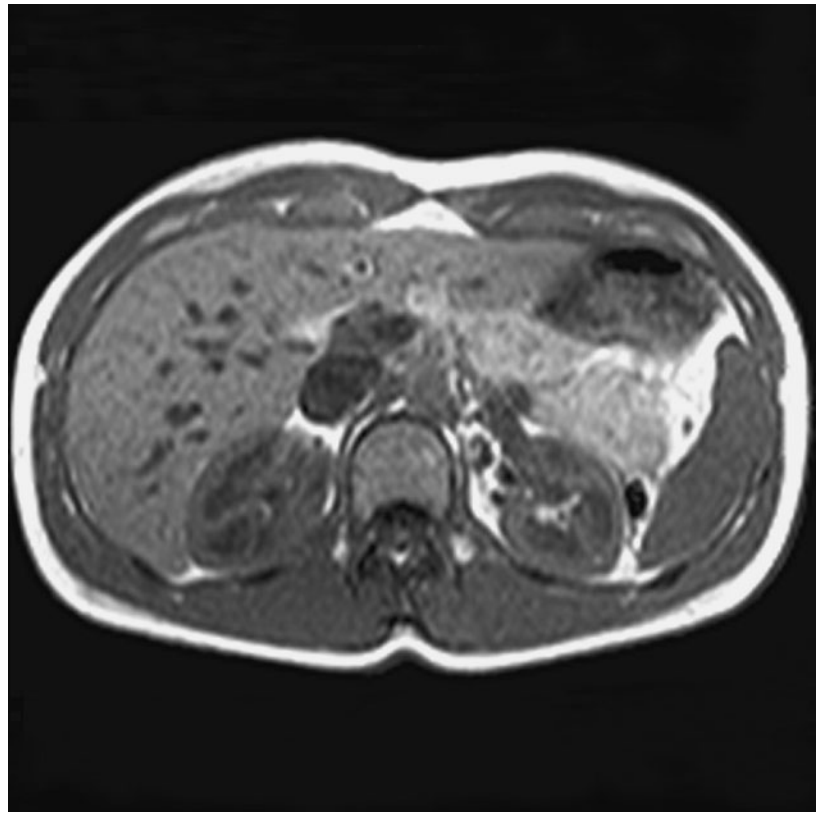

Figure 11.11 Axial fast incoherent (spoiled) GRE T1-weighted image through the kidneys.

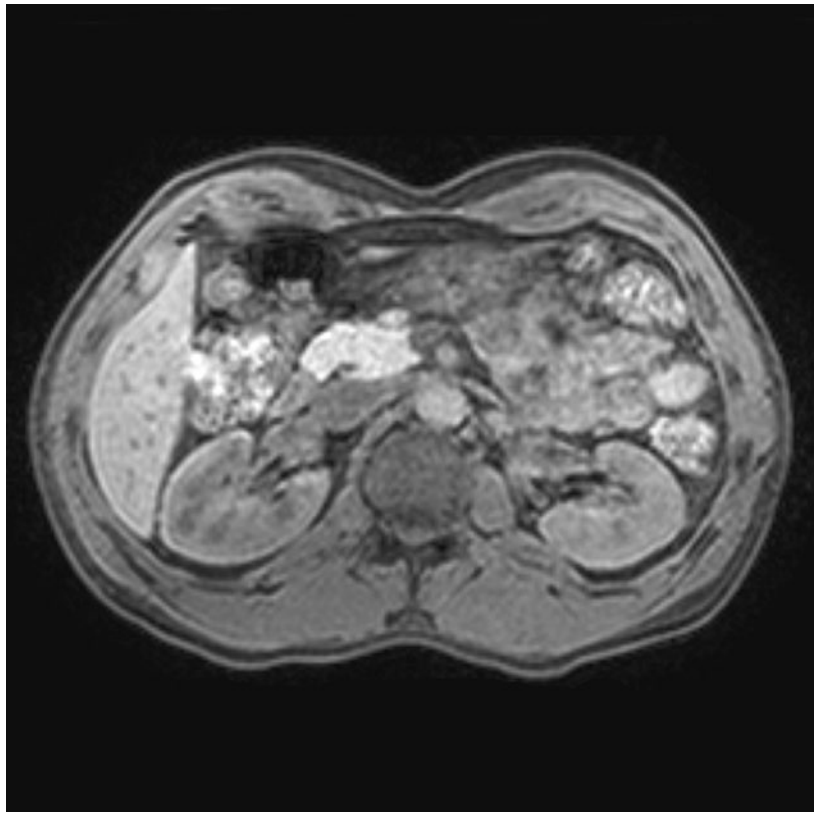

Figure 11.12 Axial incoherent (spoiled) GRE T1 with tissue suppression.

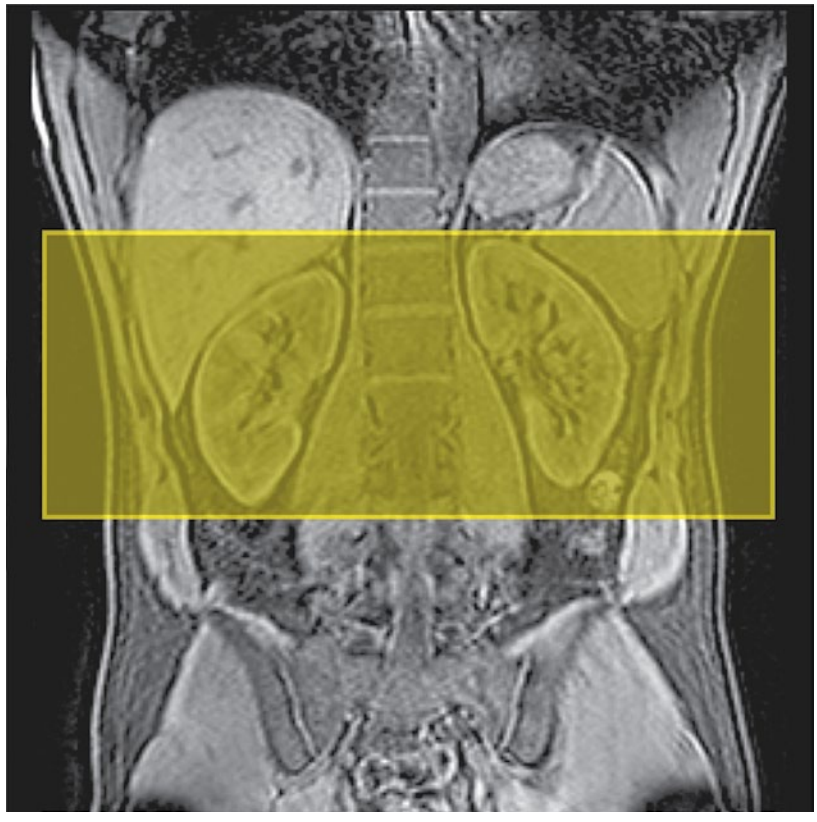

Figure 11.13 Coronal incoherent (spoiled) GRE T1 weighted through the abdomen demonstrating slice prescription boundaries and orientation for axial imaging of the kidneys.

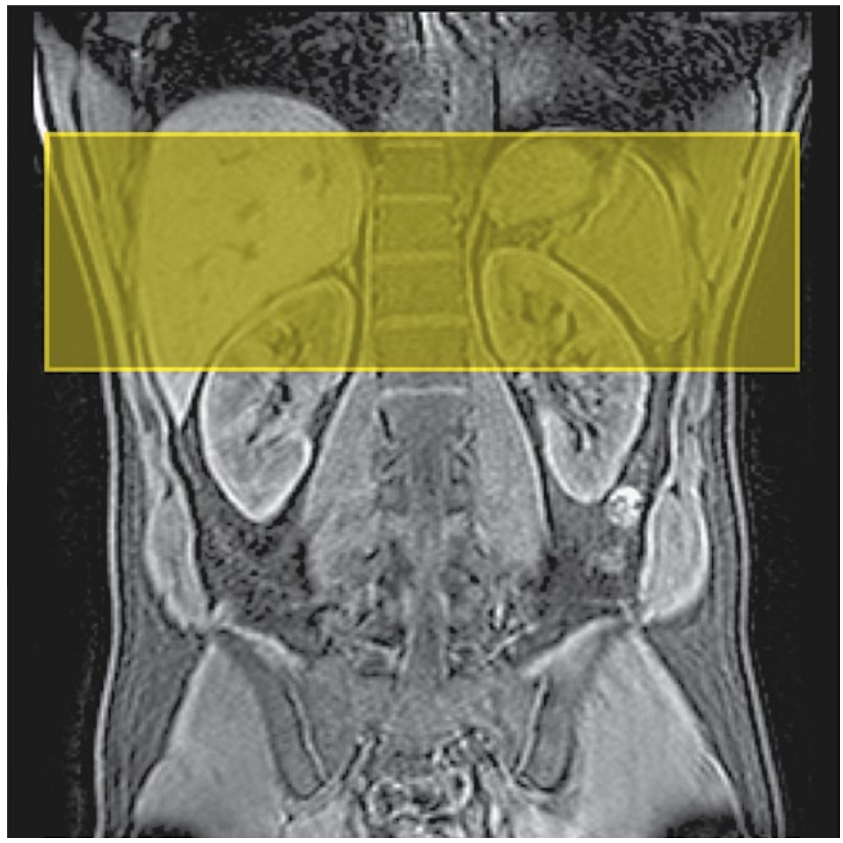

Figure 11.14 Coronal incoherent (spoiled) GRE T1 weighted through the abdomen demonstrating slice prescription boundaries and orientation for axial imaging of the adrenals.

Image optimization

Technical issues

The inherent SNR and CNR of the abdominal contents are usually excellent due to their high proton density, and the use of a torso array coil increases this even further. In addition, parallel imaging techniques using multi-array coils reduce scan times significantly. Spatial resolution is important, especially when imaging relatively small structures such as the kidneys and adrenal glands, which therefore require thin slices/gap. However, this is often difficult to achieve when using the body coil, a large FOV and in the presence of respiratory and flow artefact. The use of a torso array coil greatly improves resolution in the abdomen. In addition, parallel imaging techniques can be used to improve resolution while keeping scan times short. SE sequences usually produce the best contrast in the abdomen, but result in fairly lengthy scan times. For this reason, breath-hold GRE or SS-FSE sequences are often preferred. FSE used in conjunction with a rectangular/asymmetric FOV allows PD and T2 images to be obtained in a shorter scan time.

Artefact problems

The main source of artefact in this area is from respiratory movement and flow in the aorta and the IVC. When possible, the scan should be performed breath-hold. The patient should get clear instructions on breath-hold technique. In cases of breath-hold difficulty, a short period of hyperventilation before breath-holding may be helpful. The scan should be performed during expiration because the kidney position is more constant in expiration than in inspiration. If the sequence is too long to perform in one breath-hold, RC or respiratory triggering is often required and significantly reduces respiratory ghosting. Another technique of respiratory motion control is respiratory gating by use of a navigator pulse. Spatial pre-saturation pulses placed S and I to the FOV are necessary to reduce flow motion artefact arising from the aorta and IVC. As the kidneys and adrenals are retroperitoneal structures, a spatial pre-saturation band brought into the FOV and placed over the anterior abdominal wall reduces respiratory artefact significantly without obscuring important anatomy. GMN also minimizes flow and, in some cases, respiratory motion, but it increases the signal in vessels and the minimum TE.

Chemical shift artefact is often troublesome in the kidneys, especially at higher field strengths. This is due to retroperitoneal fat being adjacent to fluid-filled kidneys. Narrowing the receive bandwidth increases this artefact but, if used in conjunction with fat suppression techniques, results in a significant improvement in SNR and a reduction in chemical shift. However, this strategy increases the minimum TE and is therefore reserved for T2-weighted sequences. Bowel motion is also troublesome but is effectively reduced by the administration of antispasmodic agents given IV, IM or subcutaneously prior to the examination.

Patient considerations

Careful explanation of the procedure is important. Ensure that the patient is as comfortable as possible. Some antispasmodic agents given IM may cause nausea, but fruit juice given after the study can alleviate this. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is sometimes useful in conjunction with dynamic imaging to visualize the uptake of contrast in the kidneys (see *Dynamic imaging* under *Pulse sequences* in Part 1). Vascular imaging of the renal arteries is

a common technique discussed later (see *Vascular imaging* later in this chapter). Contrast may also be necessary to increase the conspicuity of the adrenal glands. Recently, functional imaging of the kidneys after the administration of macromolecular contrast agents has been advocated in the evaluation of a variety of renal diseases. These agents are almost totally excreted by the kidneys, thereby improving the conspicuity of lesions that have different perfusion characteristics.

Pancreas

Basic anatomy (Figure 11.15)

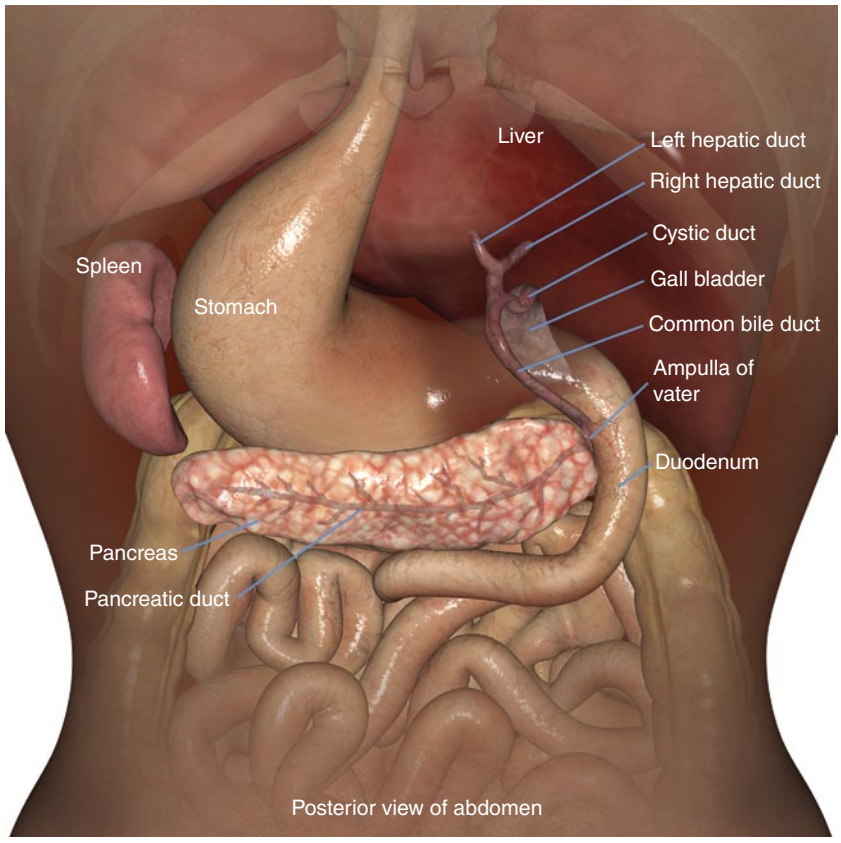

Figure 11.15 The pancreas and related structures.

Common indications

- Pancreatic tumours
- Pancreatic duct obstruction

Equipment

- Body coil/multi-phased array/multi-array coil
- RC bellows
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with the RC bellows securely attached. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the third lumbar vertebra, or the lower costal margin.

Suggested protocol

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Thick slices/gaps are prescribed on either side of the vertical alignment light, from the posterior abdominal muscles to the anterior abdominal wall. The area from the pubis symphysis to the diaphragm is included in the image.

P 60 mm to A 40 mm

Axial FSE/SE/breath-hold fast incoherent (spoiled) GRE T1 +/– tissue suppression/in and out of phase imaging

As for coronal T1, except thin slices/gap are prescribed through the pancreas (Figure 11.16).

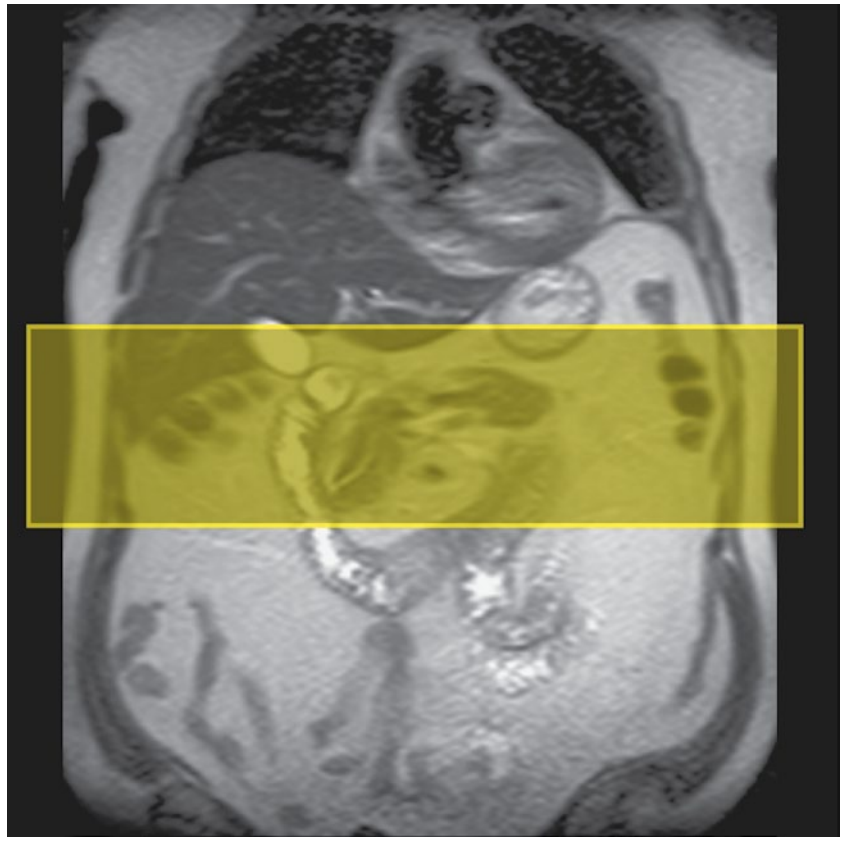

Figure 11.16 Coronal FSE T1-weighted image through the abdomen demonstrating slice prescription boundaries and orientation for axial imaging of the pancreas.

Axial FSE / SS-FSE T2 or BGRE T2* (Figures 11.17 and 11.18)

Slice prescription as for axial T1.

Axial breath-hold fast incoherent (spoiled) GRE T1 (Figure 11.19)

For visualization of small pancreatic tumours +/– contrast.

SS-FSE (Figures 11.20 and 11.21)

As for MRCP technique described in the biliary system. Demonstrates pancreatic duct obstruction.

Diffusion imaging

Diffusion imaging used in conjunction with parallel imaging techniques may be useful to detect pancreatic adenocarcinoma and for differentiation from benign and cystic lesions.

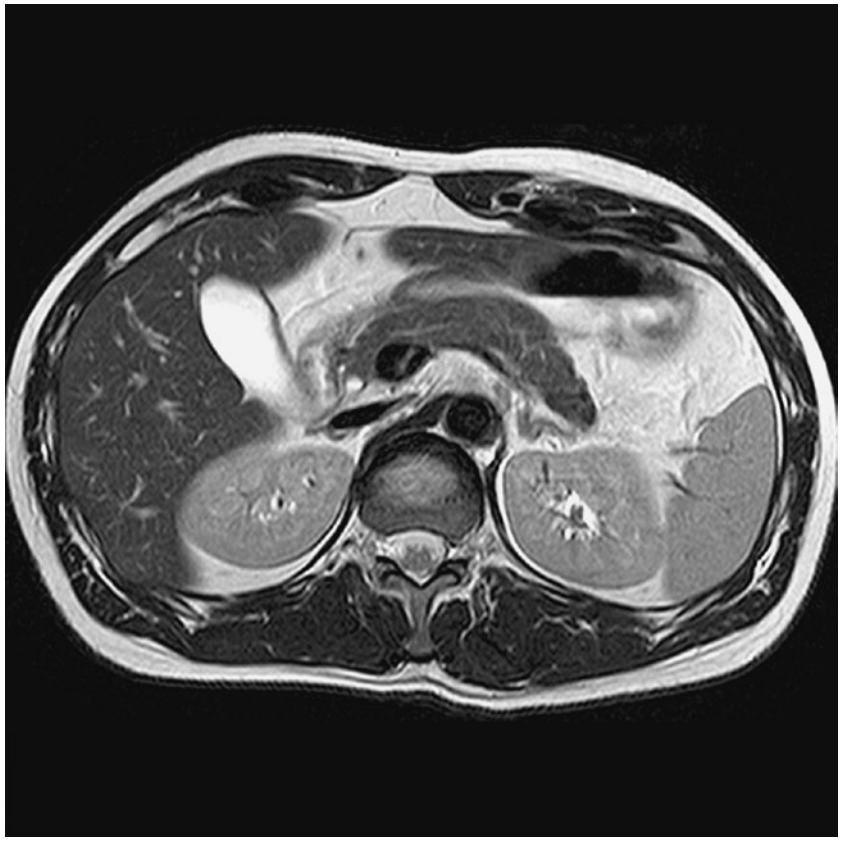

Figure 11.17 Axial high resolution FSE T2 of the pancreas.

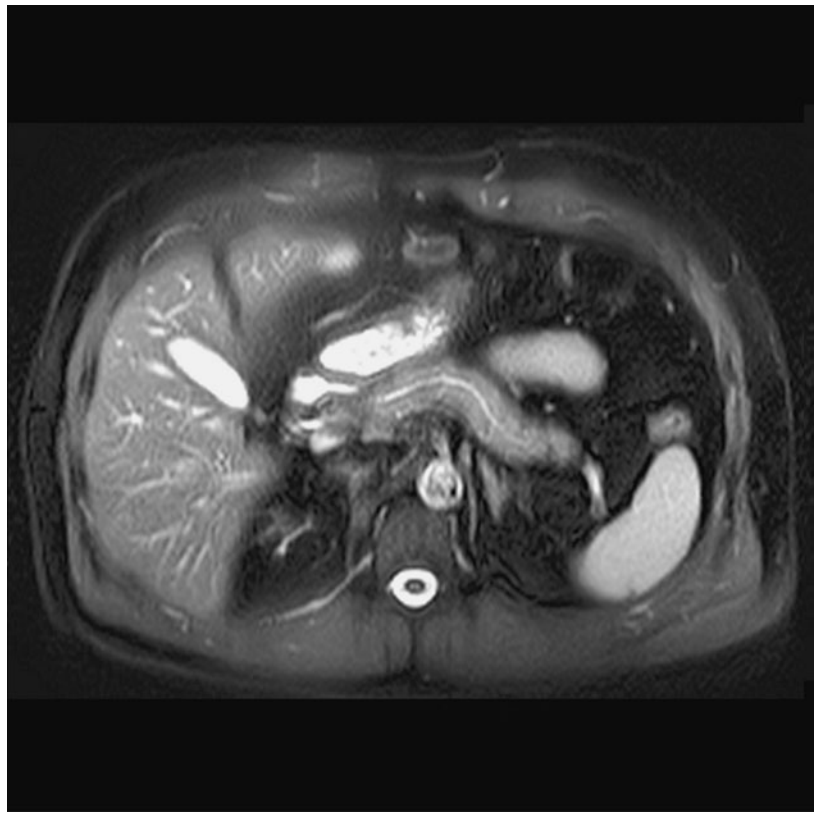

Figure 11.18 Axial SS-FSE T2 of the pancreas during free breathing.

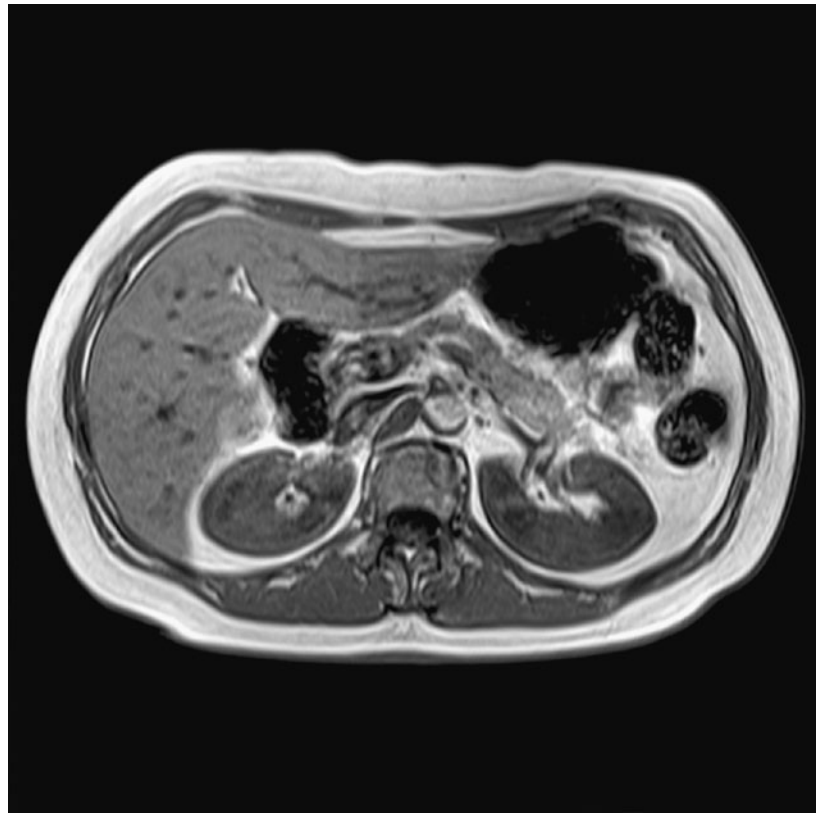

Figure 11.19 Axial fast incoherent (spoiled) T1-weighted image of the pancreas.

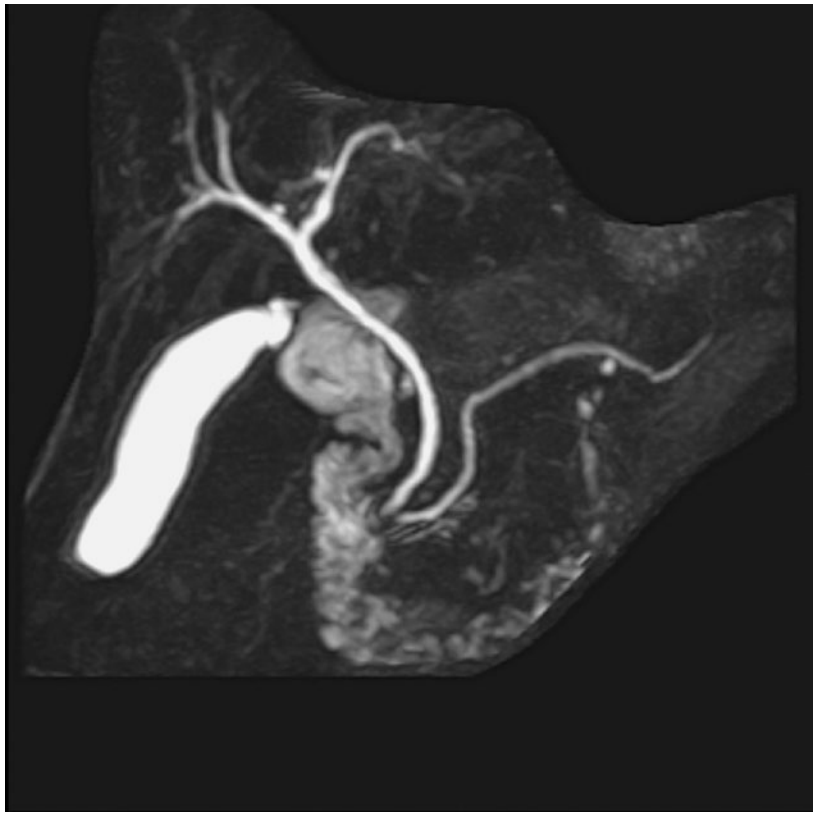

Figure 11.20 MRCP of the pancreatic duct.

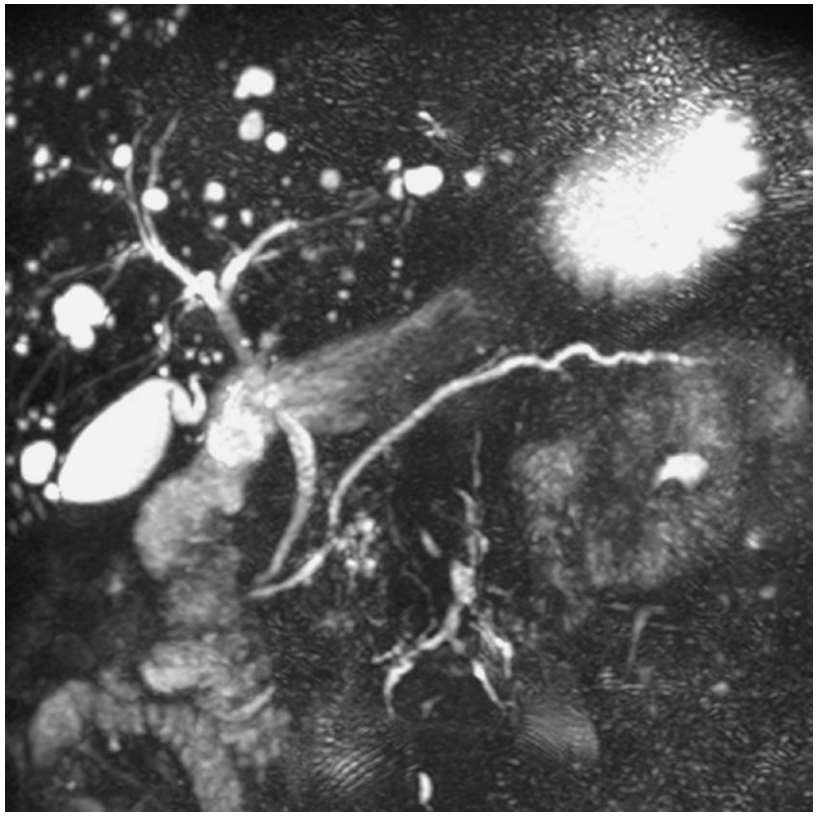

Figure 11.21 MRCP of the pancreatic duct and the rest of the biliary system.

Image optimization

Technical issues

The inherent SNR and CNR of the abdominal contents are usually excellent due to their high proton density, and the use of a torso array coil increases this even further. In addition, parallel imaging techniques using multi-array coils reduce scan times significantly. Spatial resolution is also important, especially when imaging relatively small structures such as the pancreas that require thin slices/gap. However, good resolution is often difficult to achieve when using the body coil and a large FOV, and in the presence of respiratory and flow artefact. A torso phased array coil greatly improves the SNR that can then be traded for resolution. In addition, parallel imaging techniques can be used to improve resolution while keeping scan times short. SE sequences usually produce the best contrast in this region but result in fairly lengthy scan times, and therefore, FSE is usually used.

Artefact problems

The main source of artefact in this region is from respiratory and flow motion in the aorta and IVC. When possible, the scan should be performed with the patient holding their breath. The patient should get clear instructions on the breath-hold technique. In cases of breath-hold difficulty, a short period of hyperventilation before breath-holding may be helpful. The scan should be performed during expiration because the kidney position is more constant in expiration than in inspiration. If the sequence is too long to perform in one breath-hold, RC or respiratory triggering is often required and significantly reduces respiratory ghosting. Another technique of respiratory motion control is respiratory gating by use of a navigator. Spatial pre-saturation pulses placed S and I to the FOV are necessary to reduce flow motion artefact in the aorta and IVC. GMN also minimizes flow motion, but as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences. Additional shimming may be required before tissue suppression sequences. Gastric and bowel motion is also troublesome in this area due to the proximity of the stomach and the duodenum to the pancreas. This artefact is effectively reduced by the administration of antispasmodic agents given IV, IM or subcutaneously prior to the examination.

Patient considerations

Careful explanation is essential if breath-holding sequences are to be performed. Some antispasmodics given IM may cause nausea, which can be remedied by giving the patient fruit juice after the scan. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is often necessary in conjunction with dynamic imaging to visualize small pancreatic lesions. Positive and negative oral contrast agents to delineate bowel, and therefore the pancreas, can be useful. Recently, studies have been performed using secretin as an enhancement agent. This stimulates the release of fluid into the pancreatic duct, thereby improving visualization on T2-weighted images. There may also be a role for secretin in the evaluation of pancreatic function.

Vascular imaging

Common indications

- Preoperative assessment of aortic thrombus, occlusion, stenosis and dissection
- Demonstration of major vascular anomalies
- Portal or hepatic vein thrombosis
- Evaluation of hepatic vascular anatomy prior to tumour resection
- Renal vein thrombosis
- Assessment of vasculature prior to and after renal transplantation

Equipment

- Body coil/volume torso array/multi-array coil
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch and is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the third lumbar vertebra, or the lower costal margin.

For localized imaging, the horizontal alignment light passes through the vessel to be imaged.

Suggested protocol

MRA is now a well-established technique but has its limitations. Coronal or sagittal breath-hold incoherent (spoiled) GRE localizers may be followed by axial 2D or 3D TOF-MRA that are then reconstructed in a number of planes. Although 2D TOF-MRA provides coverage, venetian blind artefact and poor resolution reduce image quality. 3D TOF-MRA provides better resolution but less coverage (see *Pulse sequences* in Part 1). Therefore, alternative methods of visualizing abdominal vascular anatomy such as breath-hold incoherent (spoiled) GRE T1 imaging before, during and after administration of a bolus of contrast and SE black-blood and GRE bright-blood sequences are important.

CE-MRA of the abdominal aorta and renal arteries is a well-established technique. A small bolus of gadolinium is given via cannula in the ante-cubital fossa, the acquisition timed to the arrival of the bolus in the area of interest (see *Dynamic imaging* in Part 1). Fast incoherent (spoiled) GRE is the sequence of choice and the coronal plane is used (Figure 11.22).

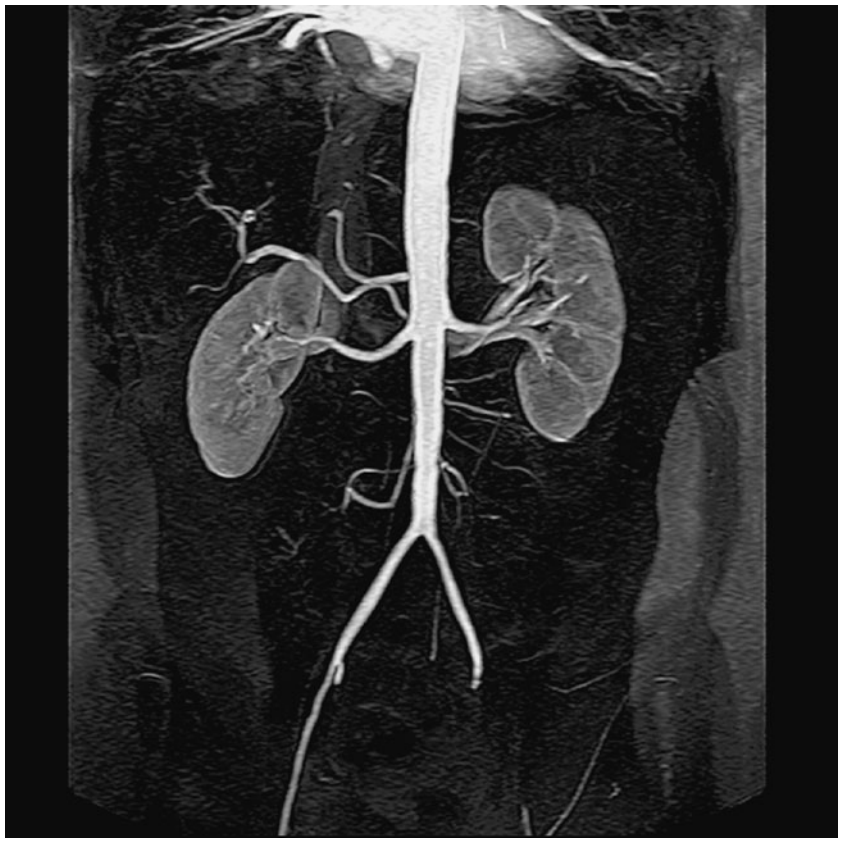

Figure 11.22 Coronal breath-hold incoherent (spoiled) GRE T1-weighted image during dynamic contrast enhancement.

When used in conjunction with SE sequences, spatial pre-saturation pulses produce black blood. If a signal persists in a vessel, it may indicate either slow flow or occlusion. When used in conjunction with GRE sequences, GMN produces bright blood. If a signal void is seen within the vessel, it may indicate either slow flow or occlusion.

Due to recent events involving NSF and gadolinium, several manufacturers have developed non-contrast-enhanced MRA techniques based on steady-state sequences like BGRE. Contrast is produced by utilizing a spatially selective inversion pulse to suppress stationary tissue within the imaging volume. This pulse also suppresses signal from the blood in the imaging volume such as the venous blood (Inhance Inflow IR, syngo NATIVE and B-TRANCE).

Other non-contrast-enhanced techniques utilize a 3D FSE in which the contrast mechanism for visualizing vessels is based on the difference in intravascular signal between maximal and minimal flow during the cardiac cycle. In a diastolic image, both arteries and veins are bright. In a systolic image, arteries appear dark due to dephasing of the signal in the fast flowing blood and veins are bright. Therefore, in the subtracted image, only the arteries are visible (syngo NATIVE SPACE and TRANCE).

Image optimization

Technical issues

The SNR and CNR in vascular imaging of the abdomen are improved by the use of phased array coils. In addition, parallel imaging techniques allow for reduced scan times or improved resolution. However, when contrast enhancement is used, images can be acquired rapidly at the expense of SNR and CNR, as gadolinium provides enough contrast to visualize vessel structure. Additional options, such as centric k-space filling or propeller imaging (where k-space is filled in rotating strips), permit improved temporal resolution when the contrast agent is in the imaging volume.

If conventional MRA is used, to optimize vessel contrast on TOF-MRA sequences, spatial pre-saturation bands are placed S to the FOV to visualize the IVC, and I to the FOV to demonstrate the aorta. Vessel conspicuity is increased by the implementation of GMN, which increases signal in vessels, and MT, which suppresses background signal (see *Pulse sequences* in Part 1).

When using BGRE sequences with an inverting pulse, the inversion time (TI) determines how much and how far fresh blood enters into the imaging volume. However, as TI also influences background suppression, the operator can optimize the TI to control the preferred balance between vessel visibility and background suppression. The optimal TI depends on the manufacturer, so it is important to read their literature.

Artefact problems

Respiratory motion is a potential source of artefact in these examinations. Venetian blind artefact, commonly seen in 2D TOF-MRA sequences, is also caused by respiration and pulsatile flow (see *Vascular imaging* in Part 1). The implementation of breath-hold techniques is often, therefore, necessary. Gated TOF-MRA and the utilization of travelling pre-saturation bands may be implemented to reduce pulsatile artefacts.

Patient considerations

Due to excessively loud gradient noise associated with some sequences, earplugs/headphones must always be provided to prevent hearing impairment.

Contrast usage

The use of MRA, in conjunction with contrast enhancement to improve image quality, is an important technique. Enhancing agents shorten the T1 of blood, thereby increasing vessel contrast in sequences that are

sensitive to T1. In addition, agents that remain in the blood for delayed vascular imaging (blood pool agents) are sometimes used. For contrast-enhanced MRA studies, early acquisitions demonstrate the arterial phase, mid-term acquisitions the capillary phase and later acquisitions the venous phase. Therefore, timing of each acquisition after injection is important. This is usually automated by the system where data acquisition is triggered by an increase in signal detected by a navigator as the gadolinium arrives in the aorta.

Key points

- The inherent SNR and CNR of the abdominal contents are usually excellent due to their high proton density, and the use of a torso array coil increases this even further. In addition, parallel imaging techniques using multi-array coils reduce scan time significantly.
- The liver is the most MR-imaged organ in the abdomen, which is hindered by respiratory, flow and peristaltic artefacts. Careful explanation of the procedure and breath-holding is therefore important.
- Contrast usage is quite common to investigate liver pathology.
- Chemical shift artefact is often troublesome in the kidneys, especially at higher field strengths. This is due to retroperitoneal fat being adjacent to fluid-filled kidneys. Narrowing receive bandwidth, in conjunction with fat suppression techniques, results in a significant improvement in SNR and a reduction in chemical shift and is employed in T2W sequences.
- For vascular imaging, several manufacturers have developed non-contrast-enhanced MRA techniques based on steady-state sequences like BGRE.

12 Pelvis

Handbook of MRI Technique, Fourth Edition. Catherine Westbrook.

Companion website: www.wiley.com/go/westbrook/mritechnique

Table 12.1 Summary of parameters

1.5T		3T	
SE		**SE**	
Short TE	Min–30 ms	Short TE	Min–15 ms
Long TE	70 ms+	Long TE	70 ms+
Short TR	600–800 ms	Short TR	600–900 ms
Long TR	2000 ms+	Long TR	2000 ms+
FSE		**FSE**	
Short TE	Min–20 ms	Short TE	Min–15 ms
Long TE	90 ms+	Long TE	90 ms+
Short TR	400–600 ms	Short TR	600–900 ms
Long TR	4000 ms+	Long TR	4000 ms+
Short TEL	2–6	Short TEL	2–6
Long ETL	16+	Long ETL	16+
IR T1		**IR T1**	
Short TE	Min–20 ms	Short TE	Min–20 ms
Long TR	3000 ms+	Long TR	300 ms+
TI	200–600 ms	TI	Short or null time of tissue
Short ETL	2–6	Short ETL	2–6
STIR		**STIR**	
Long TE	60 ms+	Long TE	60 ms+
Long TR	3000 ms+	Long TR	3000 ms+
Short TI	100–175 ms	Short TI	210 ms
Long ETL	16+	Long ETL	16+
FLAIR		**FLAIR**	
Long TE	80 ms+	Long TE	80 ms+
Long TR	9000 ms+	Long TR	9000 ms + (TR at least 4 × TI)
Long TI	1700–2500 ms (depending on TR)	Long TI	1700–2500 ms (depending on TR)
Long ETL	16+	Long ETL	16+
Coherent GRE		**Coherent GRE**	
Long TE	15 ms+	Long TE	15 ms+
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Incoherent GRE		**Incoherent GRE**	
Short TE	Minimum	Short TE	Minimum
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Balanced GRE		**Balanced GRE**	
TE	Minimum	TE	Minimum
TR	Minimum	TR	Minimum
Flip angle	>40°	Flip angle	>40°
SSFP		**SSFP**	
TE	10–15 ms	TE	10–15 ms
TR	<50 ms	TR	<50 ms
Flip angle	20–40°	Flip angle	20–40°

(*Continued*)

Table 12.1 (*Contd.*)

1.5T and 3T			
Slice thickness 2D		**Slice thickness 3D**	
Thin	2–4 mm	Thin	<1 mm
Medium	5–6 mm	Thick	>3 mm
Thick	8 mm		
FOV		**Matrix**	
Small	<18 cm	Coarse	256×128/256×192
Medium	18–30 cm	Medium	256×256/512×256
Large	>30 cm	Fine	512×512
		Very fine	>1024×1024
NEX/NSA		**Slice number 3D**	
Short	1	Small	<32
Medium	2–3	Medium	64
Multiple	>4	Large	>128
PC-MRA 2D and 3D		**TOF-MRA 2D**	
TE	Minimum	TE	Minimum
TR	25–33 ms	TR	28–45 ms
Flip angle	30°	Flip angle	40–60°
VENC venous	20–40 cm/s	**TOF-MRA 3D**	
VENC arterial	60 cm/s	TE	Minimum
		TR	25–50 ms
		Flip angle	20–30°

The figures given are for 1.5T and 3T systems. Parameters are dependent on field strength and may need adjustment for very low or very high field systems

Male pelvis

Basic anatomy (Figure 12.1)

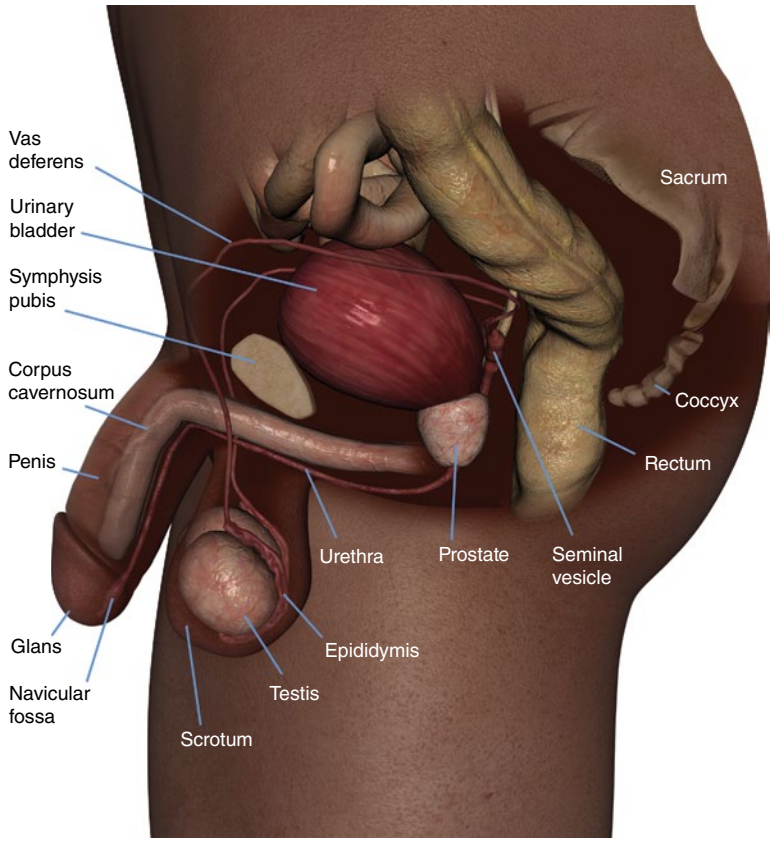

Figure 12.1 Sagittal section through the male pelvis showing midline structures.

Common indications

- Localization of undescended testicles
- Prostatic lesions
- Carcinoma of the bladder
- Rectal lesions
- Infertility
- Impotence

Equipment

- Body coil/phased array pelvic coil/multi-array coil and local rectal coil for prostate imaging (can be used in conjunction with a phased/multi-array coil)

- Compression bands and foam immobilization pads
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch. Foam pads and compression bands can be applied across the patient's lower pelvis to reduce respiratory and bowel motion (unless the patient cannot tolerate this). The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through a point midway between the pubis symphysis and the iliac crests. If a local rectal coil is used, it should be carefully inserted prior to the examination. Ensure that it is correctly positioned and fully inflated.

Suggested protocol

Coronal breath-hold fast incoherent (spoiled) GRE/SE/FSE T1 (Figure 12.2)

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Thick slices/gaps are prescribed from the coccyx to the anterior aspect of the pubis symphysis. The area from the pubis symphysis to the iliac crests is included in the image.

P 60 mm to A 60 mm

Sagittal localizers used in conjunction with a large FOV are useful to confirm the correct positioning of a rectal coil and to demonstrate nodes and bony metastases in patients with suspected prostatic carcinoma.

L 25 mm to R 25 mm

Sagittal SE/FSE T2

Demonstrates organs that lie in the midline (bladder, rectum, prostate, penis). Medium or thick slices/gaps are prescribed from the left to the right pelvic side walls (Figure 12.3). Unless lymph node involvement is suspected, small structures such as the prostate require high-resolution imaging using the rectal coil and thin slices/gap prescribed through the ROI only. Tissue suppression pulses are often necessary when using FSE sequences.

Axial SE/FSE T2 (Figure 12.4)

Demonstrates organs that lie laterally (lymph nodes). Medium or thick slices/gaps are prescribed from the pelvic floor to the iliac crests (Figure 12.5). Unless lymph node involvement is suspected, small structures such as the prostate require high-resolution imaging using the rectal coil and thin slices/gap prescribed through the ROI only. Tissue suppression pulses are often necessary when using FSE sequences.

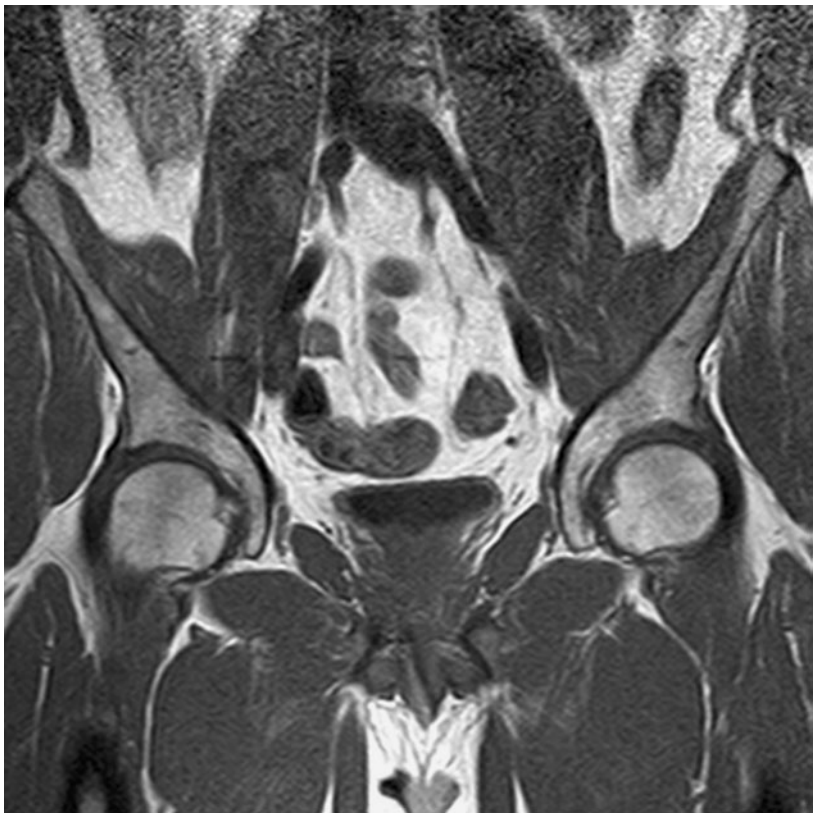

Figure 12.2 Coronal FSE T1-weighted image through the male pelvis.

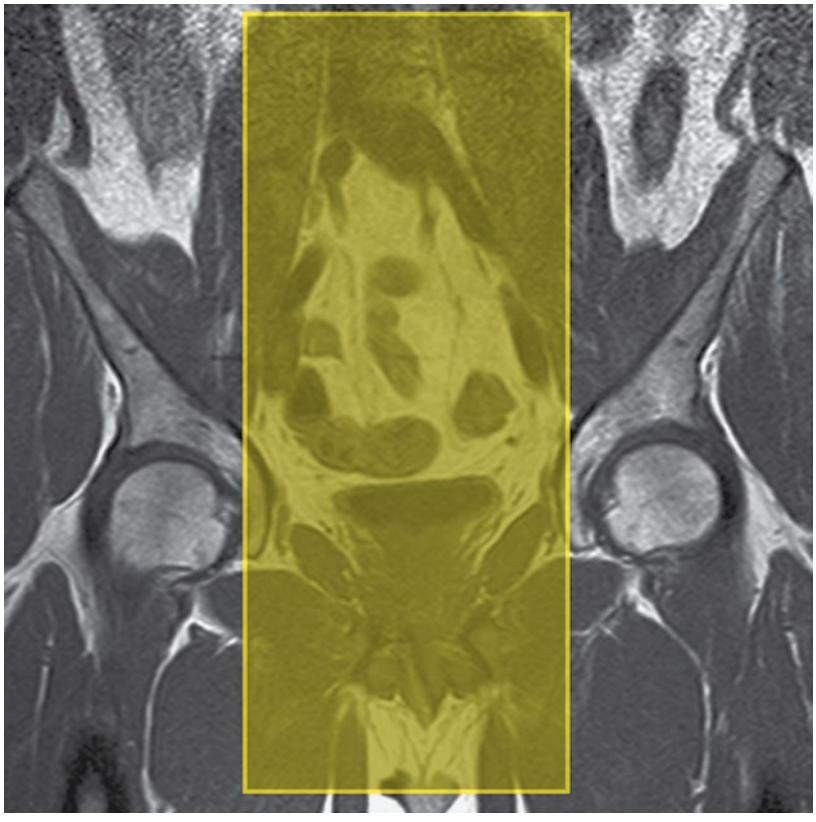

Figure 12.3 Coronal FSE T1-weighted image through the male pelvis to show slice prescription boundaries and orientation for sagittal imaging.

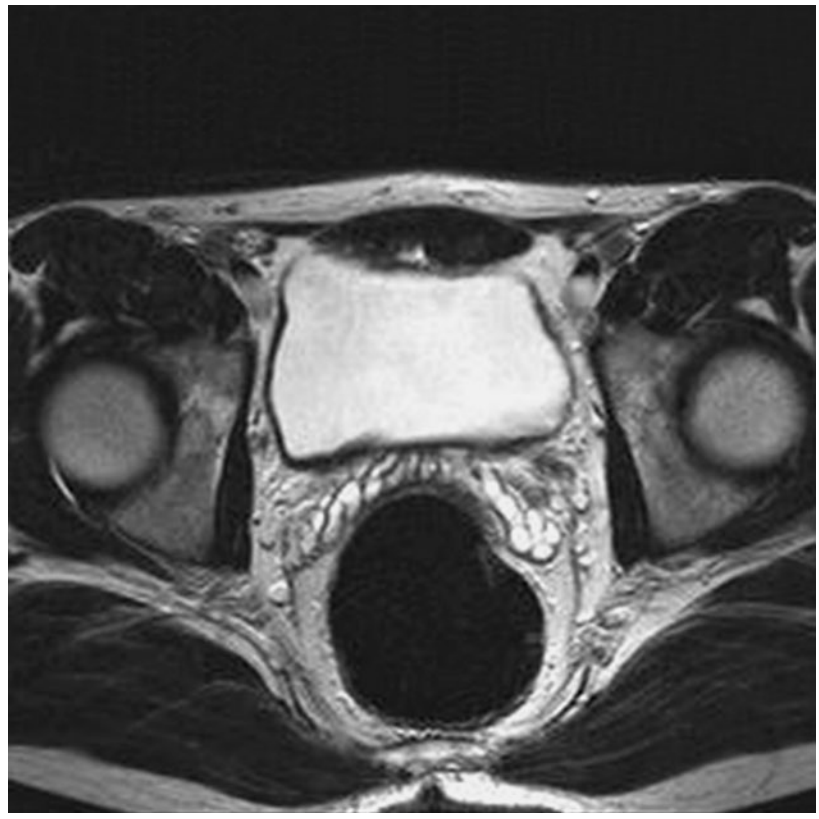

Figure 12.4 Axial FSE T2-weighted image through a normal male pelvis (rectal coil in situ).

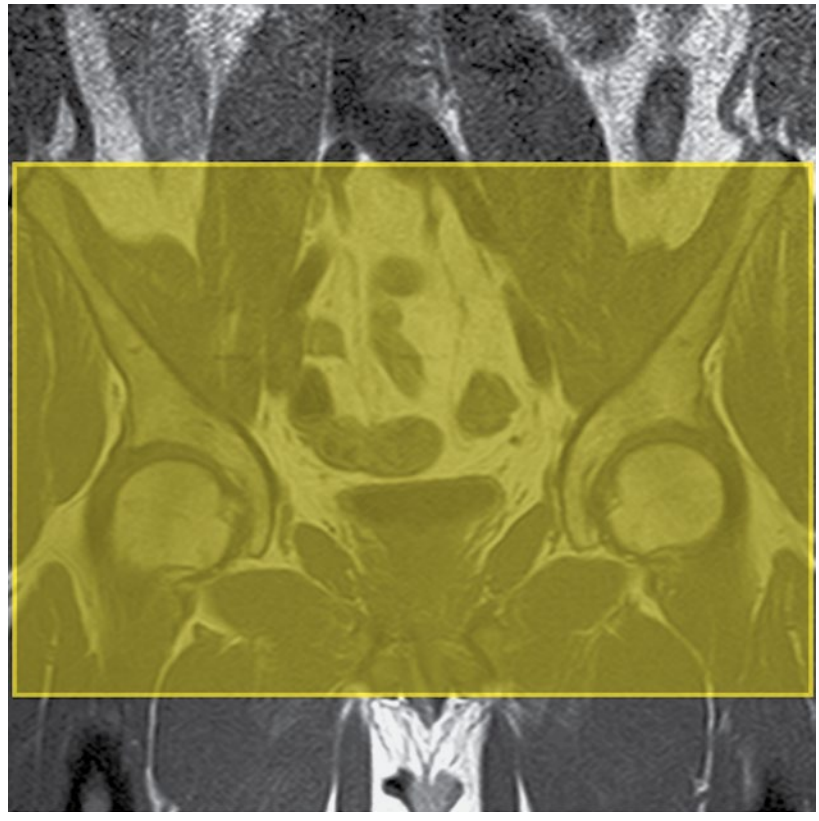

Figure 12.5 Coronal FSE T1-weighted image through the male pelvis to show slice prescription boundaries and orientation for axial imaging.

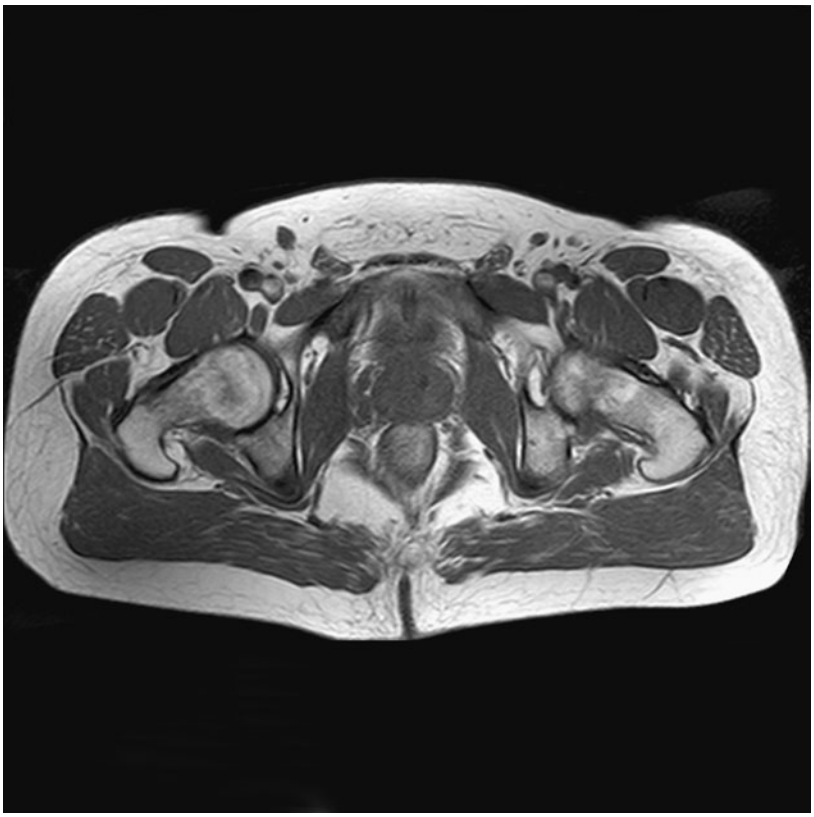

Figure 12.6 Axial FSE T1-weighted image of a normal male pelvis.

Axial SE/FSE T1 (Figure 12.6)

Slice prescription as for axial T2.

Coronal SE/FSE T2 (Figure 12.7)

Slice prescription as for coronal SE/FSE T1.

Tissue suppression pulses are often necessary when using FSE sequences.

Additional sequences

Fast incoherent (spoiled) GRE T1 +/– contrast (Figure 12.8)

Rapid imaging after contrast allows dynamic evaluation of enhancing pelvic vessels responsible for potency (see *Dynamic imaging* under *Pulse sequences* in Part 1).

SS-FSE/SE-EPI/GRE-EPI/diffusion imaging

Real-time imaging of pelvic organs, especially the prostate, enables biopsies and laser ablations of lesions under MR control. DWI used in conjunction

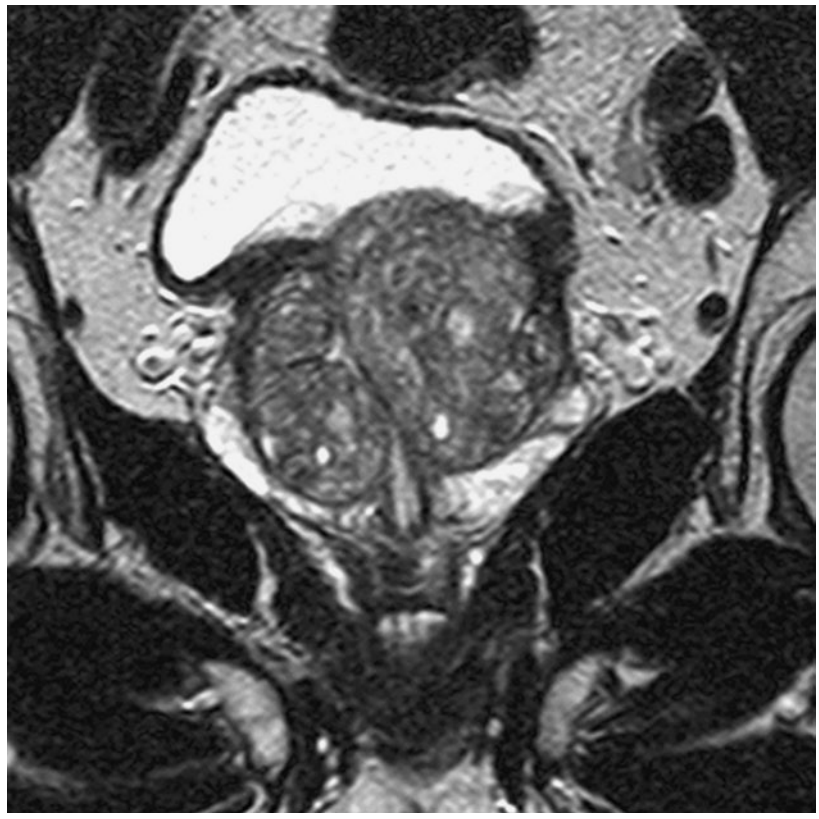

Figure 12.7 Coronal FSE T2-weighted image demonstrating an abnormal prostate gland.

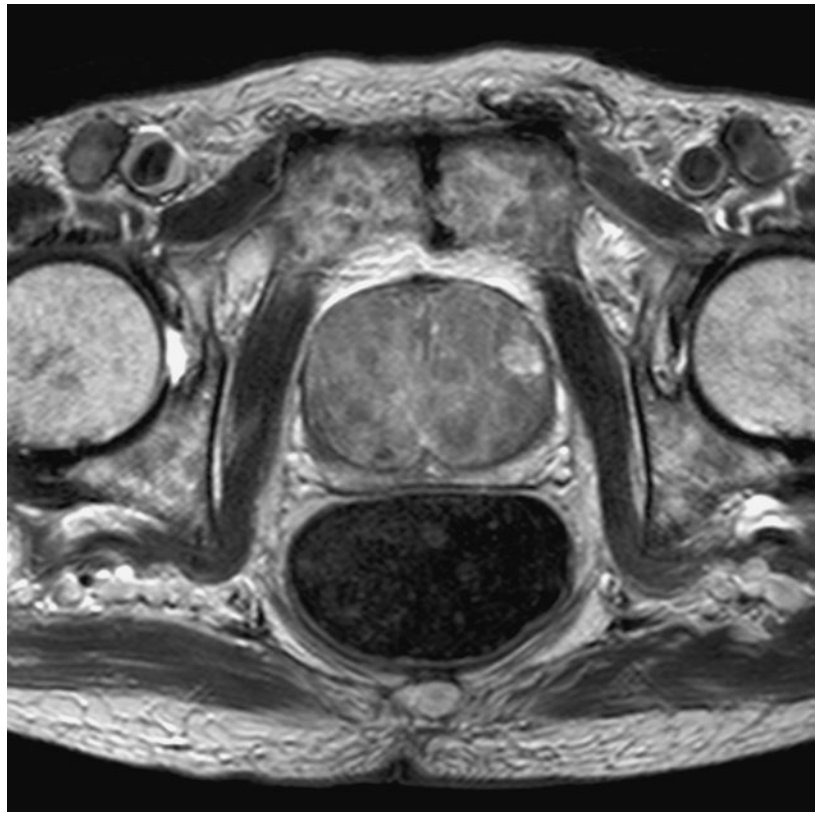

Figure 12.8 Incoherent (spoiled) GRE T1 of the prostate using a rectal coil.

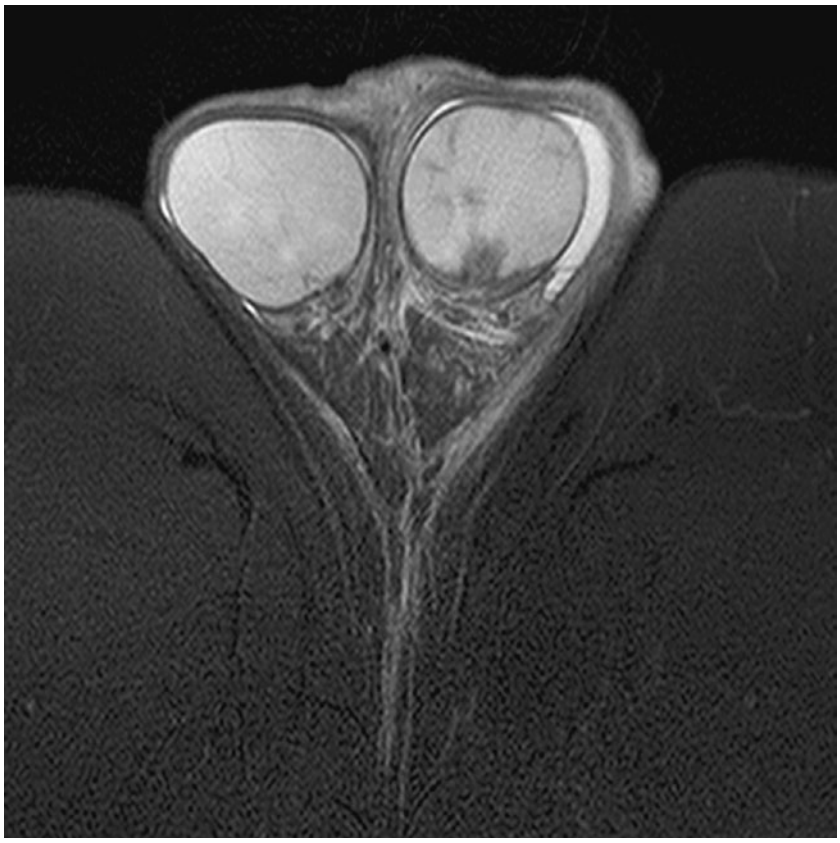

Figure 12.9 Axial FSE T2-weighted image of the scrotum acquired with a surface coil. This was performed for the evaluation of testicular carcinoma.

with parallel imaging techniques is proving useful in the differentiation of malignant from benign lesions especially in the prostate gland. In addition, small FOV high-resolution images of the scrotum may be useful for the evaluation of testicular carcinoma (Figure 12.9).

Image optimization

Technical issues

The pelvis offers excellent SNR and contrast, especially when phased array, multi-array or local rectal coils are used. As a result, spatial resolution is easily obtainable without compromising signal. In addition, the use of parallel imaging techniques can significantly reduce scan times or increase resolution. FSE provides very good results in the pelvis, as respiration and bowel motion are less troublesome than in the abdomen. In addition, a rectangular/asymmetric FOV is routinely implemented with the long axis of the rectangle S to I in the sagittal images, and R to L in the axials. The combination of FSE, a rectangular/asymmetric FOV, and local or phased array or multi-array coils (where a small FOV is implemented) enables the acquisition of very fine matrix sizes in conjunction with a short scan time.

Oversampling is sometimes not available with a rectangular/asymmetric FOV. If so, ensure that the FOV is large enough to incorporate the whole of the pelvis, or apply spatial pre-saturation bands A and P to reduce aliasing. If SE is selected, a fine matrix may still be utilized to provide good spatial resolution and a fairly short scan time. Fat suppression techniques are often beneficial, especially on FSE T2 images.

Artefact problems

Bowel motion is reduced by compression and administering antispasmodic agents IV, IM or subcutaneously prior to the examination. Compression also reduces respiratory motion by encouraging the patient to breathe from their upper abdomen and chest, rather than their pelvis. Spatial pre-saturation pulses applied S and I to the FOV reduce flow motion artefact in the IVC, aorta and iliac vessels. GMN further reduces flow artefact, but as it increases signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences. Additional shimming may be required before tissue suppression sequences.

When imaging with a local rectal coil, rectal spasm commonly causes artefact. The phase and frequency axes are swapped on the sagittal and axial images so that this artefact does not obscure the prostate. In addition, oversampling is often necessary on these small FOV images, as anatomy exists outside the FOV in the phase direction, but within the signal-producing volume of the coil.

Patient considerations

The patient should fast for at least 4 h and empty the bladder and bowel just before the examination to reduce blurring from motion artefacts and ghosting due to bowel peristalsis and bladder motion. Some patients may not be able to tolerate compression, especially if they have had recent abdominal surgery. Compression can also make a claustrophobic patient feel more trapped. Under these circumstances, placing the patient prone has the same (albeit lesser) effect as compression. In addition, if the ROI lies posteriorly (e.g. fistulae in the buttocks), placing the patient prone positions the ROI nearer to magnetic isocentre, thereby increasing image quality. Some antispasmodic agents given IM may cause nausea, but fruit juice given after the study can alleviate this. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast may be given to enhance the conspicuity of certain lesions, especially in examinations of the prostate, pelvis masses and vasculature. Oral or rectal contrast agents including air (administered carefully) to label and demonstrate the rectum and lower gastrointestinal tract are sometimes used.

Female pelvis

Basic anatomy (Figure 12.10)

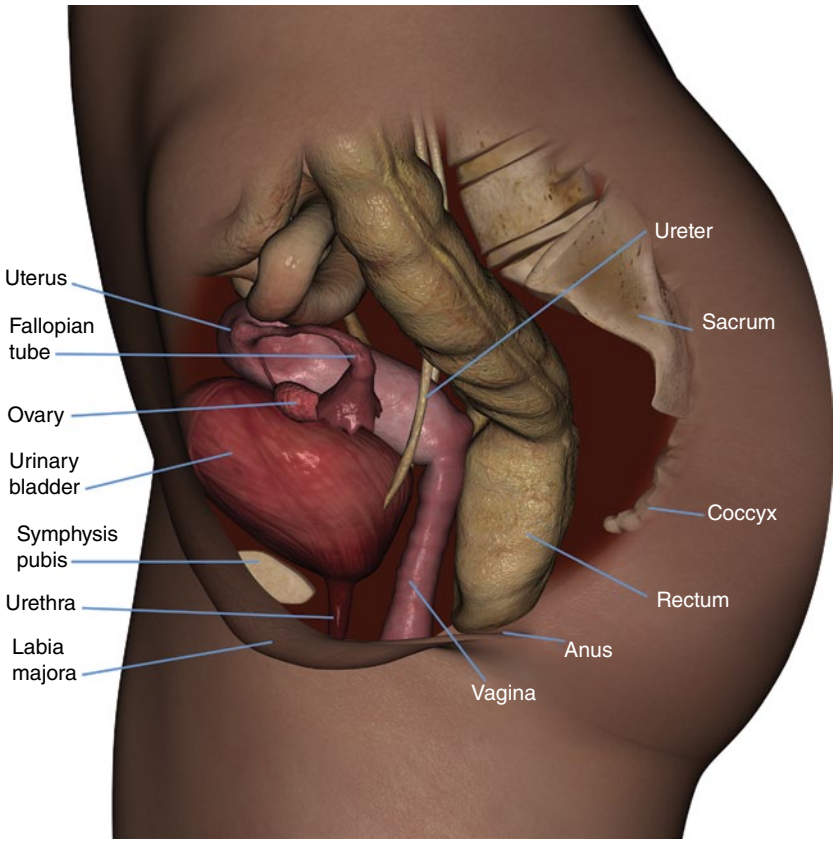

Figure 12.10 Sagittal section through the female pelvis showing midline structures.

Common indications

- Assessment of congenital abnormalities of the urogenital tract
- Cervical lesions
- Uterine lesions
- Benign uterine tumours, for example, leiomyoma and fibroids
- Bladder lesions
- Rectal lesions
- Infertility

Equipment

- Body coil/phased array pelvic coil/multi-array coil
- Compression bands and foam immobilization pads if using the body coil
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch. Foam pads and compression bands can be applied across the patient's lower pelvis to reduce respiratory and bowel motion (unless the patient cannot tolerate this). The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through a point midway between the pubis symphysis and the iliac crest. If a local rectal coil is used, it should be carefully inserted prior to the examination. Ensure that it is correctly positioned and fully inflated.

Suggested protocol

Coronal breath-hold fast incoherent (spoiled) GRE/SE/FSE T1

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Thick slices/gaps are prescribed from the coccyx to the anterior aspect of the pubis symphysis. The area from the pubis symphysis to the iliac crests is included in the image.

P 60 mm to A 60 mm

Sagittal localizers are useful to confirm the correct positioning of a rectal coil and to evaluate the uterus.

L 25 mm to R 25 mm

Sagittal SE/FSE T2 (Figures 12.11 and 12.12)

Demonstrates organs that lie in the midline (bladder, uterus, rectum, cervix). Medium or thick slices/gaps are prescribed from the left to the right pelvic side walls (see Figure 12.3). Unless lymph node involvement is suspected, small structures such as the cervix require high-resolution imaging using the rectal coil and thin slices/gap prescribed through the ROI only. Tissue suppression pulses are often necessary when using FSE sequences.

Axial SE/FSE T2

Demonstrates organs that lie laterally (ovaries, lymph, nodes). Medium or thick slices/gaps are prescribed from the pelvic floor to the iliac crests (see Figure 12.5). Unless lymph node involvement is suspected, small structures such as the cervix require high-resolution imaging using the rectal coil and thin slices/gap prescribed through the ROI only. Tissue suppression pulses are often necessary when using FSE sequences.

Axial SE/FSE T1 (+/– tissue suppression)

Slice prescription as for axial T2. The fat-saturated T1WI sequence is specifically necessary to characterize fat or haemorrhage within the adnexa when there is a clinical suspicion of dermoid or endometriosis.

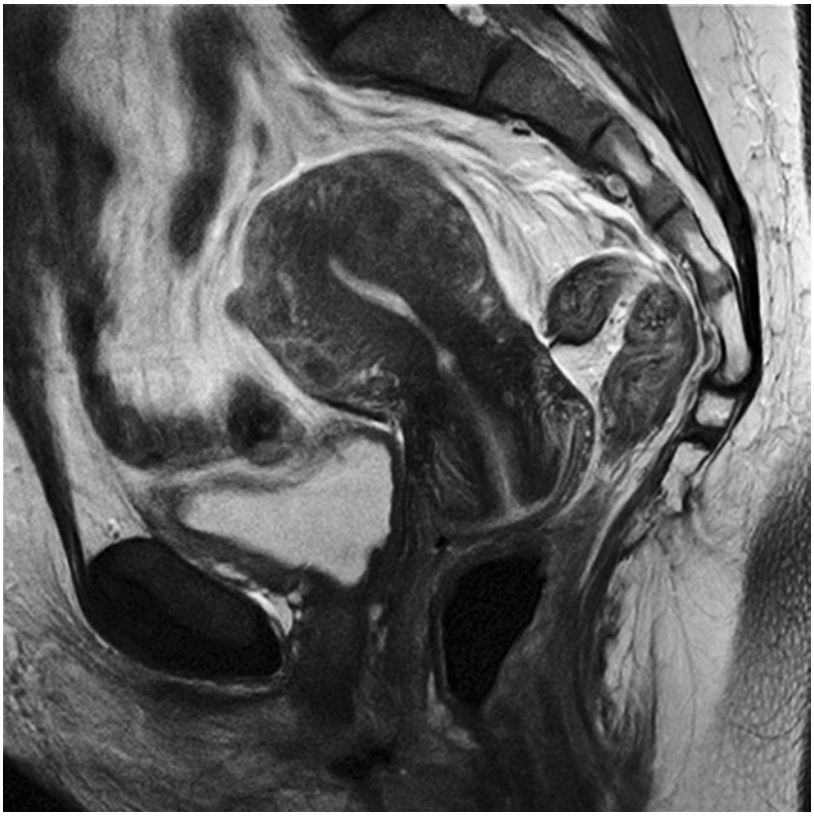

Figure 12.11 Sagittal FSE T2-weighted image through a female pelvis.

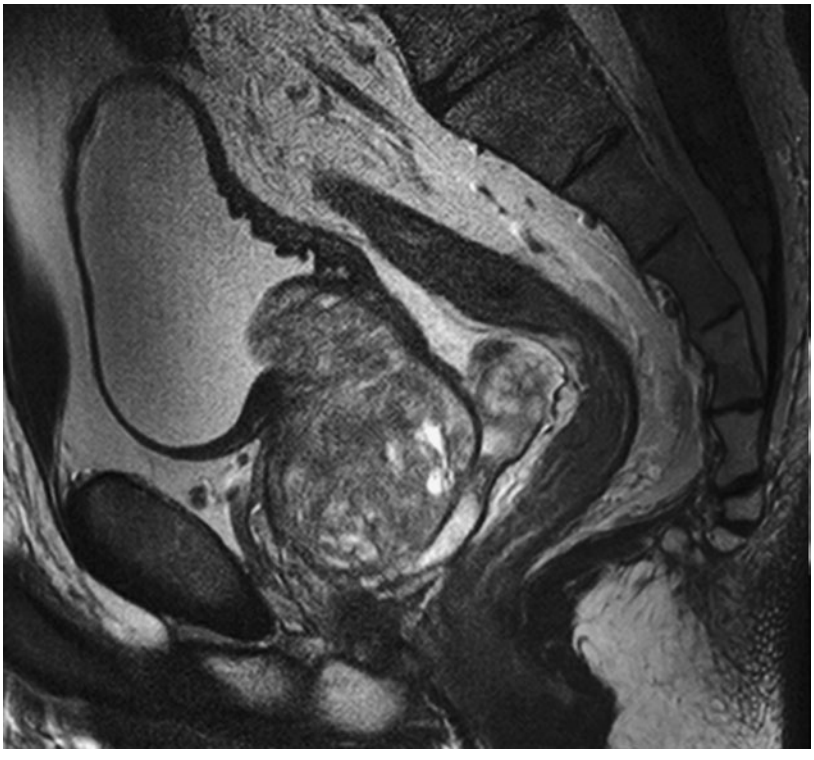

Figure 12.12 Sagittal FSE T2-weighted image demonstrating a large mass in the cervix. In this case, the lesion has obstructed the endometrial cavity, causing distension.

Coronal SE/FSE T2

Slice prescription as for coronal SE/FSE T1.

Tissue suppression pulses are often necessary when using FSE sequences.

Additional sequences

SS-FSE/GRE-EPI/SE-EPI/diffusion imaging

Real-time imaging enables biopsies and laser ablations of lesions under MR control. In addition, cine imaging of the uterus is useful to evaluate uterine contractility in a variety of disorders, and this technique may be used to evaluate the pelvic floor. DWI, which may be used in conjunction with parallel imaging techniques, may be used to differentiate malignant from benign lesions and to evaluate tumour response to therapy.

Image optimization

Technical issues

The pelvis offers excellent SNR and contrast, especially when phased array, multi-array or local rectal coils are used. As a result, spatial resolution is easily obtainable without compromising signal. In addition, the use of parallel imaging techniques can significantly reduce scan times or increase resolution. FSE provides very good results in the pelvis, as respiration and bowel motion are less troublesome than in the abdomen. In addition, a rectangular/asymmetric FOV is routinely implemented with the long axis of the rectangle S to I in the sagittal images, and R to L in the axials. The combination of FSE, a rectangular/asymmetric FOV, and local or phased array coils (where a small FOV is implemented) enables the acquisition of very fine matrix sizes in conjunction with a short scan time. T2 weighting is optimal for evaluating the structure of the uterus.

On some systems, oversampling is not available with a rectangular/asymmetric FOV. If so, ensure that the FOV is large enough to incorporate the whole of the pelvis, or apply spatial pre-saturation bands A and P to reduce aliasing. If SE is selected, a fine matrix may still be utilized to provide good spatial resolution and a fairly short scan time. Fat suppression techniques are often beneficial especially on FSE T2 images where fat and pathology return a similar signal.

Artefact problems

Bowel motion is reduced by compression and administering antispasmodic agents IV, IM or subcutaneously prior to the examination. Compression also reduces respiratory motion by encouraging the patient to breathe from their upper abdomen and chest, rather than their pelvis. Spatial pre-saturation pulses applied S and I to the FOV reduce flow

motion artefact in the IVC, aorta and iliac vessels. GMN further reduces flow artefact, but as it increases signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences. Additional shimming may be required before tissue suppression sequences.

Patient considerations

The patient should fast for at least 4 h and empty the bladder and bowel before the examination to reduce blurring from motion artefacts and ghosting due to bowel peristalsis and bladder motion. Some patients may not be able to tolerate compression, especially if they have had recent abdominal surgery or have large lesions. Compression can also make a claustrophobic patient feel more trapped. Under these circumstances, placing the patient prone has the same (albeit lesser) effect as compression. In addition, if the ROI lies posteriorly (e.g. fistulae in the buttocks), placing the patient prone positions the ROI nearer to the magnetic isocentre, thereby increasing image quality. Some antispasmodic agents given IM may cause nausea, which can be alleviated by giving orange juice after the scan. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast may be given to enhance the conspicuity of certain lesions, especially in the cervix, uterus and ovaries. Dynamic imaging after contrast administration may improve tumour localization and staging and also help in monitoring response to therapy. Oral or rectal contrast agents including air (administered carefully) to label and demonstrate the rectum and lower gastrointestinal tract are sometimes useful.

Obstetrics

Common indications

- Evaluation of pelvic–cephalic disproportion in the second or third trimester of pregnancy, or post-delivery
- Placenta praevia
- Evaluation of pelvic disease incidental to pregnancy and foetal abnormalities

Equipment

- Body coil/multi-coil array
- Compression bands (if tolerable post-partum)
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through a point midway between the pubis symphysis and the iliac crest. Compression should not be applied in pregnancy or immediately post-Caesarean section.

Suggested protocol

Sagittal SE T1

Medium slices/gaps are prescribed on either side of the longitudinal alignment light to include the pubis symphysis and the sacrum. System software can be used to measure pelvic inlet and outlet dimensions.

L 15 mm to R 15 mm

Sagittal/coronal/axial SE/FSE/SS-FSE T1 and T2

As in standard protocol, for pelvic disease incidental to pregnancy and to evaluate foetal abnormalities.

Image optimization

Technical issues

MRI may be used to measure pelvic proportions, and to evaluate pelvic lesions incidental to pregnancy. The purpose of MRI pelvimetry is to

visualize the bony landmarks of the sacrum and the pubis symphysis so that accurate measurements can be made. Good SNR or spatial resolution is, therefore, usually unnecessary and, as these patients may have to be fitted into a busy schedule at short notice, scan time is the most important factor. If the coarsest matrix and lowest NEX/NSA are used, the above protocol takes only 1 or 2 min to acquire.

If examining the pelvis for foetal abnormalities or incidental pelvic disease, good resolution may be difficult to achieve due to foetal movement. Sedation of the foetus by injection of drugs via the umbilical vein may be used to still the foetus if clinically justified. Alternatively, fast sequences such as SS-FSE or BGRE sequences may be utilized very effectively. A rectangular/asymmetric FOV improves resolution, although the bulk of the abdomen in the AP axis may cause aliasing.

Artefact problems

Foetal and bowel motion may interfere with the image, but not usually enough to obscure the bony landmarks necessary for pelvimetry measurements. Spatial pre-saturation pulses placed S and I to the FOV reduce flow in the aorta and IVC. Take great care if placing pre-saturation bands over the foetus as these increase the RF deposition within the infant. Minimizing the scan time is the best way of diminishing the effect of foetal movement in the image. Respiratory artefact is occasionally troublesome but RC is rarely necessary and breath-holding techniques can often be used.

Patient considerations

In most countries, MRI is as yet not indicated in the first trimester of pregnancy as the possible risks are unknown. However, in the second and third trimesters, MRI is often preferred to CT or other imaging modalities that use ionizing radiation. In the United States, the Food and Drug Administration (FDA) approves the use of MR in all three trimesters if MR negates the use of more invasive testing. In the later stages of pregnancy, the patient may feel faint when lying in the supine position from the baby pressing on the IVC. Slightly raising one hip sometimes relieves this, but in pelvimetry studies, it also complicates the calculation of the pelvic size, as the patient is no longer truly sagittal. This is overcome by obliquing the sagittals from a localizer, but this lengthens the scan time due to the extra sequences involved. It is probably advisable to keep the patient supine and complete the scan as quickly as possible, rather than oblique her. Compression should not be used if the patient is pregnant or immediately post-Caesarean section. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not usually given as the effect of the administration of contrast to pregnant and lactating patients has not yet been established.

Key points

- Compression bands (if tolerated) and foam pads are important aids for good diagnostic imaging in pelvic imaging. These reduce respiratory and bowel movement. Antispasmodic drugs are effective in further reducing bowel artefacts.
- Sagittal T2W sequence is the ideal first sequence to assess the majority of the organs lying in the midline of the pelvis.
- Generally, the pelvic protocol would include T2W sequence in all three planes, and T1 GRE sequence in the axial plane for dynamic imagine. T1W SE or FSE can also be used.
- In female pelvic imaging, the fat-saturated T1W sequence is specifically necessary to characterize fat or haemorrhage within the adnexa when there is a clinical suspicion of dermoid or endometriosis.
- DWI, which may be used in conjunction with parallel imaging techniques, is fast becoming a necessary addition to pelvic protocol to differentiate malignant from benign lesions and to evaluate tumour response to therapy.

13 Upper limb

Handbook of MRI Technique, Fourth Edition. Catherine Westbrook.

Companion website: www.wiley.com/go/westbrook/mritechnique

Table 13.1 Summary of parameters

1.5T		3T	
SE		**SE**	
Short TE	Min–30 ms	Short TE	Min–15 ms
Long TE	70 ms+	Long TE	70 ms+
Short TR	600–800 ms	Short TR	600–900 ms
Long TR	2000 ms+	Long TR	2000 ms+
FSE		**FSE**	
Short TE	Min–20 ms	Short TE	Min–15 ms
Long TE	90 ms+	Long TE	90 ms+
Short TR	400–600 ms	Short TR	600–900 ms
Long TR	4000 ms+	Long TR	4000 ms+
Short TEL	2–6	Short TEL	2–6
Long ETL	16+	Long ETL	16+
IR T1		**IR T1**	
Short TE	Min–20 ms	Short TE	Min–20 ms
Long TR	3000 ms+	Long TR	300 ms+
TI	200–600 ms	TI	Short or null time of tissue
Short ETL	2–6	Short ETL	2–6
STIR		**STIR**	
Long TE	60 ms+	Long TE	60 ms+
Long TR	3000 ms+	Long TR	3000 ms+
Short TI	100–175 ms	Short TI	210 ms
Long ETL	16+	Long ETL	16+
FLAIR		**FLAIR**	
Long TE	80 ms+	Long TE	80 ms+
Long TR	9000 ms+	Long TR	9000 ms + (TR at least 4 × TI)
Long TI	1700–2500 ms (depending on TR)	Long TI	1700–2500 ms (depending on TR)
Long ETL	16+	Long ETL	16+
Coherent GRE		**Coherent GRE**	
Long TE	15 ms+	Long TE	15 ms+
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Incoherent GRE		**Incoherent GRE**	
Short TE	Minimum	Short TE	Minimum
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Balanced GRE		**Balanced GRE**	
TE	Minimum	TE	Minimum
TR	Minimum	TR	Minimum
Flip angle	>40°	Flip angle	>40°
SSFP		**SSFP**	
TE	10–15 ms	TE	10–15 ms
TR	<50 ms	TR	<50 ms
Flip angle	20–40°	Flip angle	20–40°

(*Continued*)

Table 13.1 (*Contd.*)

1.5T and 3T			
Slice thickness 2D		**Slice thickness 3D**	
Thin	2–4 mm	Thin	<1 mm
Medium	5–6 mm	Thick	>3 mm
Thick	8 mm		
FOV		**Matrix**	
Small	<18 cm	Coarse	256×128/256×192
Medium	18–30 cm	Medium	256×256/512×256
Large	>30 cm	Fine	512×512
		Very fine	>1024×1024
NEX/NSA		**Slice number 3D**	
Short	1	Small	<32
Medium	2–3	Medium	64
Multiple	>4	Large	>128
PC-MRA 2D and 3D		**TOF-MRA 2D**	
TE	Minimum	TE	Minimum
TR	25–33 ms	TR	28–45 ms
Flip angle	30°	Flip angle	40–60°
VENC venous	20–40 cm/s	**TOF-MRA 3D**	
VENC arterial	60 cm/s	TE	Minimum
		TR	25–50 ms
		Flip angle	20–30°

The figures given are for 1.5T and 3T systems. Parameters are dependent on field strength and may need adjustment for very low or very high field systems.

Shoulder

Basic anatomy (Figure 13.1)

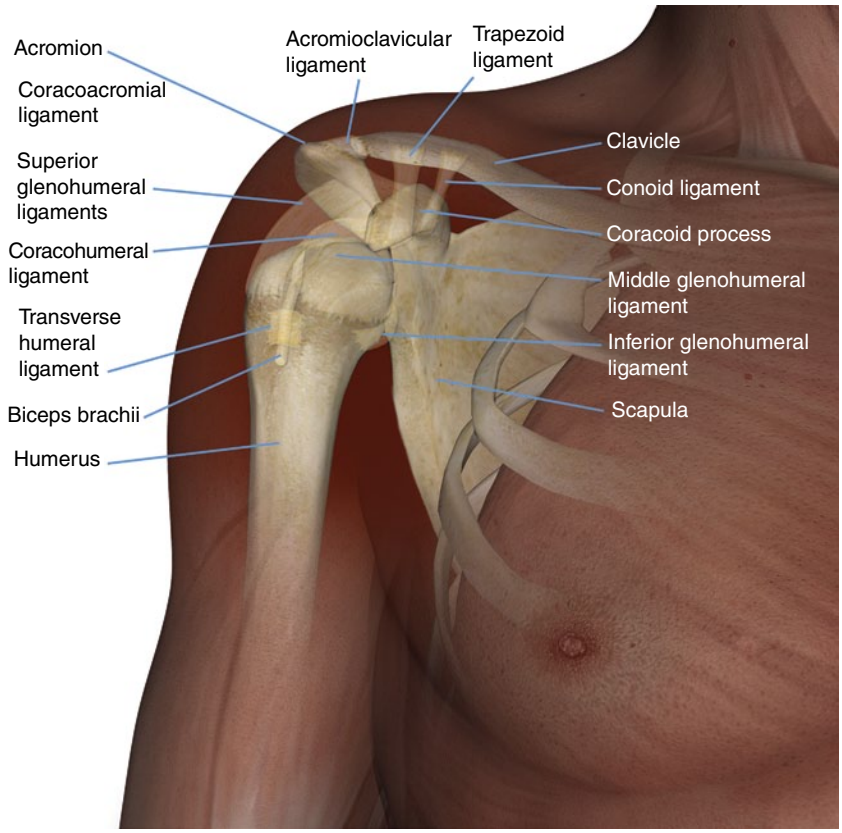

Figure 13.1 Anterior view of the right shoulder showing bony structures and main ligaments.

Common indications

- Evaluation of shoulder pain
- Diagnosis of impingement syndrome
- Suspected rotator cuff tear
- Evaluation of recurrent dislocation (instability, subluxation, dislocation)
- Hill–Sachs lesion, Bankart lesion, labrum lesion
- Frozen shoulder syndrome

Equipment

- Dedicated shoulder coil or flexible surface coil
- Immobilization pads and straps
- Earplugs/headphones

Patient positioning

The patient lies supine with the arms resting comfortably by the side. Slide the patient across the table to bring the shoulder under examination as close as possible to the centre of the bore. Relax the shoulder to remove any upward 'hunching'. The arm to be examined is strapped to the patient, with the thumb up (neutral position) and padded so that the humerus is horizontal. Place the coil to cover the humeral head and the anatomy superior and medial to it. If a surface or flexible coil is used, care must be taken to ensure that the flat surface of the coil is parallel to the Z axis when it is placed over the humeral head (Figure 1.1). Centre the FOV on the middle of the glenohumeral joint. Patient and coil immobilization are essential for a good result. If possible, instruct the patient to breathe abdominally rather than with the thorax and place sandbags on the upper chest. This reduces movement artefact. Instruct the patient not to move the hand during sequences. The patient is positioned so that the longitudinal alignment light and the horizontal alignment light pass through the shoulder joint.

Suggested protocol

Axial/coronal incoherent (spoiled) GRE/SE/FSE T1

Acts as a localizer if three-plane localization is unavailable and ensures that there is adequate signal return from the whole joint. Medium slices/gaps are prescribed relative to the horizontal alignment light so that the supraspinatus muscle is included in the image.

Axial localizer: I 0 mm to S 25 mm

Axial SE/FSE T2 or coherent GRE T2* (Figure 13.2)

Thin slices/gaps are prescribed from the top of the acromio-clavicular joint to below the inferior edge of the glenoid (Figure 13.3). The bicipital groove on the lateral aspect of the humerus to the distal supraspinatus muscle is included in the image. The axial projection displays joint cartilage and glenoid labrum, intra-osseous changes associated with Hills–Sachs deformity, and the condition of muscles and tendons of the rotator cuff.

Coronal/oblique SE/FSE T1 (Figure 13.4)

Thin slices/gaps are prescribed from the infra-spinatus posteriorly to the supraspinatus anteriorly and angled parallel to the supraspinatus muscle (Figures 13.5 and 13.6). This is best seen on a superior axial view, but coverage is easier to assess on an axial image through the lower third of the humeral head. The superior edge of the acromion to the inferior aspect of the subscapularis muscle (about 1 cm below the lower edge of the glenoid), and the deltoid muscle laterally, and the distal third of the supraspinatus muscle medially are included on the image.

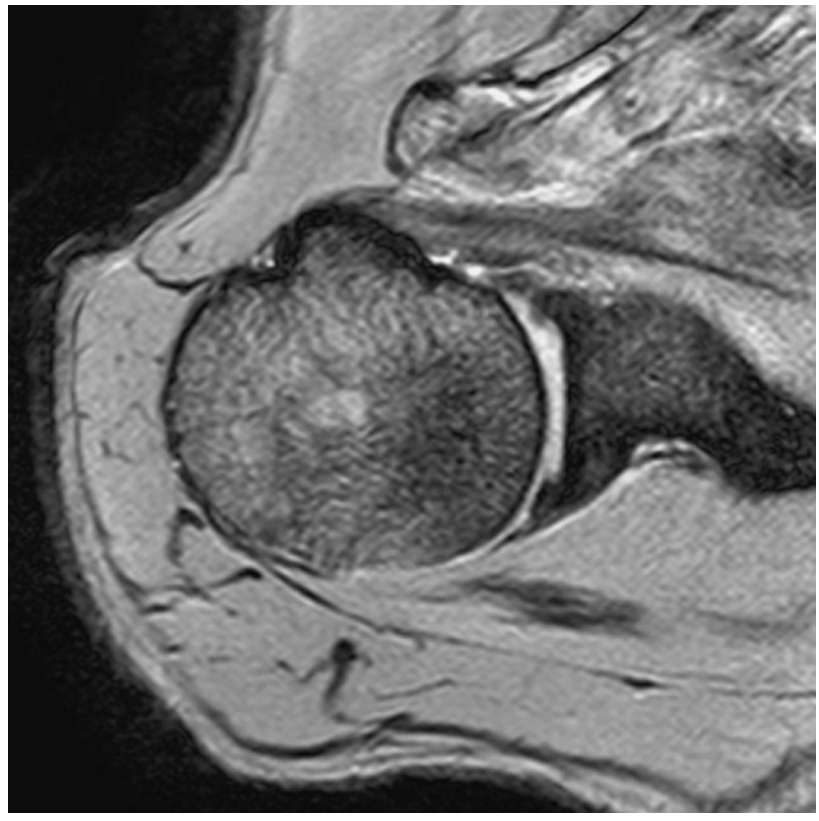

Figure 13.2 Axial GRE T2*-weighted image of the shoulder showing normal appearances.

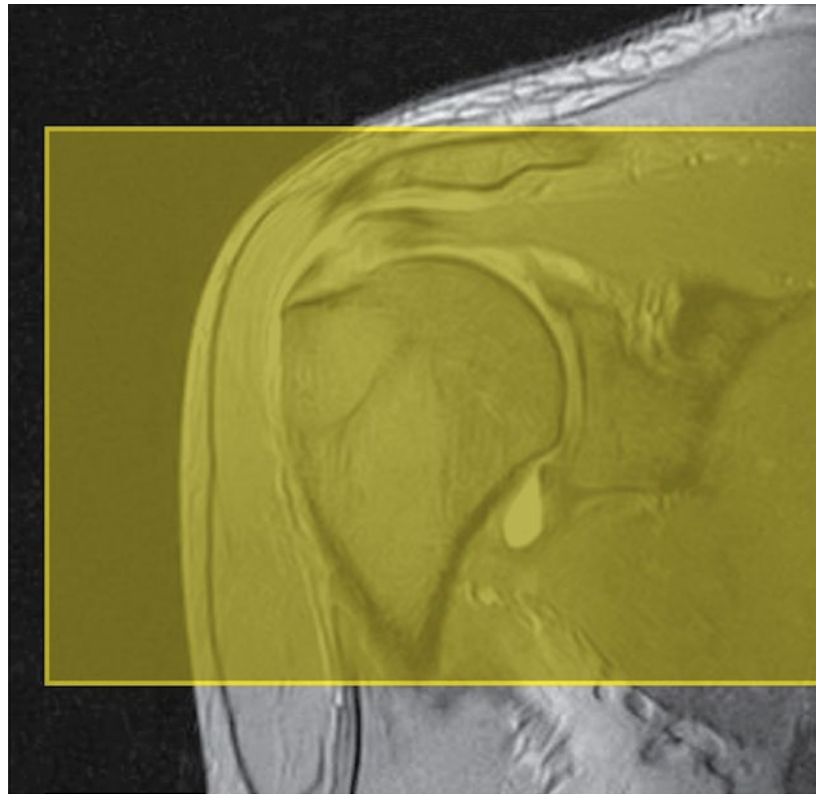

Figure 13.3 Axial GRE T2*-weighted image showing slice prescription boundaries and orientation for axial imaging of the shoulder.

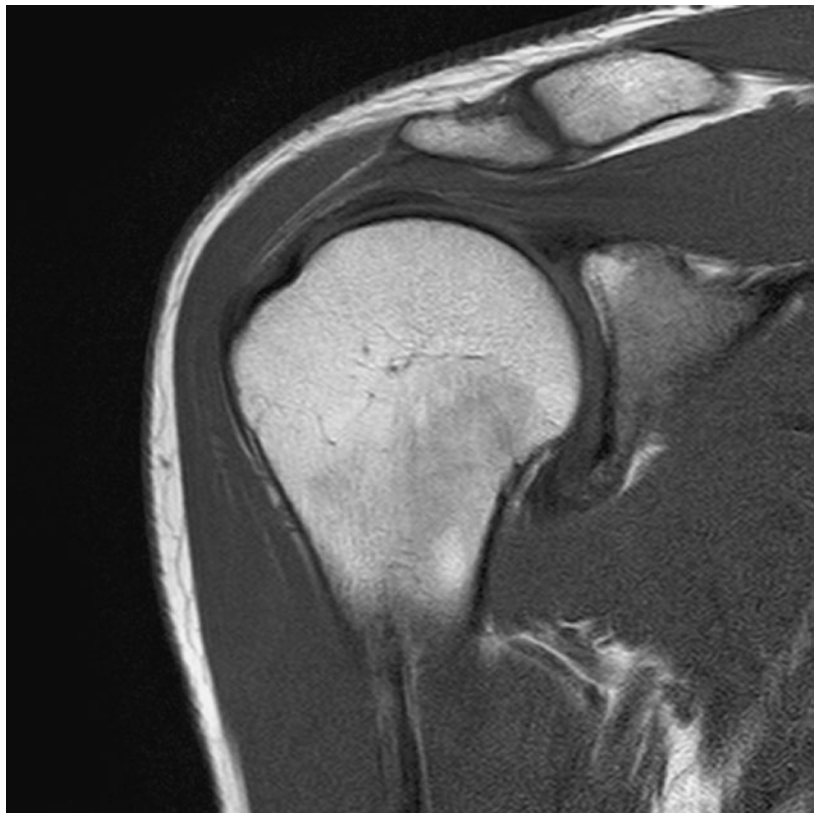

Figure 13.4 Coronal/oblique T1-weighted FSE through the shoulder.

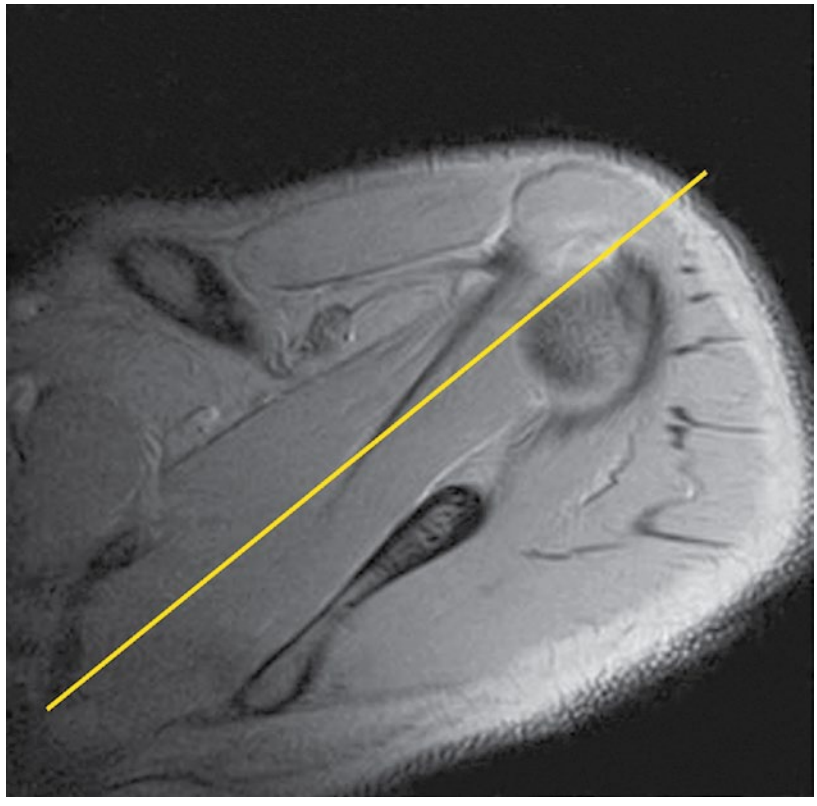

Figure 13.5 Axial SE T1-weighted localizer of the shoulder showing the angle of the supraspinatus muscle.

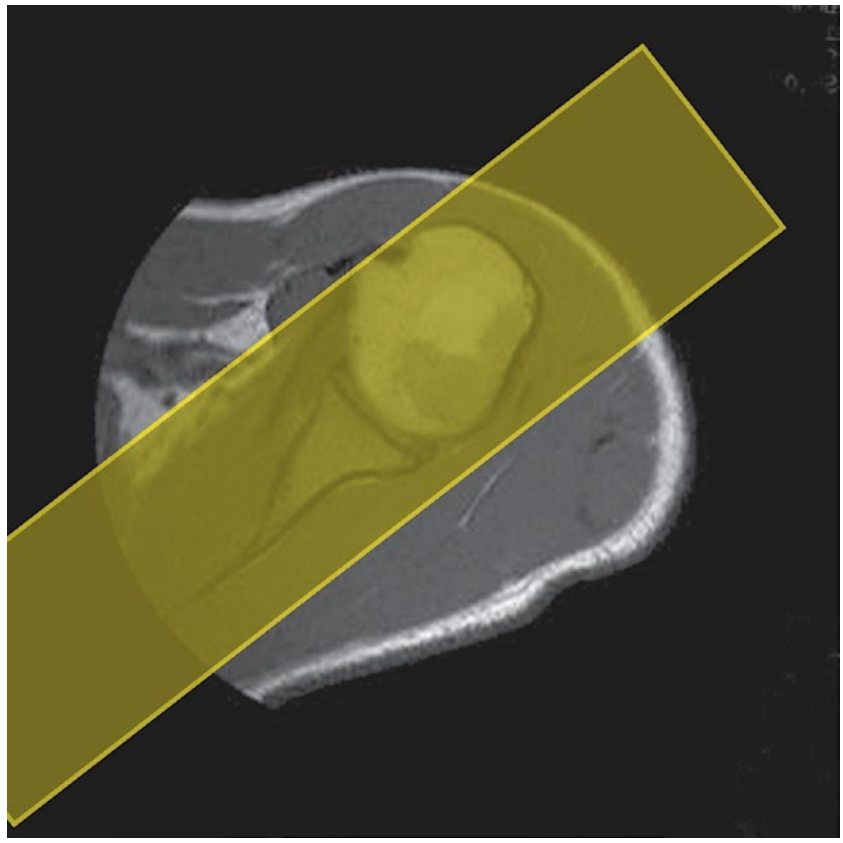

Figure 13.6 Axial Oblique T1-weighed image showing slice prescription boundaries and orientation for coronal oblique imaging of the shoulder

Coronal/oblique SE/FSE T2 +/– tissue suppression (Figures 13.7 and 13.8)

Slice prescription as for coronal/oblique T1.

Fat-suppressed T2-weighted images clearly display muscle tears, trabecular injury, joint fluid and tendon tears. If SE is used, tissue suppression may not be necessary. On most systems, the level of fat suppression is adjustable. Reducing the level of fat suppression improves SNR.

Axial SE/FSE/oblique T1+ tissue suppression

Thin slices/gap are prescribed from the top of the acromio-clavicular joint to below the inferior edge of the glenoid

Additional sequences

Sagittal/oblique SE/FSE T1

As for coronal/oblique T1, except slices are prescribed from medial to the glenoid cavity to the bicipital groove laterally. The area from the distal portion of the joint capsule to the superior border of the acromion is included in the image (Figure 13.9).

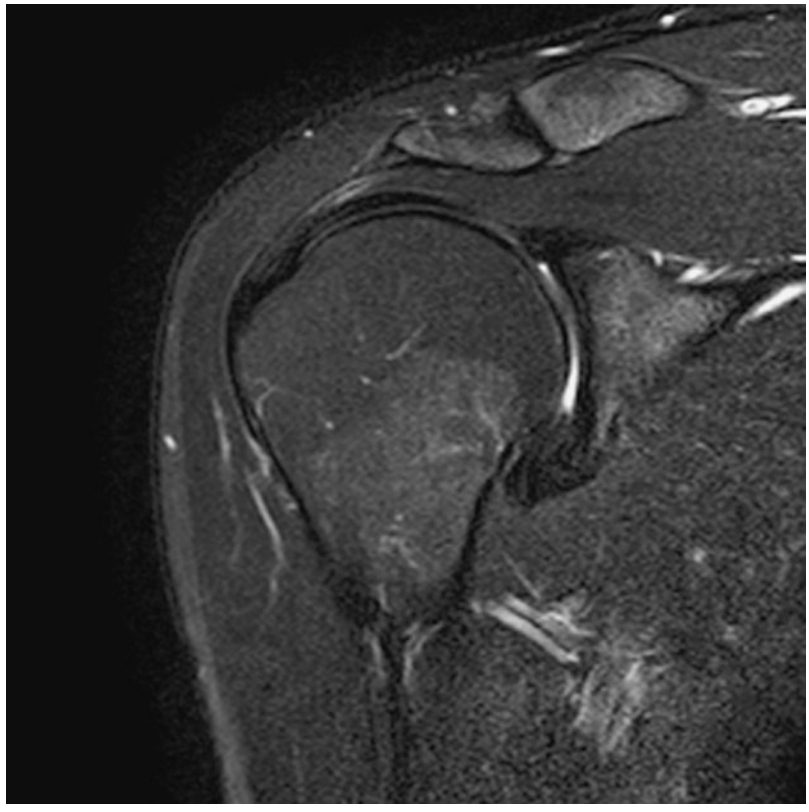

Figure 13.7 Coronal/oblique FSE T2-weighted image with tissue suppression.

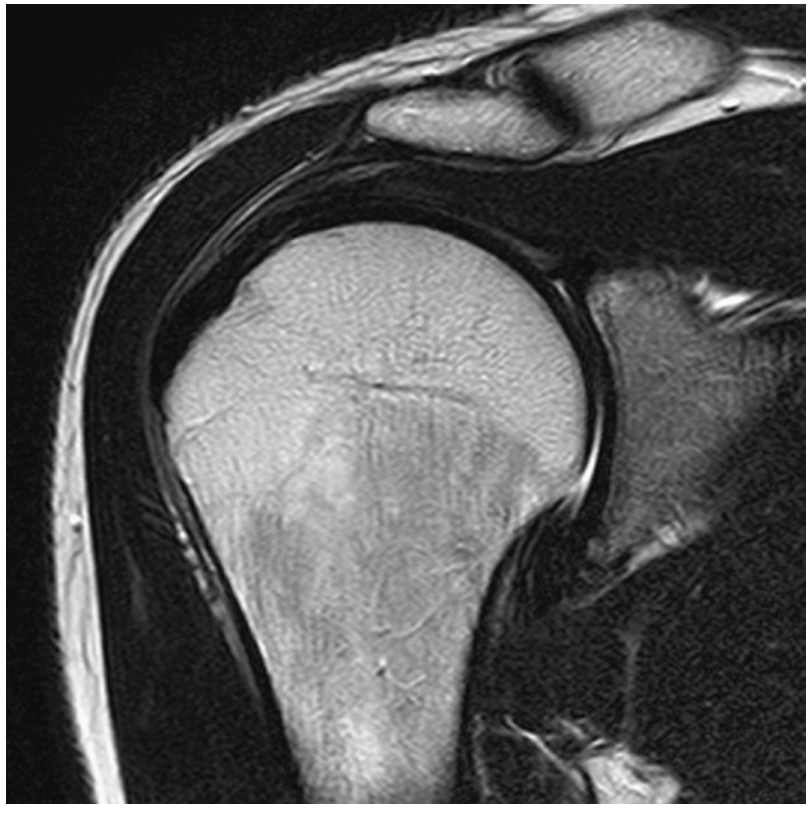

Figure 13.8 Coronal/oblique FSE T2-weighted image.

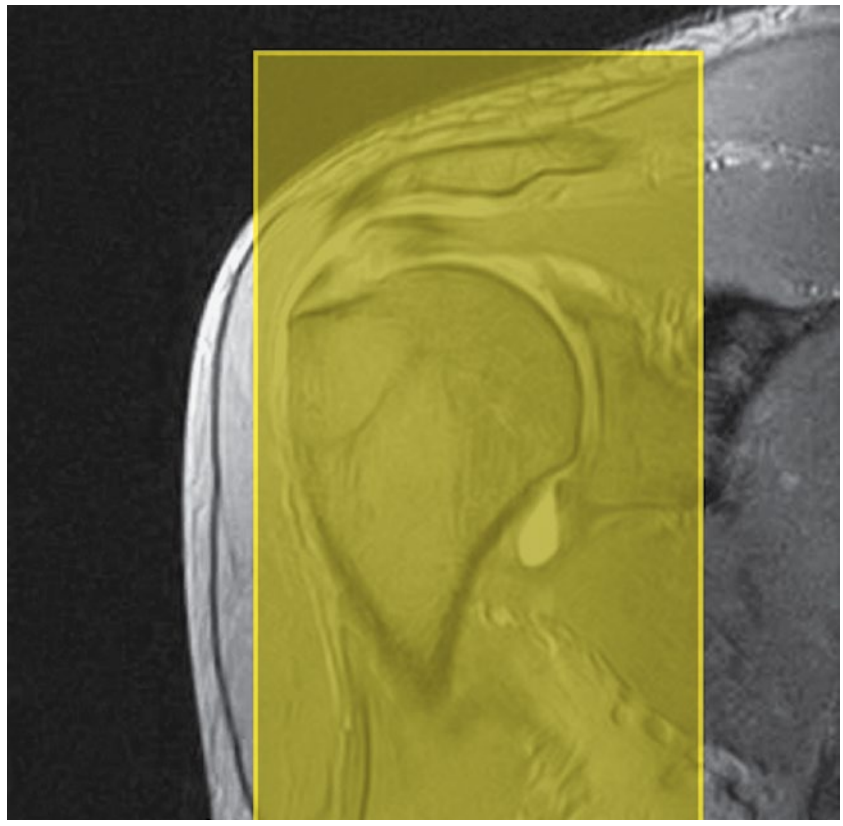

Figure 13.9 Coronal/oblique GRE T2-weighted image showing slice prescription boundaries and orientation for sagittal imaging of the shoulder.

Sagittal/oblique/axial FSE PD/T2 +/– tissue suppression

This sequence provides a combination of anatomical display, tendon assessment, display of joint cartilage and sensitivity to trabecular damage.

3D FSE with variable refocused flip angle PD or T2 contrast +/– tissue suppression

This sequence provides 3D visualization of tendon assessment and joint cartilage and is very sensitive to trabecular damage.

3D GRE T2* BGE/GRE

This sequence provides a 3D visualization and a better detection of the joint cartilage lesions.

MR arthrography (Figures 13.10 and 13.11)

The intra-articular use of gadolinium (MR arthrography) is used to diagnose rotator cuff tears, glenoid labral disruption, bicipital tendon and chondral defects. The technique usually involves injecting a very dilute

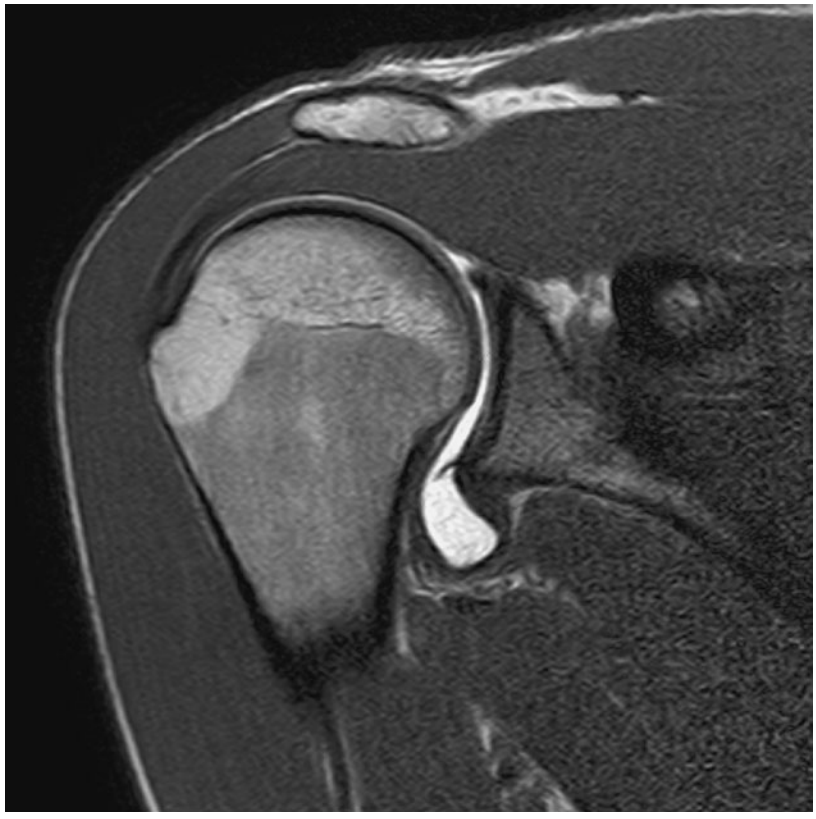

Figure 13.10 Coronal/oblique T1-weighted arthrogram.

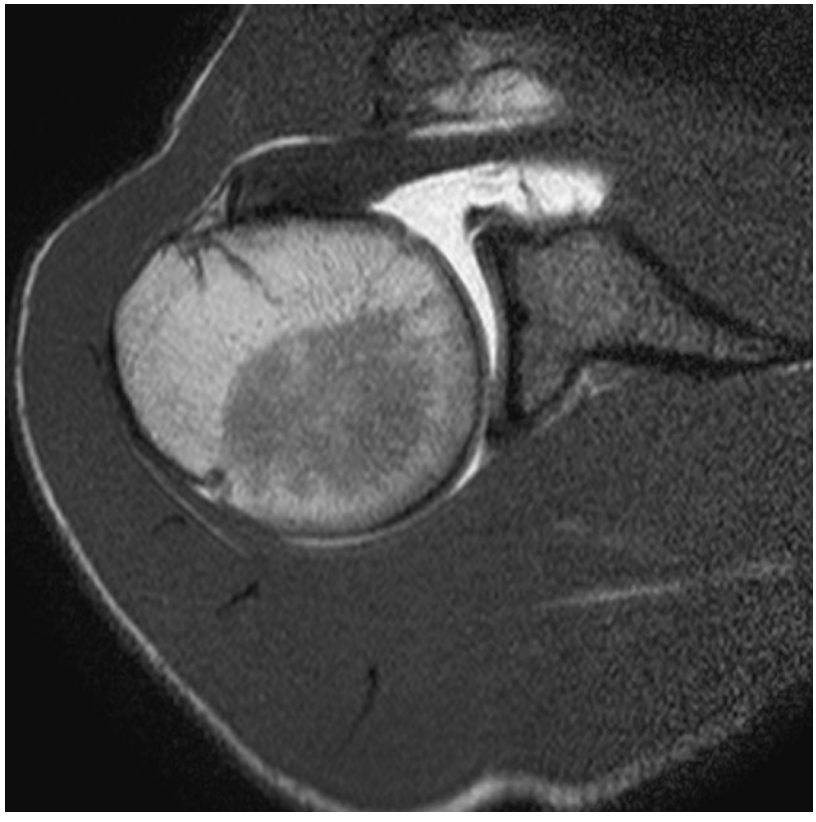

Figure 13.11 Axial T1-weighted arthrogram.

solution of contrast in saline (1:100) or a very weak concentration of gadolinium into the joint capsule under fluoroscopic control followed by conventional MR imaging. Alternatively, saline injection followed by fat-suppressed T2-weighted FSE sequences, or examining the joint after prolonged exercise to exacerbate a joint effusion, may be effective.

Sequences after arthrography:

- *axial/oblique T1 + tissue suppression*
- *coronal/oblique T2 + tissue suppression*
- *coronal/oblique PD + tissue suppression*
- *coronal/oblique T1 + tissue suppression*
- *sagittal/oblique T2 + tissue suppression*
- *3D T1 FS: FSE or GRE with isotropic voxels can be used instead of conventional 2D FSE.*

Image optimization

Technical issues

The TE influences the signal of the muscle in musculoskeletal imaging. A very long TE produces T2-weighted images in which muscle is hypointense. The SNR is therefore reduced, but fluid detection is improved. Tissue suppression techniques can also be used to enhance the signal from fluid even further; however, larger voxels may be required to compensate for the inherent drop in SNR. By choosing a moderate TE, muscle still retains signal (a grey-level intensity) and the images are PD weighted. The SNR is however higher, and the spatial resolution can be better than a T2-weighted image. This kind of contrast is used to detect fluid and retain an anatomical image. Tissue suppression techniques are recommended with this kind of weighting because signal from fluid is reduced. Cartilage lesions can be better detected when TE is high (at least 30–40 ms) because the signal from normal cartilage decreases.

The SNR of the shoulder is largely dependent on the quality and type of coil used. Generally, dedicated shoulder coils return a much higher and more uniform signal than a surface coil, and therefore, the technique is adapted accordingly. If using a dedicated coil, thin slice thickness and higher matrices can be used to achieve the necessary spatial resolution without unduly lengthening the scan time. If the signal not high enough, some resolution may have to be sacrificed in order to maintain the SNR and keep the scan time within reasonable limits. Newly developed surface coils, with a high number of coil elements, can be configurated as high performance shoulder coils. However, spatial resolution is the key to accuracy in shoulder imaging, and the resolution must be as high as possible (pixel size below 0.8 mm). SE and FSE are usually the sequences of choice, but coherent GRE and STIR are useful to visualize joint fluid. STIR may provide better results than fat-suppressed FSE if magnet shimming is suboptimal.

Artefact problems

If possible, instruct the patient to breathe abdominally rather than with the thorax, and place sandbags on the upper chest. This reduces movement artefact from breathing. Spatial pre-saturation pulses (bands) placed I and medial to the shoulder under investigation are usually very effective at reducing phase ghosting from breathing and flow from the subclavian vessels. GMN also minimizes flow artefact, but as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences. However, GMN effectively increases the contrast of synovial fluid in T2- and T2*-weighted images. The use of propeller k-space filling techniques is also beneficial. In coronal/oblique and axial imaging, the FOV is offset so that the centre of the shoulder is in the centre of the image. Additional shimming may be required if tissue suppression techniques are used as fat suppression may not be homogeneous for all the patients.

For high degrees of obliquity (>45°) some systems automatically swap the direction of the phase and frequency axes and, because this can cause severe aliasing problems, antialiasing software is required. Moreover, because a coronal oblique prescription is not a coronal oblique acquisition but a sagittal/oblique acquisition, some systems alter the presented orientation and the anatomical markers (a right shoulder could look like a left). The same problems can arise in sagittal/oblique imaging. To avoid these problems, position the patient in slight rotation with the scapula parallel to the table. If this is not possible, check the direction of phase encoding for every oblique scan prescription, and use anatomical markers in sagittal/oblique images to confirm the scanner's labelling of anterior and posterior. To minimize aliasing, phase encoding should run A–P on axials and sagittal/obliques, and S–I on the coronal/obliques. Alternatively, spatial pre-saturation pulses can be positioned to minimize artefact from the medial edges of the coil.

A phenomenon known as the 'magic angle' causes increased signal intensity in tendons in short TE sequences when tendons are orientated at an angle of 55° to the main field. Normally, tendons produce little or no signal on conventional MRI sequences because tendons consist of parallel ordered bundles of collagen fibres. This structural anisotropy causes a local static magnetic field which, when superimposed on to the static field, increases spin–spin interactions and therefore shortens T2 relaxation rates so much that the tendon has a low signal intensity.

However, the rate at which spin dephasing is increased is proportional to the angle between the main field and the long axis of the tendon. Because of this relationship, additional spin dephasing caused by the structural anisotropy of tendons decreases to 0 when this angle is 55°. Therefore, at this angle, the T2 relaxation time increases, causing a high signal intensity when using short TEs. The increased signal can mimic pathology such as tendonitis in normal tendons. It is seen in many tendons especially supraspinatus and Achilles tendons as well as in the wrist. The magic angle effect can be eliminated by repositioning the tendon or by increasing the TE above 60 ms (but not too high as signal from muscle reduces with very long TEs.).

Patient considerations

Ensure that the patient is comfortable and well informed of the procedure. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment. Padding should be placed to prevent the patient's skin from coming in direct contact with the scanner bore and be placed in any area in which the patient's body may form a 'conductive loop'. Also it is important that there is no direct contact with the skin and the surface coil (insert pads). Provide all cooperative patients with the 'Patient Alert' squeeze bulb. Inform the patient that you are close to him/her in the operator room, and also in direct communication.

Contrast usage

Contrast is not routinely used in shoulder imaging except for direct and indirect MR arthrography. For information on direct MR arthrography, please see previous section under *Additional sequences*. Indirect MR arthrography involves the administration of intravenous diluted gadolinium and is sometimes used when direct arthrography is not feasible. Although indirect MR arthrography has some disadvantages when compared with direct MR arthrography, it does not require fluoroscopic guidance or invasive joint injection. It is also superior to non-contrast MR imaging in delineating structures when there is minimal joint fluid. In addition, vascularized or inflamed tissue enhances with this method.

Humerus

Basic anatomy (Figure 13.12)

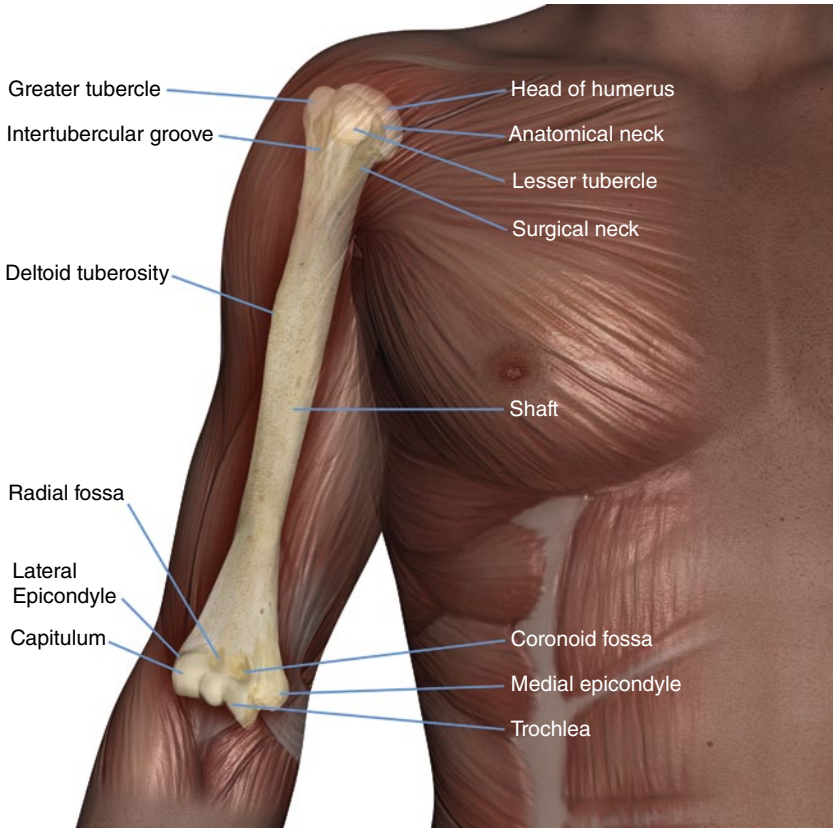

Figure 13.12 Anterior view of the right humerus.

Common indications

- Diagnosis and assessment of bony and soft tissue abnormalities (mass lesions, muscle tears, deformity)
- A single-sided examination is usually preferred as bilateral examinations severely compromise resolution

Equipment

- Body multi-array coil/long surface coil placed under the humerus
- Immobilization pads and straps
- Plastic ruler
- Earplugs/headphones

Patient positioning

If the upper arm is under investigation, the patient lies supine on the examination couch with their arms resting at their sides. If, however, the ROI is near the elbow, the patient may lie prone with their arm stretched above their head (swimmer's position). This ensures that the area under examination is at isocentre and offset imaging is avoided. However, the swimmer's position can be difficult to maintain for long periods of time, and it is therefore advisable to reserve it for fitter patients. In both positions, it is necessary to place the coil lengthwise along the long axis of the humerus.

When imaging with the arm at the side, raise the unaffected side about 45° and bring the arm under examination as close as possible to the longitudinal alignment light. The top half of the body array should be positioned with its lateral edge wrapped well around the arm and touching the lower element edge. This avoids placing the arm at the coil edge. Additionally, for full humerus imaging, the top half of the array is slid up to cover the shoulder, while the base portion is used to image from the elbow up. Use immobilization straps to secure the coil, the patient and supporting pillows.

If the patient is in the swimmer's position, the longitudinal alignment light lies along the midline of the humerus. In both positions, the horizontal alignment light passes through the centre of the coil or midway between the shoulder and the elbow. The arm and coil may be raised with foam pads until the vertical alignment light lies through the centre of the arm, so avoiding a vertical offset. Use the plastic ruler to measure from the transverse alignment light to the joints to ensure the full length of the arm fits within the long axis of the FOV. If not, include either the shoulder or elbow depending on the location of the lesions. When a lesion is palpable, place an oil- or water-filled marker over it. For large lumps or scars, place a marker at each end.

Suggested protocol

Coronal/sagittal incoherent (spoiled) SE/FSE T1

Acts as a localizer if three-plane localization is unavailable, but if the patient has been positioned correctly, it may act as a diagnostic sequence. Coronal localizers should be used for lesions located in the RL axis and sagittal localizers for lesions in the AP axis.

Coronal imaging: Medium slices/gap are prescribed on either side of the vertical alignment light and offset to the middle of the humerus (if the arm is at the side). No offset is necessary in the swimmer's position as the longitudinal alignment light corresponds to the middle of the humerus. The whole of the humerus, from the elbow to the shoulder, is included in the image.

P 25 mm to A 25 mm

Sagittal imaging: Medium slices/gaps are prescribed on either side of the longitudinal light in the swimmer's position or on either side of the offset

measurement when imaging with the arms at the side. The whole of the humerus, from the elbow to the shoulder, is included in the image.

L 25 mm to R 25 mm
(swimmer's position)

Sagittal STIR

Medium slices/gap are prescribed to cover the whole of the humerus from the glenoid to the proximal radius and ulna, and orientated along the long axis of the humerus. This sequence is useful to identify lesions in the soft tissues and marrow space and display their extent.

Coronal FSE/SE T1

Thin slices/gap are prescribed to cover the humerus from back to front and orientated along the long axis of the humerus. This sequence provides an anatomical display of the upper arm and may identify lesions located in the marrow space.

Axial SE/FSE T1

Medium slices/gap are prescribed and positioned to include lesions seen on the coronal or sagittal images. Axial images are used to localize lesions within significant anatomical compartments and must extend well above and below the lesions. Breach of the marrow space, extension within or through muscle compartments and association with the neurovascular bundle are all significant characteristics.

Axial FSE T2 + tissue suppression/STIR

Slice prescription as for axial T1.

STIR sequences are usually needed if the arm is by the side or if the ROI is away from the longitudinal isocentre. Tissue suppression is more effective in the swimmer's position when the ROI is at isocentre.

Image optimization

Technical issues

The inherent contrast is relatively good in this area due to the apposition of muscle and fat. The TE influences the signal of the muscle in musculoskeletal imaging. A very long TE produces T2-weighted images in which muscle is hypo-intense. The SNR is therefore reduced but fluid detection is improved. Tissue suppression can also be used to enhance the signal from fluid even further; however, larger voxels may be required to compensate for the inherent drop in SNR. By choosing a moderate TE, muscle still retains signal (a grey-level intensity) and the images are PD weighted. The SNR is however higher and the spatial resolution can be better than a T2-weighted image. This kind of contrast is used to detect fluid and retain an anatomical image. Tissue suppression techniques are recommended with

this kind of weighting because signal from fluid is reduced. Cartilage lesions can be better detected when TE is high (at least 30–40 ms) because the signal from normal cartilage decreases.

Medium slice thickness and resolution, combined with sensitive coils, permit a fast examination so that higher-resolution axial images can be acquired when lesions are close to the neurovascular bundle, or cortical bone breach is not obvious.

The FOV is usually extended on the coronals and sagittals so that the entire length of the humerus is visualized. This is especially important in the diagnosis of bony tumours to ensure that any additional skip lesions are identified. The associated scan time reductions of FSE enable the implementation of medium to high matrices, without unduly lengthening the scan time. In the coronal and sagittal planes, a rectangular/asymmetric FOV is beneficial to maintain resolution with the long axis of the rectangle placed S to I. In coronal imaging, an offset square FOV or oversampling is required to avoid aliasing, especially when using a large coil.

When using FSE with T2 weighting, the muscles return a lower signal than in SE and fat returns a higher signal (see *Pulse sequences* in Part 1). Tissue suppression techniques are, therefore, usually necessary to distinguish fat from pathology but will reduce SNR. Multiple NEX/NSA are required to compensate or, alternatively, the coil can be placed anteriorly over the arm.

Artefact problems

Patient movement is sometimes troublesome in the swimmer's position as the patient is more likely to be uncomfortable. Careful immobilization or laying the patient supine instead is beneficial. Pulsation from the humeral vessels is reduced by using spatial pre-saturation pulses placed S and I to the FOV and I on axial imaging. Medial spatial pre-saturation pulses also reduce aliasing. GMN can be implemented, but as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences. Chemical shift artefact must be kept within one pixel, particularly in axial imaging, to delineate the interface of marrow and cortical bone and the edges of muscle compartments clearly. Additional shimming may be required before tissue suppression sequences.

Patient considerations

Patients must be carefully positioned if the swimmer's position is used and immobilized with foam pads for comfort. To allow accurate assessment of mass lesions, MRI should be performed before biopsy. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast may be useful for visualizing some soft tissue abnormalities but it is not routinely used.

Elbow

Basic anatomy (Figures 13.13 and 13.14)

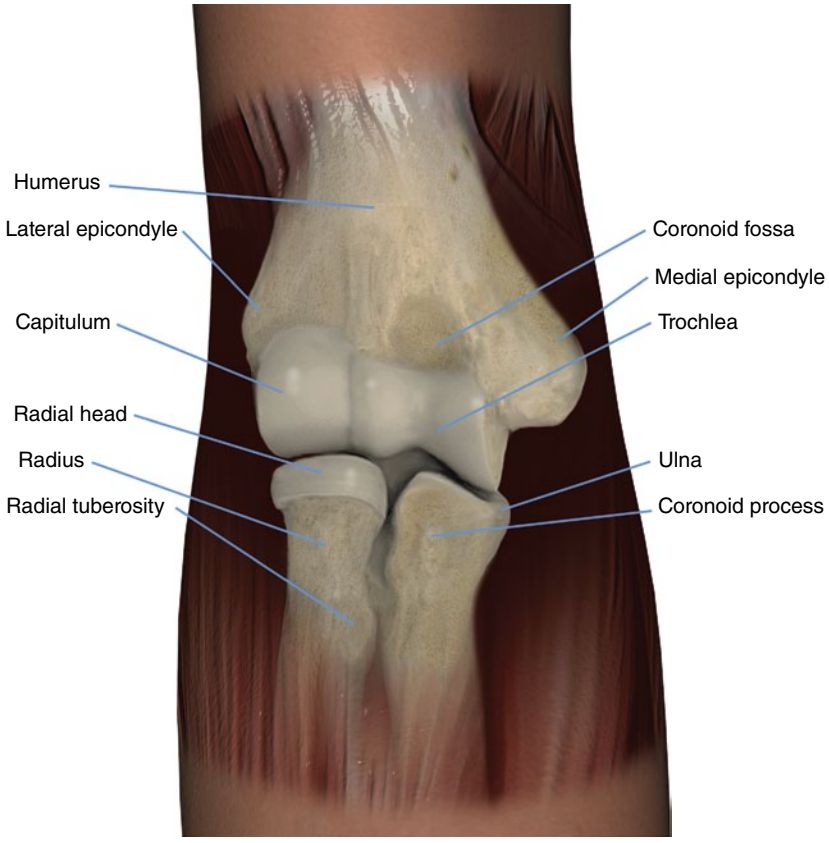

Figure 13.13 Anterior view of the right elbow showing the bony components.

Common indications

- Osteochondral defects and loose bodies
- Evaluation of avascular necrosis (AVN) in the radial head and capitulum
- Ulnar nerve compression
- Trauma, particularly ulnar collateral ligament injury
- Soft tissue mass lesions
- Muscle tear and rupture

Equipment

- Small surface coils combined as an array/Helmholtz pair/flexible coils/surface coil fixed anteriorly to the joint
- Immobilization pads and straps

- Plastic elbow slabs
- Earplugs or headphones

Patient positioning

The patient lies either supine with their arm at the side or prone in the swimmer's position with the elbow under examination extended above the head and the other arm down by the side. While this ensures that the area under examination is at isocentre, it is difficult to maintain for long periods of time, and it is therefore advisable to reserve it for fitter patients.

With the more common supine position, the body is obliqued and drawn across the table to place the elbow as close as possible to the midline whilst lying clear of the body. The elbow and wrist are secured in a relaxed position. Plastic back slabs and/or rigid coils help to maintain the position and reduce muscular motion. The arm and coil are raised using foam pads so that the vertical alignment light lies through the centre of the joint, so avoiding a vertical offset. The longitudinal alignment light lies between the humeral condyles.

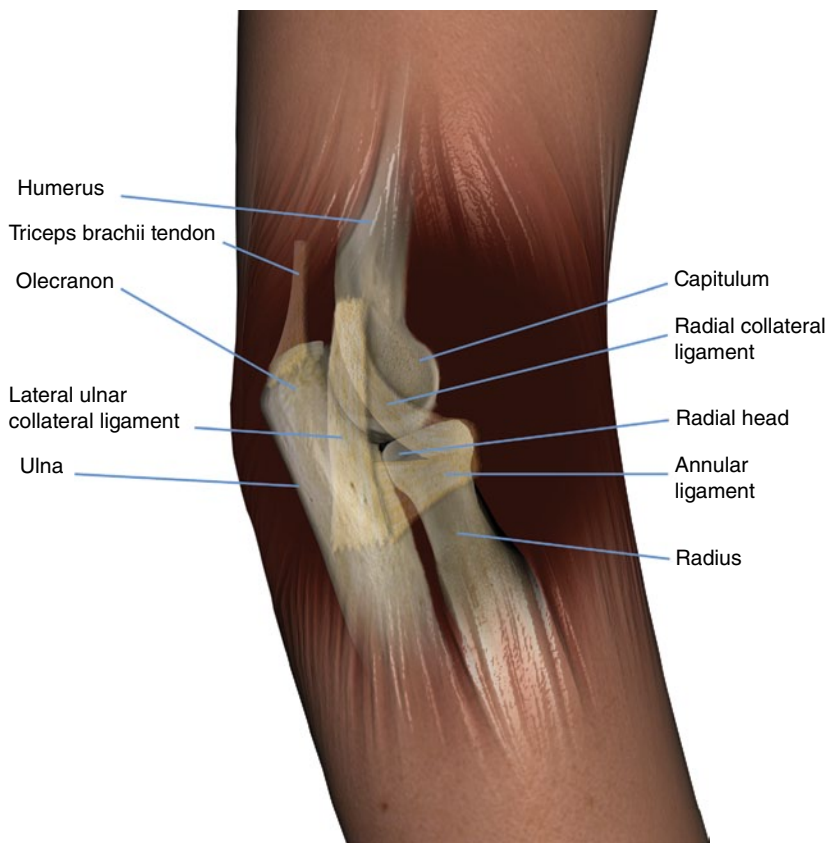

Figure 13.14 Sagittal view of the right elbow showing ligaments on the lateral aspect.

Suggested protocol

Coronal/multi-planar incoherent (spoiled) GRE/SE/FSE T1

Acts as a localizer if three-plane localization is unavailable, but if the patient is positioned correctly, it may act as a diagnostic sequence. All main imaging scan planes are aligned to the anatomical axes of the elbow. As the elbow is in a relaxed oblique position, fast localizers can be used to find and establish these planes. Fast, low-resolution localizers can also be set up with small FOVs to rapidly assess the need for antialiasing options. Thin slices/gaps are prescribed on either side of the vertical alignment light or with an offset if the arms are at the side. The whole of the elbow joint is included in the image.

Coronal localizer: P 20 mm to A 20 mm

Coronal SE/FSE T1 (Figure 13.15)

Thin slices/gaps are prescribed through a line joining the humeral epicondyles from the posterior to the anterior skin surfaces. The distal humerus, elbow joint and proximal radius and ulna, including the lateral and medial skin margins, are included on the image.

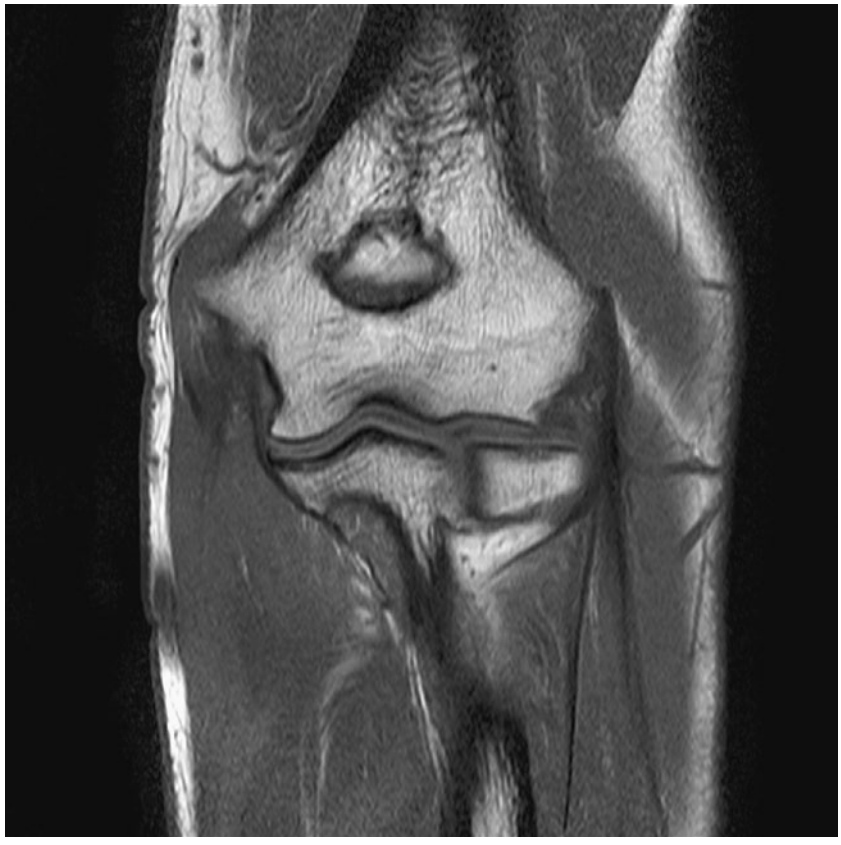

Figure 13.15 Coronal SE T1-weighted image of the elbow showing normal appearances.

Coronal FSE PD/T2 +/– tissue suppression/STIR (Figures 13.16 and 13.17)

Slice prescription as for coronal T1, except use tissue suppression for identification of occult fractures and joint degeneration.

Sagittal SE/FSE T1

Thin slices/gaps are prescribed perpendicular to the coronal slices from the medial to the lateral aspects of the elbow (Figure 13.18). This sequence is used to evaluate lesions anterior or posterior to the bony anatomy and assess the long axis of associated muscles and tendons.

Sagittal STIR (Figure 13.19) or sagittal PD +/– tissue suppression

STIR using a TI to incompletely suppress fat or a too low or PD with a weak fat suppression values

Slice prescription as for sagittal T1.

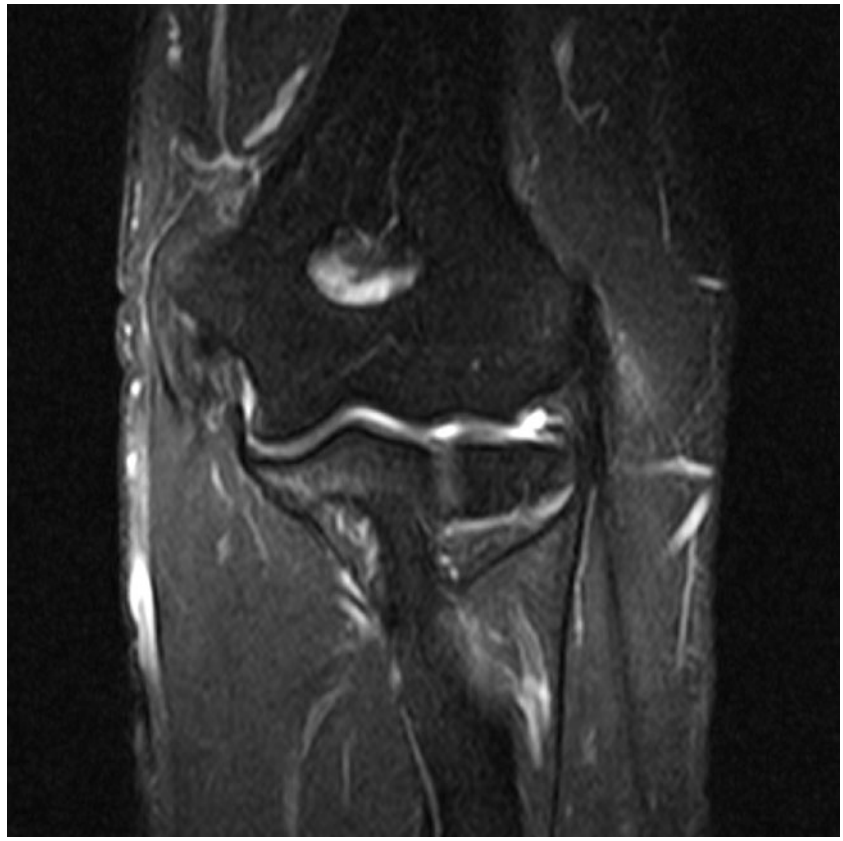

Figure 13.16 Coronal FSE T2-weighted image of the elbow with tissue suppression showing normal appearances.

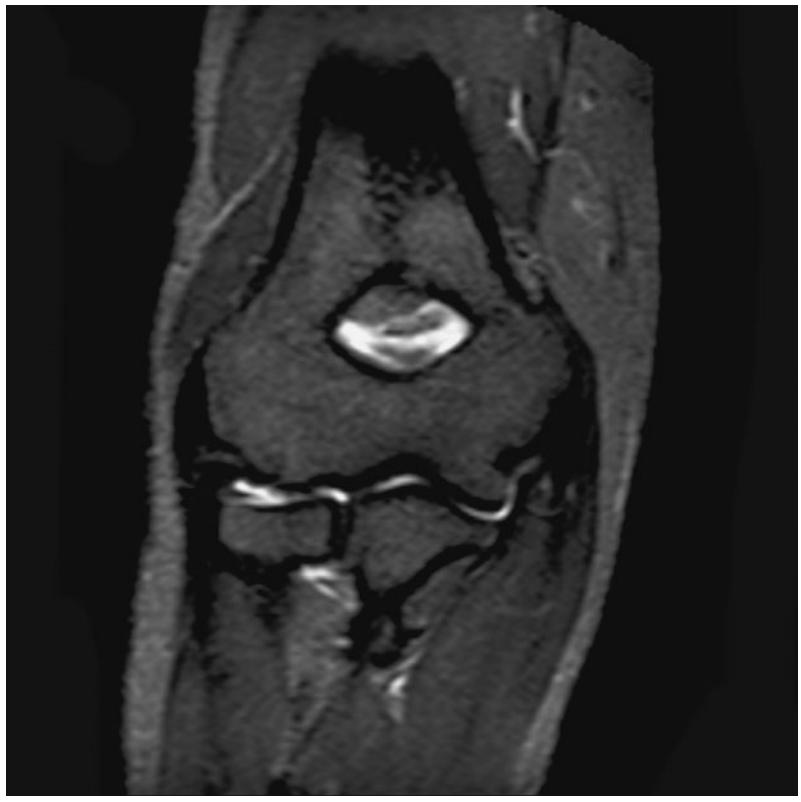

Figure 13.17 Coronal STIR.

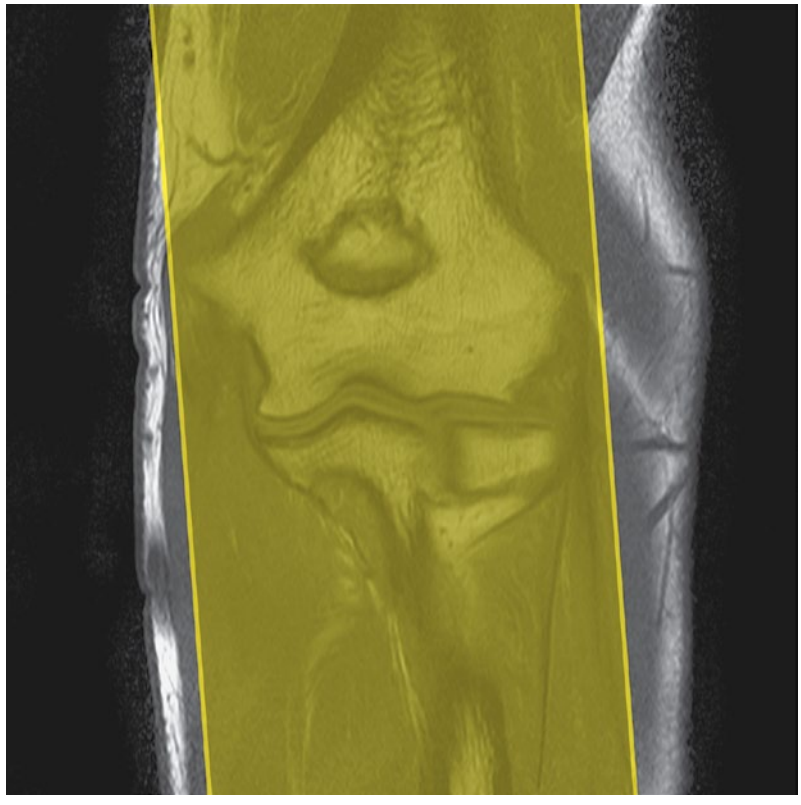

Figure 13.18 Coronal SE T1-weighted image of the elbow showing slice prescription boundaries and orientation for sagittal imaging of the elbow.

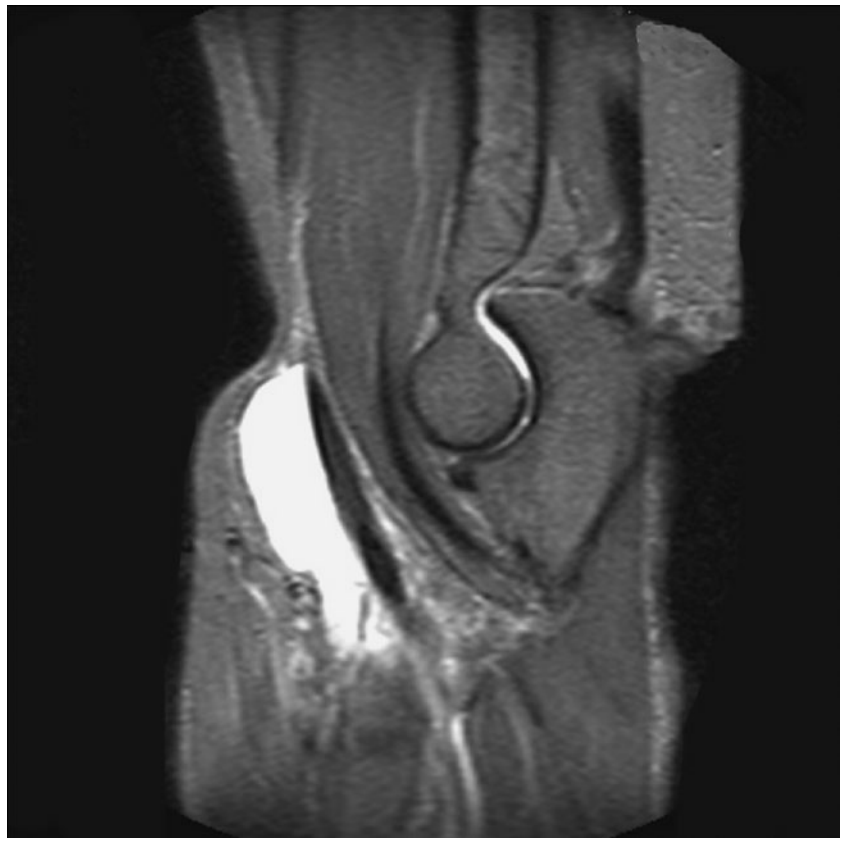

Figure 13.19 Sagittal STIR.

Axial FSE T1 or PD/T2 +/– tissue suppression (Figure 13.20)

Thin slices/gaps are aligned perpendicular to the long axis of the humerus and forearm, as determined from a coronal view (Figure 13.21). These slices are typically oblique, with the medial edge more inferior than the lateral edge.

Coherent GRE T2* +/– tissue suppression

These images display articular cartilage clearly for clarifying osteochondral defects.

Additional sequences

Incoherent (spoiled) GRE T1

Reduced signal intensity in the marrow space due to susceptibility effects, combined with high signal from muscle, makes this sequence useful in examining elbow joint anatomy.

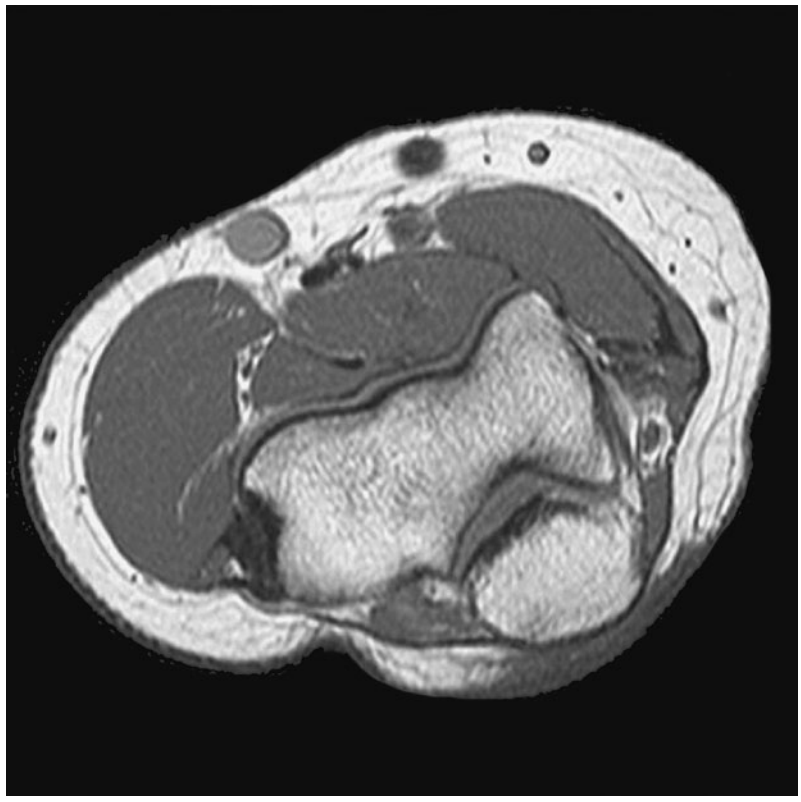

Figure 13.20 Axial FSE T1-weighted image through the elbow joint.

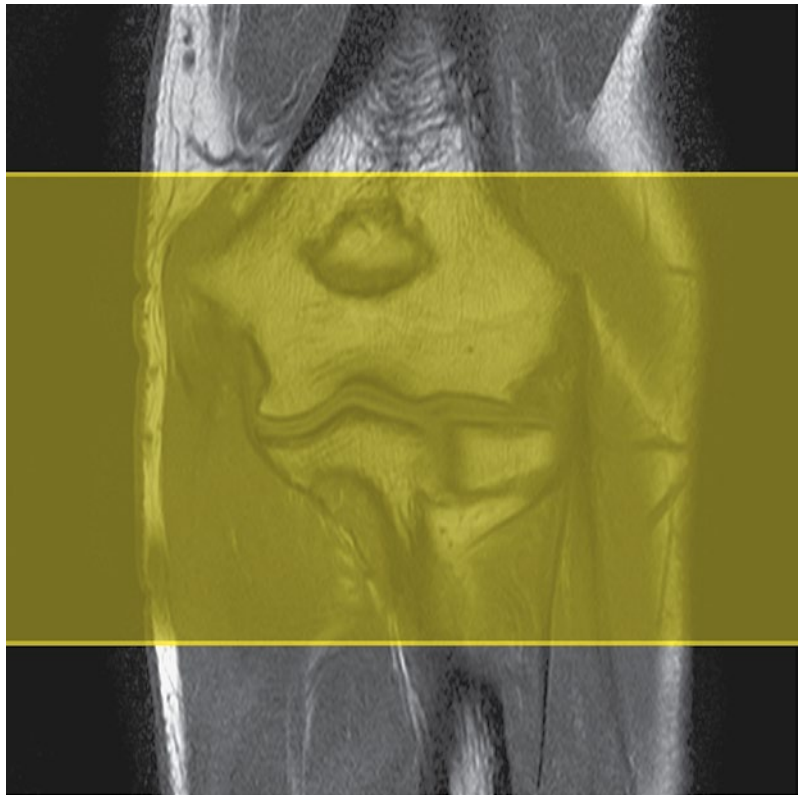

Figure 13.21 Coronal SE T1-weighted image of the elbow showing slice prescription boundaries and orientation for axial imaging of the elbow.

Coronal 3D coherent GRE PD/T2*

Thin slices and a small number of slice locations are prescribed through the joint allowing for slice wrap. The use of an isotropic data set provides further evaluation of the elbow joint.

Image optimization

Technical issues

The TE influences the signal of the muscle in musculoskeletal imaging. A very long TE produces T2-weighted images in which muscle is hypointense. The SNR is therefore reduced but fluid detection is improved. Tissue suppression can also be used to enhance the signal from fluid even further; however, larger voxels may be required to compensate for the inherent drop in SNR. By choosing a moderate TE, muscle still retains signal (a grey-level intensity) and the images are PD weighted. The SNR is however higher and the spatial resolution can be better than a T2-weighted image. This kind of contrast is used to detect fluid and retain an anatomical image. Tissue suppression techniques are recommended with this kind of weighting because signal from fluid is reduced. Cartilage lesions can be better detected when TE is high (at least 30–40 ms) because the signal from normal cartilage decreases.

High-resolution imaging is required to demonstrate the elbow joint, and therefore, image quality is mainly dependent on the quality of the coil used. If a coil pair or array is implemented, the necessary spatial resolution can be easily maintained. In most cases, the FOV is close to the periphery of the magnet bore, and therefore, extra shimming may be required to maximize SNR and image quality. FSE is commonly used to maintain high resolution in acceptable scan times. FSE also provides good contrast, but when used with T2 weighting, the muscles return a lower signal than in SE and fat remains bright (see *Pulse sequences* in Part 1). Tissue suppression is, therefore, often necessary to distinguish fat from pathology. T2* coherent GRE sequences are also used as they provide good contrast between the bony margins of the joint and synovial fluid. Volume acquisitions are sometimes valuable as very thin slices with no gap are used, and joint structures may be visualized in any plane.

Artefact problems

Patient movement can be troublesome in the swimmer's position as the patient is more likely to be uncomfortable. Careful immobilization, or laying the patient supine instead, is beneficial. Pulsation from the humeral and radial vessels is reduced using spatial pre-saturation pulses placed S and I to the FOV. GMN can also be used, but as it increases signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences. However, GMN effectively increases the contrast of synovial fluid in T2- and T2*-weighted images. If offset imaging is employed and

phase is S to I, oversampling is necessary on the coronals. In axial imaging, there is no anatomy outside the FOV in the phase direction, and in sagittal imaging, there is no offset. Therefore, oversampling is usually unnecessary in these planes. Additional shimming may be required before tissue suppression sequences.

Patient considerations

Patients must be carefully positioned if the swimmer's position is used and immobilized with pads for comfort. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast may be useful for visualizing some soft tissue abnormalities. In addition, MR arthrography is useful for visualizing partial- and full-thickness tears of the collateral ligament and delineating bands in the elbow. Sequences used in arthrography include:

- coronal FSE T1 + tissue suppression
- sagittal FSE T1 + tissue suppression
- axial FSE T1
- 3D FSE/GRE T1 + tissue suppression

Forearm

Basic anatomy (Figure 13.22)

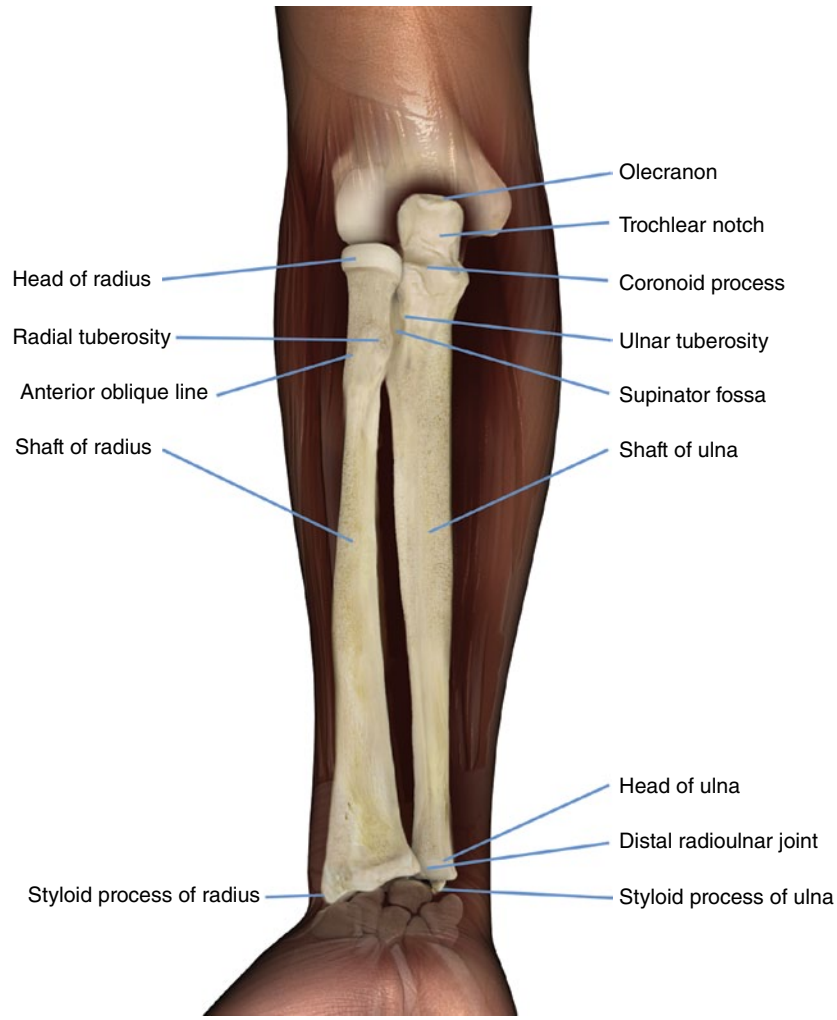

Figure 13.22 Anterior view of the right radius and ulna.

Common indications

- Visualization of bony and soft tissue abnormalities

Equipment

- Body array coil/long surface coil placed under the arm/extremity coil for focal lesions/body coil
- Immobilization pads and straps

- Plastic ruler
- Earplugs or headphones

Patient positioning

The patient may lie either supine with the arms at the side, or prone in the swimmer's position with the arm under investigation above the head and the other arm down by the side. This ensures that the area under examination is at isocentre and offset imaging is avoided. However, this position is difficult to maintain for long periods of time, and it is therefore advisable to reserve it for fit patients.

When imaging with the arm at the side, raise the unaffected side about 45° and bring the arm under examination as close as possible to the centre of the bore. The top half of the body array should be positioned with its lateral edge wrapped well around the arm and touching the lower element edge. This avoids using the edge of the coil. In addition, when imaging the whole of the forearm, the top half of the array is slid up to cover the elbow, while the base portion is used to image from the wrist up. While keeping the arm relaxed, it is important to avoid pronation of the hand. Use immobilization straps to secure the coil, patient and supporting pillows or pads. Instruct the patient not to move their fingers during data acquisition.

In both positions, the horizontal alignment light passes through the centre of the coil or midway between the elbow and the wrist. The arm and coil may be raised with foam pads until the vertical alignment light lies through the centre of the arm, so avoiding a vertical offset. Use the plastic ruler to measure from the horizontal alignment mark to each joint. This ensures that the full length of the forearm fits within the FOV. If this is not possible, include either the elbow or the wrist depending on the location of the lesions. When a lesion is palpable, place an oil- or water-filled marker over it. For large lumps or scars, place a marker at each end.

Suggested protocol

Multi-planar/coronal/sagittal incoherent (spoiled) GRE/SE/FSE T1

Acts as a localizer if three-plane localization is unavailable, but if the patient has been positioned correctly, it may act as a diagnostic sequence. Coronal localizers should be used for lesions located in the RL axis and sagittal localizers for lesions in the AP axis. Surface coil localizers can be used to quickly assess potential aliasing problems and for establishing anatomical planes.

Coronal imaging: Medium slices/gap are prescribed on either side of the vertical alignment light and offset to the middle of the forearm (if the arm is at the side). No offset is necessary in the swimmer's position as the longitudinal alignment light corresponds to the middle of the forearm. The whole of the forearm from the wrist to the elbow is included in the image.

P 25 mm to A 25 mm

Sagittal imaging: Medium slices/gaps are prescribed on either side of the longitudinal light in the swimmer's position or on either side of the offset measurement when imaging with the arms at the side. The whole of the forearm from the wrist to the elbow is included in the image.

L 25 mm to R 25 mm (swimmer's position)

Sagittal STIR

Medium slices/gap are prescribed to include the whole forearm from the distal humerus to the proximal metacarpals and orientated along the long axis of the humerus accounting for the 'carry angle' of the forearm. This sequence is fast and sensitive for identifying lesions in the soft tissues and marrow space.

Coronal FSE/SE T1

Thin slices/gaps are prescribed along the line of the forearm and from the posterior to the anterior skin surfaces.

Axial T1 FSE

Medium slices/gaps are prescribed perpendicular to the coronal slices to extend well above and below lesions seen in this and the sagittal plane. Breach of the marrow space, extension within or through muscle compartments, and association with the neurovascular bundle are all significant characteristics best assessed on axial images.

Axial FSE T2 +/– tissue suppression or STIR

Slice prescription as for axial T1.

STIR sequences are usually required if the arm is by the side or if the ROI is away from the isocentre. Tissue suppression is effective with the swimmer's positioning. The FSE sequence is optimal as it provides better resolution than STIR.

Image optimization

Technical issues

The inherent contrast is relatively good in this area due to the apposition of muscle and fat. The TE influences the signal of the muscle in musculoskeletal imaging. A very long TE produces T2-weighted images in which muscle is hypo-intense. The SNR is therefore reduced but fluid detection is improved. Tissue suppression can also be used to enhance the signal from fluid even further; however, larger voxels may be required to compensate for the inherent drop in SNR. By choosing a moderate TE, muscle still retains signal (a grey-level intensity) and the images are PD weighted.

The SNR is however higher and the spatial resolution can be better than a T2-weighted image. This kind of contrast is used to detect fluid and retain an anatomical image. Tissue suppression techniques are recommended with this kind of weighting because signal from fluid is reduced. Cartilage lesions can be better detected when TE is high (at least 30–40 ms) because the signal from normal cartilage decreases.

Medium slice thickness and resolution, combined with sensitive coils, permit a fast examination so that high-resolution axial images may be acquired for lesions close to the neurovascular bundle and when cortical bone breach is not obvious. The FOV is usually extended on the coronals and sagittals so that the entire length of the forearm is visualized. This is especially important in the diagnosis of bony tumours to ensure that any additional skip lesions are identified. The associated scan time reductions of FSE enable the implementation of medium to fine matrices, without unduly lengthening the scan time. In the coronal and sagittal planes, a rectangular/asymmetric FOV is useful with the long axis of the rectangle running along the length of the forearm. When using FSE with T2 weighting, the muscles return a lower signal than in SE and fat returns a higher signal. Tissue suppression techniques are, therefore, usually necessary to distinguish fat from pathology. Spectral fat suppression is difficult to achieve over a large FOV in the periphery of the homogeneous field, so STIR or Dixon methods are typically used in coronal and sagittal images. Axial images near isocentre in the longitudinal direction can usually support chemical fat suppression.

Artefact problems

Patient movement is sometimes troublesome in the swimmer's position as the patient is more likely to be uncomfortable. Careful immobilization, or laying the patient supine instead, is beneficial. Pulsation from the radial vessels is reduced using spatial pre-saturation pulses placed S and I to the FOV. GMN can also be used, but as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences.

Patient considerations

Patients must be carefully positioned if the swimmer's position is used, and immobilized with foam pads for comfort. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast may be useful for visualizing some soft tissue abnormalities but it is not routinely used.

Wrist and hand

Basic anatomy (Figure 13.23)

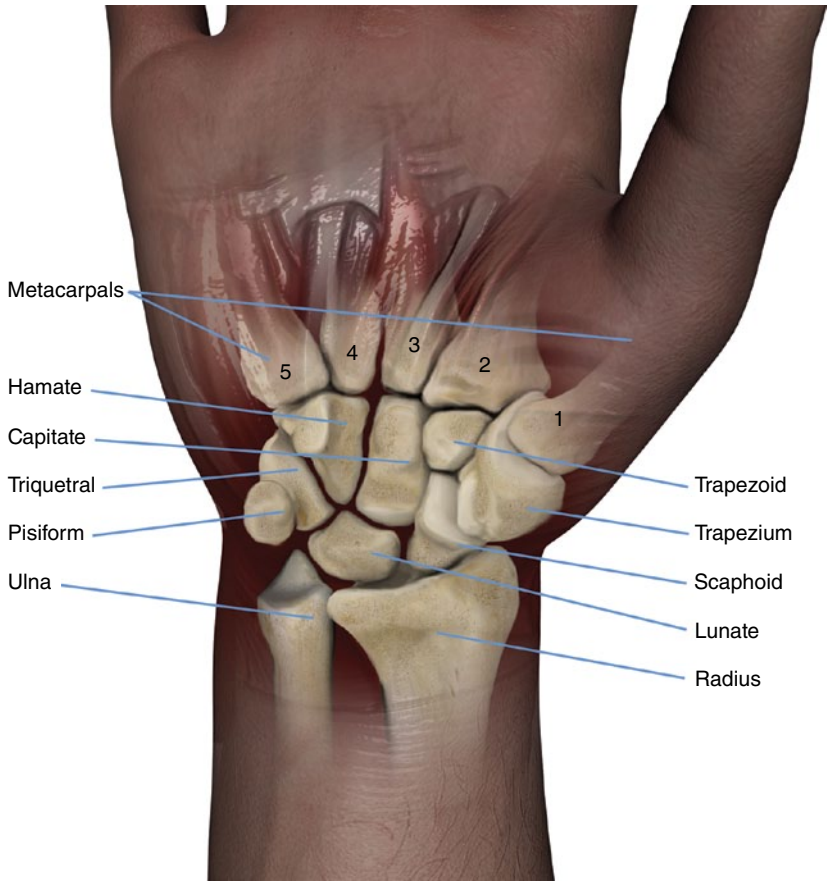

Figure 13.23 Bony structures of the wrist.

Common indications

- Assessment of wrist pain of unknown origin (tears of the triangular cartilage, osteonecrosis of the lunate (Kienböch's disease), occult ganglia)
- Assessment of AVN of the scaphoid following trauma
- Diagnosis of carpal tunnel syndrome
- Possibly valuable in early evaluation of rheumatoid arthritis
- Assessment of the scapholunate and scaphotriquetral ligaments when wrist instability is suspected
- Infection
- Tumour

Equipment

- Dedicated wrist coil (volume/Helmholtz/phased or multi-coil array)/small surface coil(s) linked by a phase harness. Very small, specially designed, local coils can be used to examine finger joints
- Immobilization pads and straps
- Earplugs or headphones

Patient positioning

The patient is usually scanned lying supine with the arm by the side with the elbow and wrist facing up to avoid pronation of the forearm. The wrist and hand are placed in a splint to prevent movement, and to aid secure coil placement. Move the patient as far as possible across the table and support the entire arm on pads to bring the wrist as close as possible to isocentre. Fit patients may be able to tolerate the swimmer's position with the palm either facing up or down with the arm bent at the elbow. If a small circular coil is used, the patient can be positioned prone or supine with the arm above the head and elbow bent so that the forearm runs across the table. The coil is fixed in the sagittal plane at vertical isocentre. If two coils are used, the wrist is placed through them to take advantage of both of the sensitive areas of the coils. As this requires active coil decoupling, check your system's operation manuals if in doubt. If the wrist is at isocentre in all three axes, the longitudinal and horizontal alignment lights are centred to the wrist. If the arm is at the side, it may be necessary to measure the horizontal offset with a plastic ruler.

Suggested protocol

Multi-planar/sagittal SE/FSE/incoherent (spoiled) GRE T1/coherent GRE T2* (Figure 13.24)

Acts as a localizer if three-plane localization is unavailable but, if the patient has been positioned correctly, may act as a diagnostic sequence. Using the body coil, medium slices/gaps are prescribed on either side of the longitudinal light in the swimmer's position or on either side of the offset with the arm at the side. The area from the inferior border of the carpal bones to the distal portion of the forearm is included in the image.

L 15 mm to R 15 mm (swimmer's position)

Axial localizer: This may be prescribed from the multi-planar localizers or the sagittal localizer. Use a surface coil to determine slice orientation for coronal imaging more accurately (Figure 13.25).

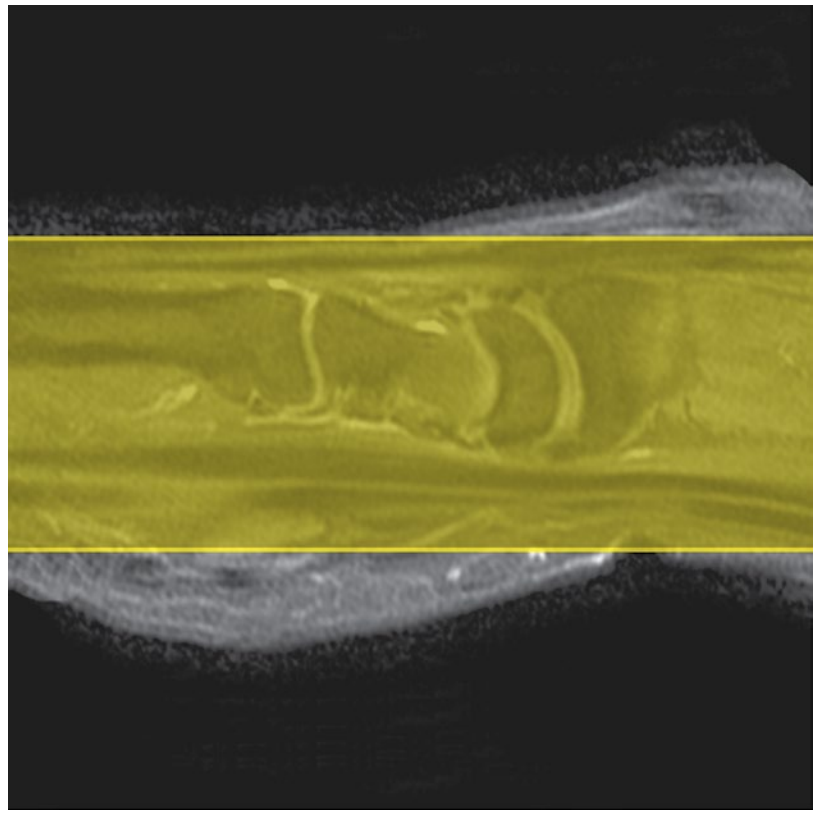

Figure 13.24 Sagittal GRE T2*-weighted localizer of the wrist showing slice prescription boundaries and orientation for coronal imaging.

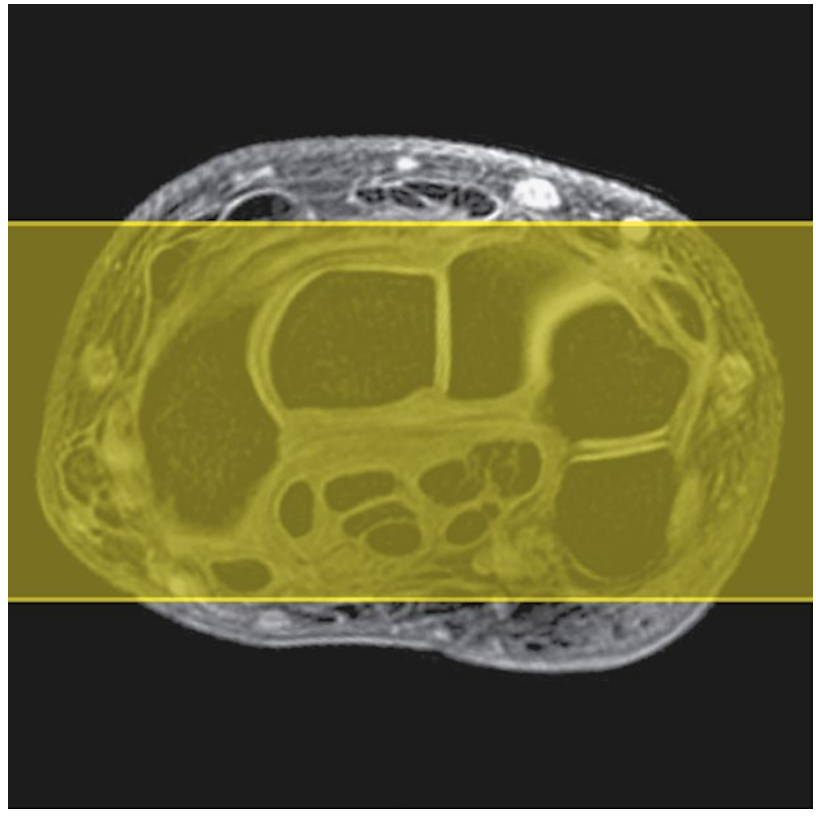

Figure 13.25 Axial GRE T2*-weighted localizer of the wrist showing slice prescription boundaries and orientation for coronal imaging.

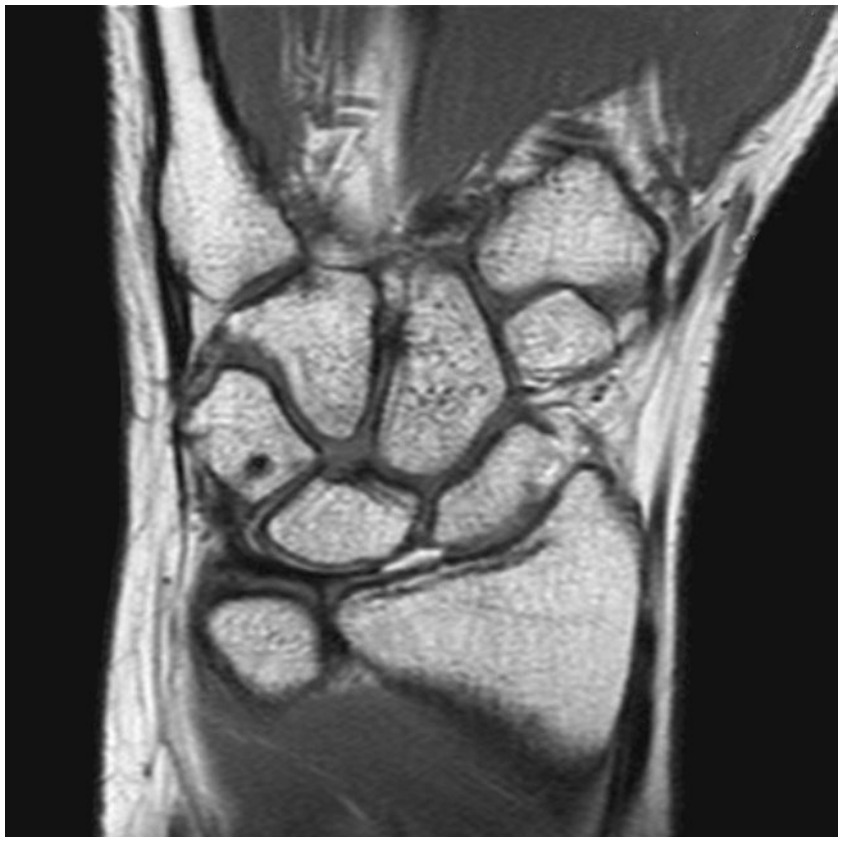

Figure 13.26 Coronal FSE T1-weighted image of the wrist showing normal appearances.

Coronal SE/FSE T1 (Figure 13.26)

Thin slices/gap or interleaved are prescribed through the joint or ROI parallel to the proximal row of the carpus as seen from the axial localizers (the distal radioulnar joint is frequently not aligned with the carpus). Displace slices inferiorly for the carpal tunnel. The area from the inferior border of the carpal bones to the distal portion of the forearm is included in the image.

Coronal SE/FSE T2 or coherent GRE T2* +/– tissue suppression (Figures 13.27 and 13.28)

Slice prescription as for coronal T1.

These sequences are useful for investigating the triangular fibrocartilage, fractures or AVN. STIR is not commonly used due to poor SNR, and therefore, good resolution is difficult to obtain.

Axial FSE T2 (Figure 13.29)

Thin slices/gaps are prescribed through the ROI orientated parallel to the proximal row of carpal bones as seen on the coronal images (Figure 13.30).

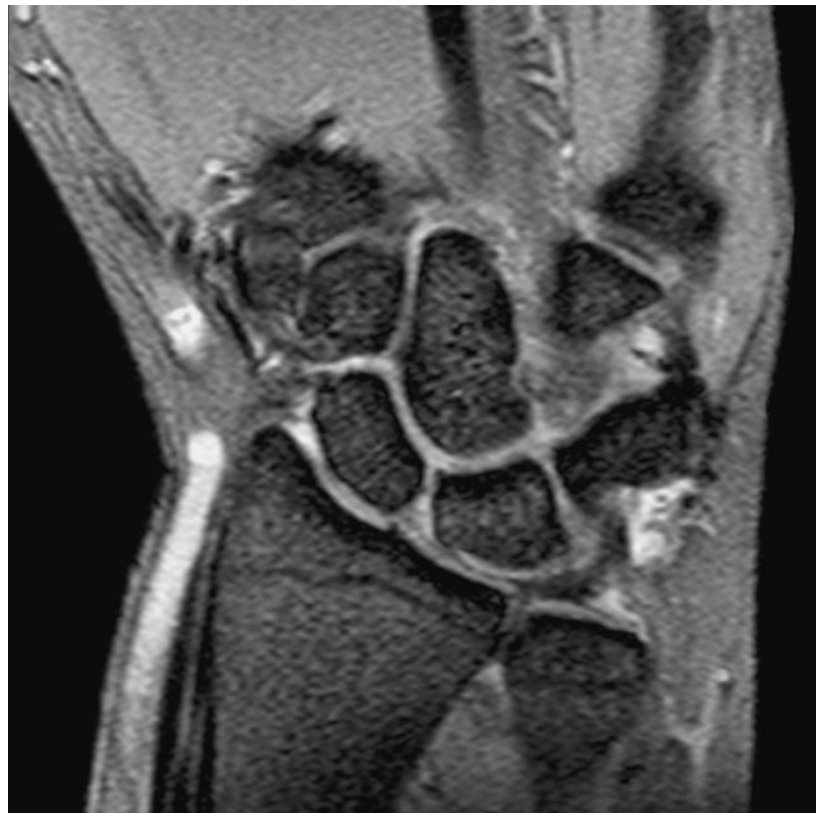

Figure 13.27 Coronal coherent GRE T2*.

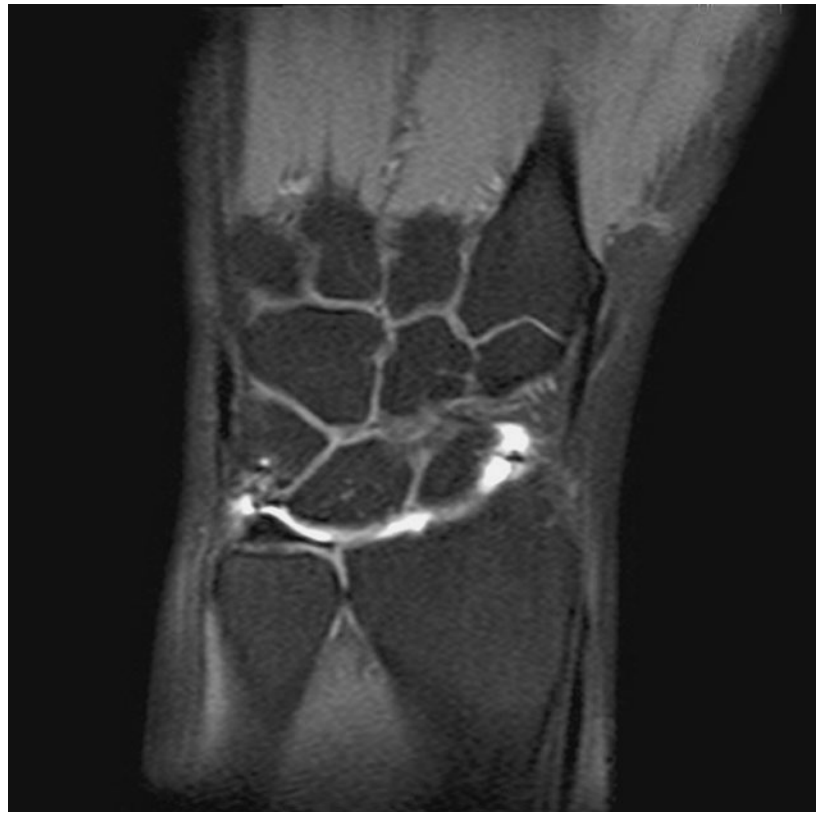

Figure 13.28 Coronal FSE T2-weighted image of the wrist with tissue suppression.

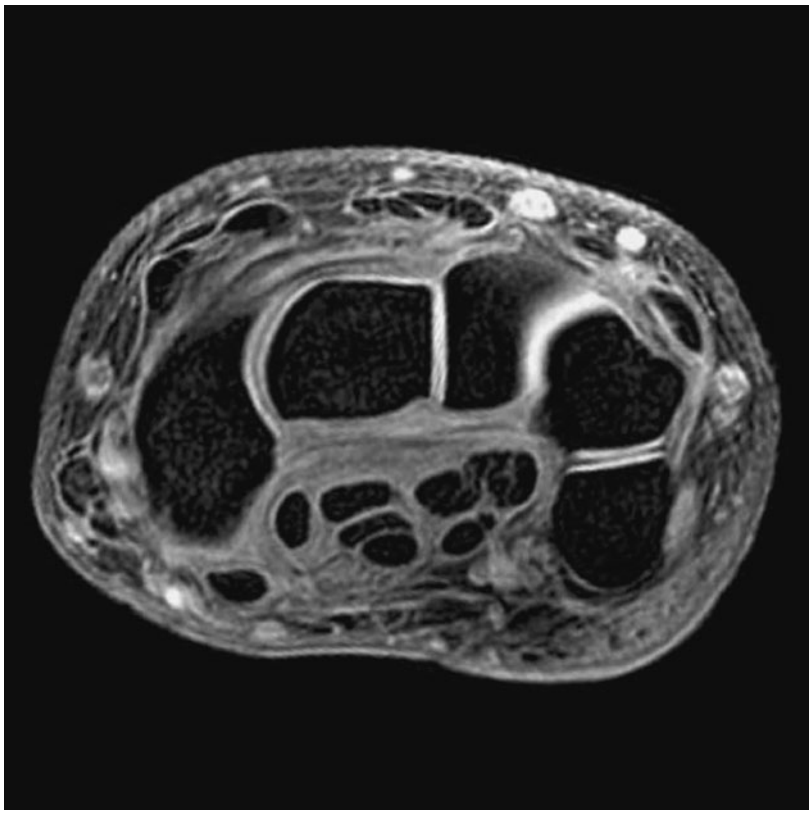

Figure 13.29 Axial FSE T2-weighted image through the carpel tunnel.

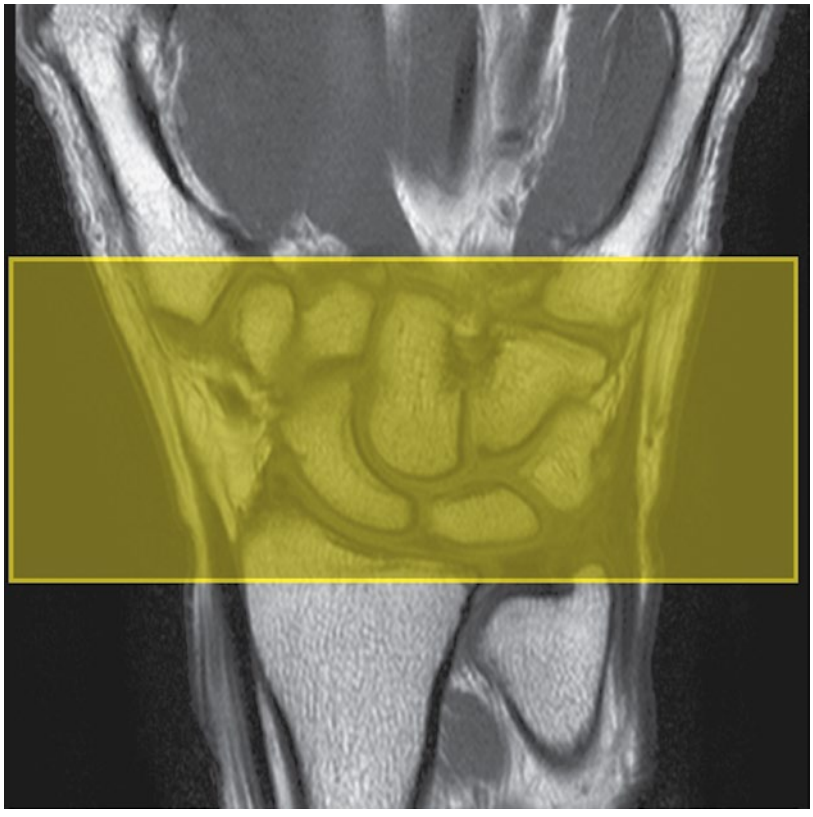

Figure 13.30 Coronal FSE T1-weighted image showing slice prescription boundaries and orientation for axial imaging of the wrist.

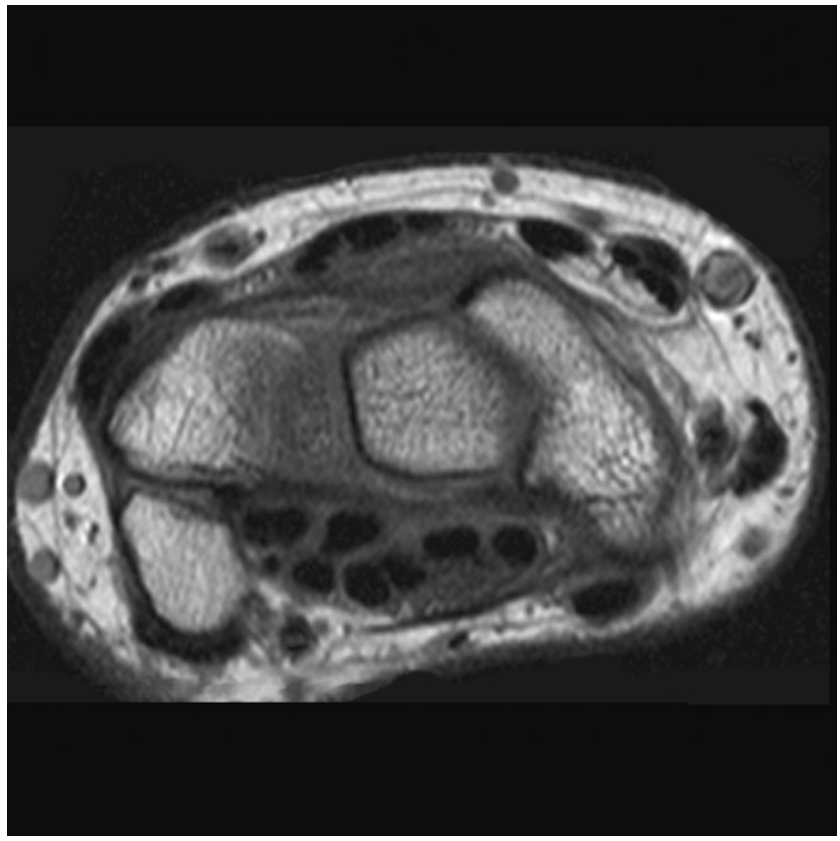

Figure 13.31 Axial FSE T1-weighted image of the wrist clearly demonstrating the carpal tunnel.

Axial FSE T1 (Figure 13.31)

Slice prescription as for axial T2.

This sequence is useful for carpal tunnel syndrome and ulnar nerve lesions.

Additional sequences

Axial PD + tissue suppression (Figure 13.32)

Slice prescription as for axial T2.

This sequence is useful for visualization of articular cartilage and carpal tunnel.

Sagittal SE/FSE T1

Thin slices/gaps are prescribed orientated perpendicular to the coronal plane. This sequence is useful for localizing dorsal ganglia (Figure 13.33).

Sagittal SE/FSE PD + tissue suppression

Slice prescription the same as for sagittal T1.

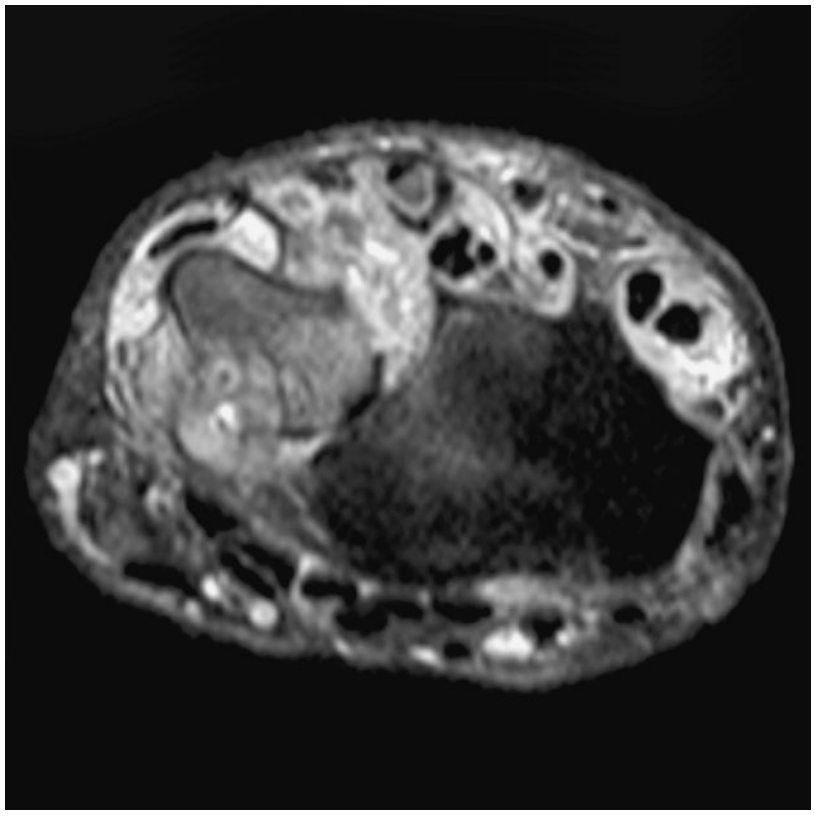

Figure 13.32 Axial FSE PD with tissue suppression.

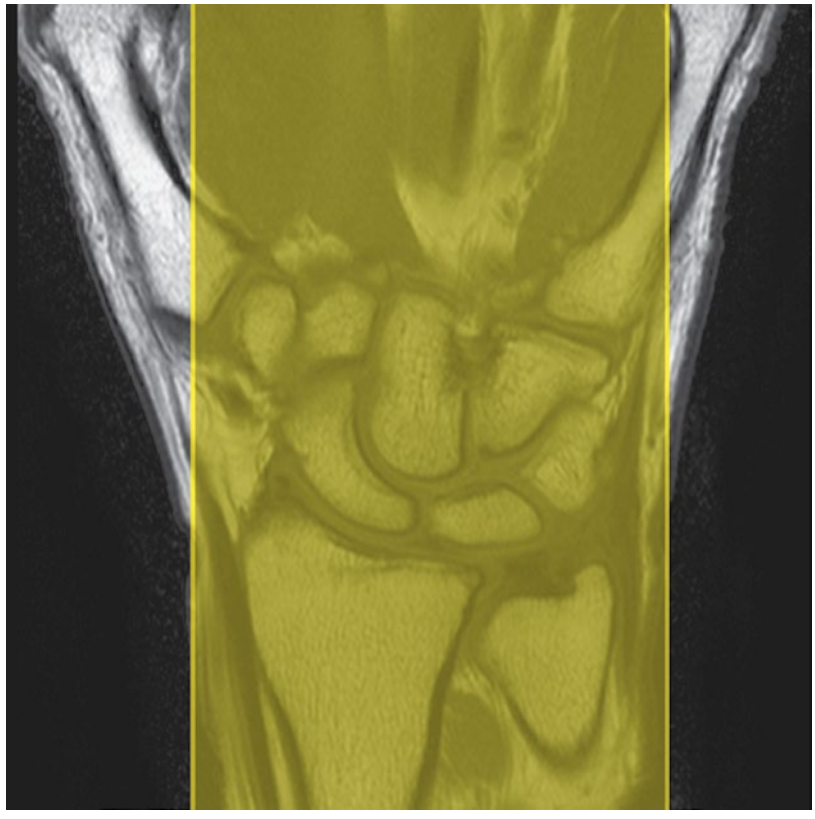

Figure 13.33 Coronal FSE T1-weighted image showing slice prescription boundaries and orientation for sagittal imaging of the wrist.

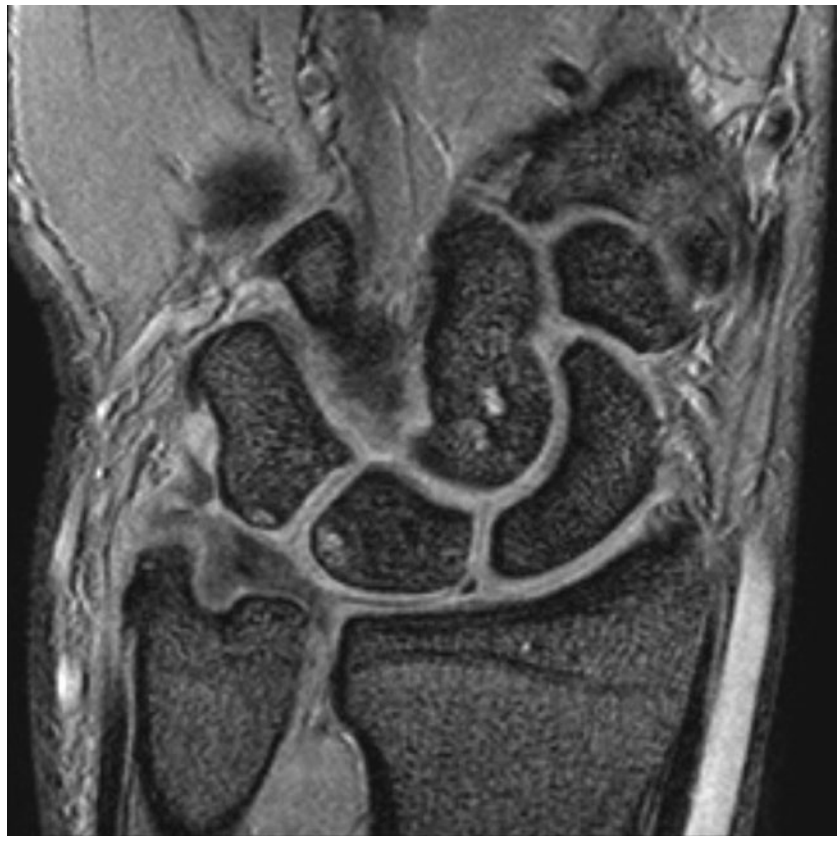

Figure 13.34 Coronal slice from a 3D T1-weighted data set.

3D incoherent (spoiled) GRE T1 or coherent GRE T2* (Figure 13.34)

Used to investigate fluid or solid pathologies with thin slices but at the expense of resolution. Hybrid contrast sequences like balanced GRE showing anatomy and fluid are also popular. Thin slices and a small number of slice locations are prescribed through the joint allowing for slice wrap.

Sagittal/axial/coronal FSE T1/T2 of the hand or fingers (Figure 13.35)

Used to investigate bone or joint abnormalities. High-resolution parameters are required.

Image optimization

Technical issues

The TE influences the signal of the muscle in musculoskeletal imaging. A very long TE produces T2-weighted images in which muscle is hypointense. The SNR is therefore reduced but fluid detection is improved. Tissue suppression can also be used to enhance the signal from fluid even further; however, larger voxels may be required to compensate for the

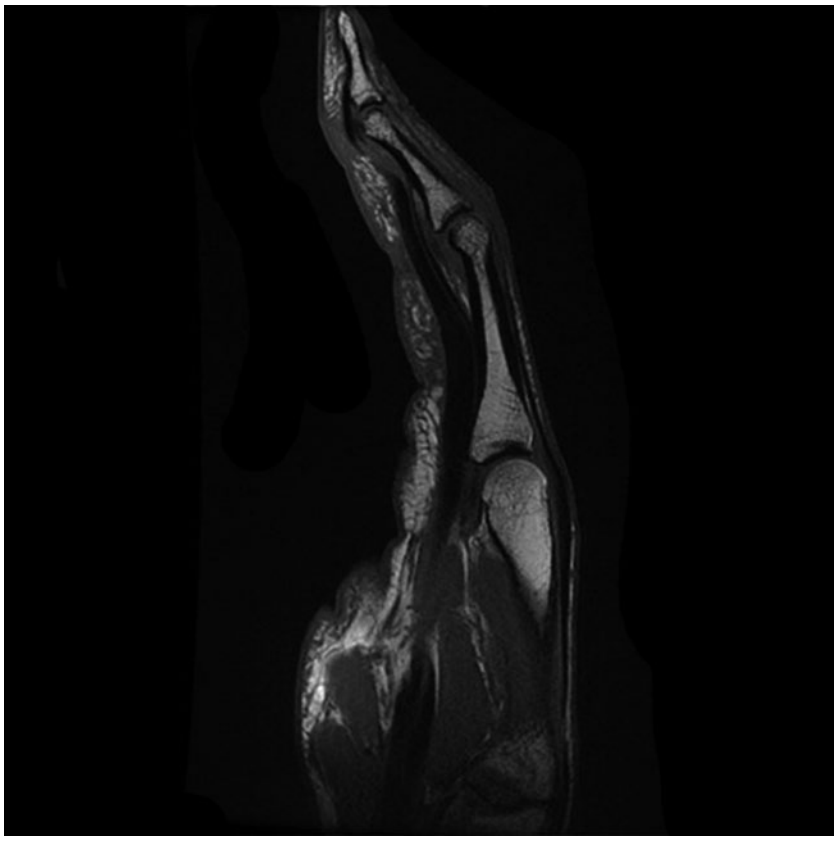

Figure 13.35 Sagittal T1-weighted image of the finger.

inherent drop in SNR. By choosing a moderate TE, muscle still retains signal (a grey-level intensity) and the images are PD weighted. The SNR is however higher and the spatial resolution can be better than a T2-weighted image. This kind of contrast is used to detect fluid and retain an anatomical image. Tissue suppression techniques are recommended with this kind of weighting because signal from fluid is reduced. Cartilage lesions can be better detected when TE is high (at least 30–40 ms) because the signal from normal cartilage decreases.

The quality of the coil is very important in the wrist. The inherent SNR and CNR are relatively low as most of the structures are bony, and there is little fat. The use of a dedicated wrist coil ensures a high and uniform signal return, so that the high resolution required in the wrist is easily obtained. Newly developed surface coils using multiple element configurations provide excellent image quality. Multiple NEX/NSA may also be necessary to improve the SNR. Very small, specially designed, surface coils may be used to examine the fingers individually. However, this type of examination is not very common at present.

High spatial resolution is essential to display the fine anatomy of the wrist adequately, and therefore, fine matrices and thin slices and interleaving are required. FSE is commonly utilized although longer ETLs and echo spacing

may induce significant blurring or compromise the diagnosis of tendon pathology in T1-weighted images (see *Pulse sequences* in Part 1).

Artefact problems

There is little artefact in this area as the vessel pulsations are not particularly strong, but spatial pre-saturation pulses placed S and I to the FOV reduce phase ghosting. Additionally, for coronal and sagittal imaging, frequency and phase can be swapped so that phase is along the axis of the arteries. GMN is not usually required to decrease flow artefact in the wrist, but it effectively increases the contrast of the synovial fluid in T2- and T2*-weighted images. Patient movement may be troublesome in the swimmer's position, especially if the scan times are lengthy. It is, therefore, necessary to ensure that the patient is carefully immobilized and comfortable. Instruct the patient not to move their fingers during the sequences. Motion induced by discomfort is often a problem. k-space filling techniques such as propeller reduce motion and flow sensitivity. Fat suppression is difficult in the periphery of the homogenous region of the magnet. Shimming improves chemical fat suppression and the quality of longer TE GRE sequences. All metal should be removed from the patient's clothing and body to preserve a good shim. Spatial pre-saturation pulses can be used to null signal from the body in axial imaging sequences or alternatively switch the phase direction to AP.

Patient considerations

Inform the patient of the possibly lengthy scan times and the importance of keeping still. Ensure that the patient is comfortable and well immobilized. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely used in the wrist; however, MR arthrography is sometimes useful in increasing the certainty of seeing perforations of the ligaments and triangular fibrocartilage. In some cases, it is useful to inject gadolinium IV to see post-operative fibrosis.

Key points

- See Chapter 14.

14 Lower limb

Handbook of MRI Technique, Fourth Edition. Catherine Westbrook.

Companion website: www.wiley.com/go/westbrook/mritechnique

Table 14.1 Summary of parameters

1.5T		3T	
SE		**SE**	
Short TE	Min–30 ms	Short TE	Min–15 ms
Long TE	70 ms+	Long TE	70 ms+
Short TR	600–800 ms	Short TR	600–900 ms
Long TR	2000 ms+	Long TR	2000 ms+
FSE		**FSE**	
Short TE	Min–20 ms	Short TE	Min–15 ms
Long TE	90 ms+	Long TE	90 ms+
Short TR	400–600 ms	Short TR	600–900 ms
Long TR	4000 ms+	Long TR	4000 ms+
Short TEL	2–6	Short TEL	2–6
Long ETL	16+	Long ETL	16+
IR T1		**IR T1**	
Short TE	Min–20 ms	Short TE	Min–20 ms
Long TR	3000 ms+	Long TR	300 ms+
TI	200–600 ms	TI	Short or null time of tissue
Short ETL	2–6	Short ETL	2–6
STIR		**STIR**	
Long TE	60 ms+	Long TE	60 ms+
Long TR	3000 ms+	Long TR	3000 ms+
Short TI	100–175 ms	Short TI	210 ms
Long ETL	16+	Long ETL	16+
FLAIR		**FLAIR**	
Long TE	80 ms+	Long TE	80 ms+
Long TR	9000 ms+	Long TR	9000 ms + (TR at least 4 × TI)
Long TI	1700–2500 ms (depending on TR)	Long TI	1700–2500 ms (depending on TR)
Long ETL	16+	Long ETL	16+
Coherent GRE		**Coherent GRE**	
Long TE	15 ms+	Long TE	15 ms+
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Incoherent GRE		**Incoherent GRE**	
Short TE	Minimum	Short TE	Minimum
Short TR	<50 ms	Short TR	<50 ms
Flip angle	20–50°	Flip angle	20–50°
Balanced GRE		**Balanced GRE**	
TE	Minimum	TE	Minimum
TR	Minimum	TR	Minimum
Flip angle	>40°	Flip angle	>40°
SSFP		**SSFP**	
TE	10–15 ms	TE	10–15 ms
TR	<50 ms	TR	<50 ms
Flip angle	20–40°	Flip angle	20–40°

(*Continued*)

Table 14.1 (*Contd.*)

1.5T and 3T			
Slice thickness 2D		**Slice thickness 3D**	
Thin	2–4 mm	Thin	<1 mm
Medium	5–6 mm	Thick	>3 mm
Thick	8 mm		
FOV		**Matrix**	
Small	<18 cm	Coarse	256 × 128/256 × 192
Medium	18–30 cm	Medium	256 × 256/512 × 256
Large	>30 cm	Fine	512 × 512
		Very fine	>1024 × 1024
NEX/NSA		**Slice number 3D**	
Short	1	Small	<32
Medium	2–3	Medium	64
Multiple	>4	Large	>128
PC-MRA 2D and 3D		**TOF-MRA 2D**	
TE	Minimum	TE	Minimum
TR	25–33 ms	TR	28–45 ms
Flip angle	30°	Flip angle	40–60°
VENC venous	20–40 cm/s	**TOF-MRA 3D**	
VENC arterial	60 cm/s	TE	Minimum
		TR	25–50 ms
		Flip angle	20–30°

The figures given are for 1.5T and 3T systems. Parameters are dependent on field strength and may need adjustment for very low or very high field systems.

Hips

Basic anatomy (Figure 14.1)

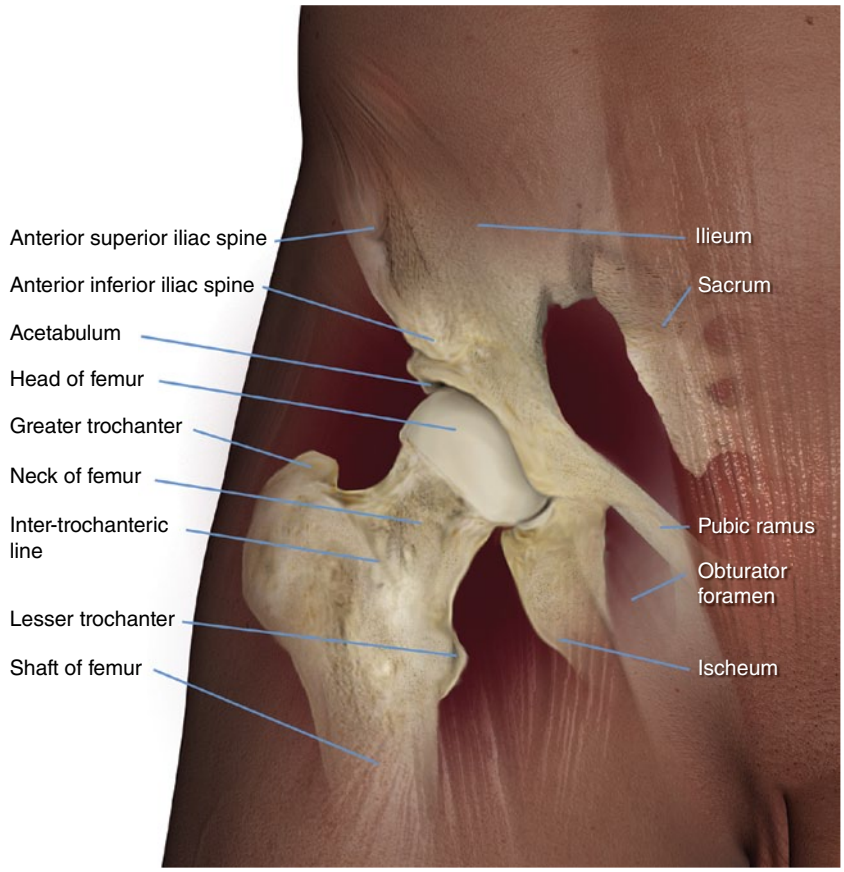

Figure 14.1 Anterior view of the right hip demonstrating bony components and ligaments.

Common indications

- Evaluation of unexplained unilateral or bilateral hip pain
- Suspected occult fracture
- Muscle tears
- Labral tears, chondral damage or other joint soft tissue pathology

Note: Bilateral and unilateral examinations of the hips are described in this section. The causes of generalized hip pain include AVN, metastatic deposits and occult fractures, which may affect both hips. Specific unilateral joint pathologies such as suspected labral tears or chondral damage require high-resolution imaging of the hip in question. However, due to the prevalence of AVN in patients presenting with hip pain, it is advisable to include a bilateral sequence in unilateral hip protocols.

Equipment

Bilateral hip imaging

- Body phased array/multi-coil array/general-purpose flexible coil/body coil
- Immobilization pads and straps
- 20° wedge sponges
- Earplugs/headphones

Single hip imaging

- Small/large flexible coil/multi-coil array/pelvis phased array/small Helmholtz pair
- Immobilization pads and straps
- 20° wedge sponges
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with their legs straight and both feet parallel to each other. This ensures that the angle of both femoral necks is the same, although they do not necessarily have to be internally rotated as in radiography of the hips. The legs are immobilized with the use of pads and straps wrapped around both feet. This enables the patient to maintain the position in a relaxed fashion.

The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the femoral heads. They are localized by palpating the femoral pulse, which is typically found 3 cm inferiorly and laterally to the midpoint of the line joining the anterior superior iliac spine (ASIS) and the pubic symphysis. If only one hip is imaged, the FOV will be offset from isocentre and image quality may be affected.

Suggested protocol: bilateral examination

Axial SE/FSE/incoherent (spoiled) GRE T1

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Thick slices/gaps are prescribed on either side of the horizontal alignment light. Both hips are included to show the location and alignment of the hips.

Axial I 25 mm to S 25 mm

Coronal FSE T2 +/– tissue suppression/STIR

Thin slices/gaps are prescribed from the posterior to the anterior margins of the musculature of the hip (from the iliacus to the anterior portion of gluteus maximus). Slices may be angled to compensate for positional

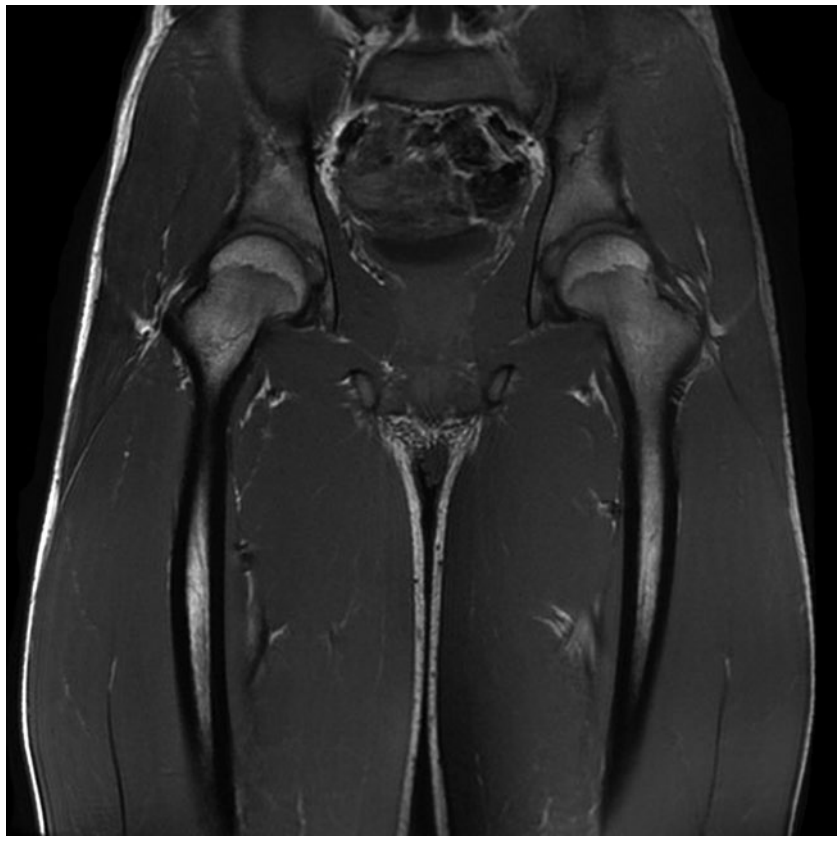

Figure 14.2 Coronal FSE T1 image of both hips and femora.

rotation of the pelvis. The images should display the lateral edges of the muscles surrounding the hips (gluteus medius), and extend from the junction of the ilium and the superior acetabulum to below the lesser trochanter.

Coronal SE/FSE T1 (Figure 14.2)

Slice prescription as for coronal T2.

Axial SE/FSE T1

Thin slices/gap are prescribed from above the articular portion of the acetabulum to the superior edge of the lesser trochanter, and aligned with the superior surface of both femoral heads to correct for positional errors (Figure 14.3).

Sagittal FSE T2/coherent GRE T2* +/– tissue suppression

Thin slices/gaps are prescribed from the lateral aspect of the greater trochanter through the articular portions of the acetabulum (Figure 14.4). These images particularly demonstrate flattening of the femoral head

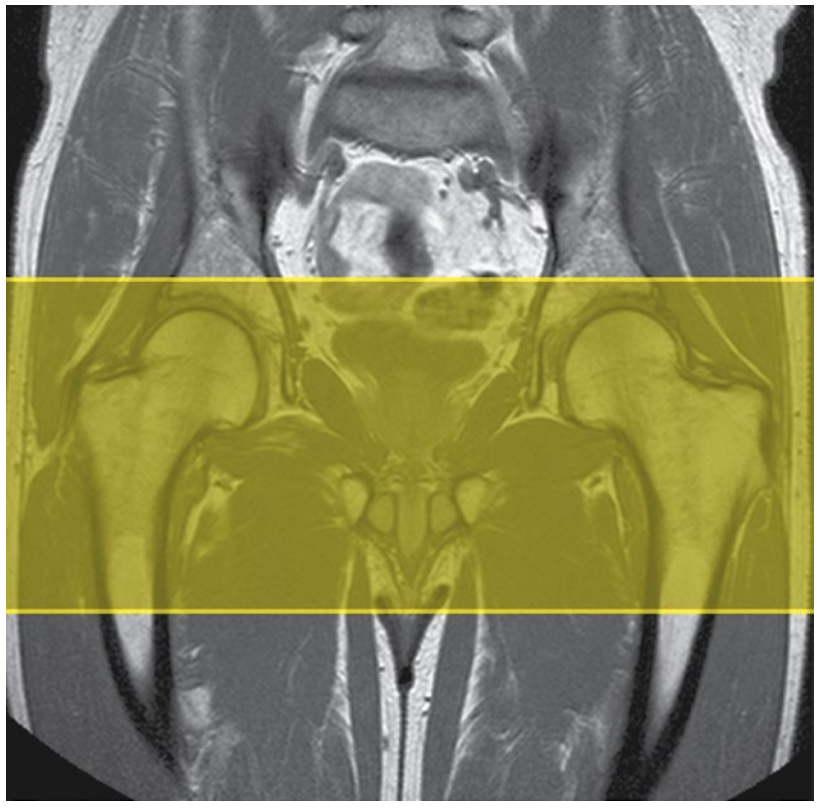

Figure 14.3 Coronal FSE T1-weighted image showing slice prescription boundaries and orientation for axial imaging of the hips.

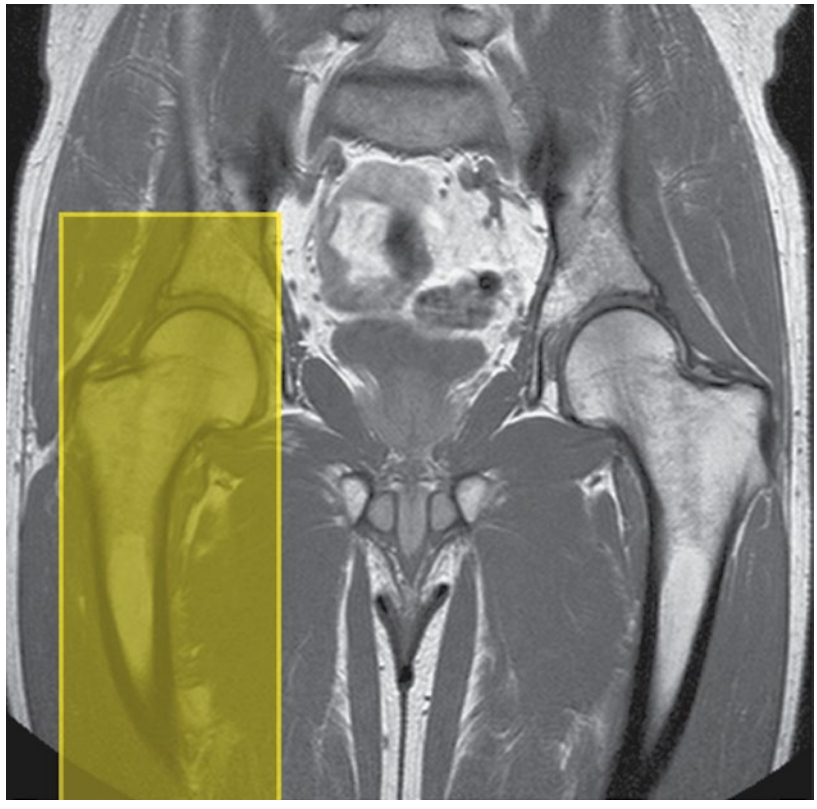

Figure 14.4 Coronal FSE T1-weighted image showing slice prescription boundaries and orientation for sagittal imaging of the hips.

associated with AVN. Generally, FSE is the sequence of choice, but GRE sequences provide excellent visualization of cartilage.

Suggested protocol: unilateral examination

This examination usually demands higher resolution than bilateral exams. Image planes should be placed relative to the anatomy of the joint rather than orthogonal to the body. Extra shimming may be required to optimize tissue suppression performance and GRE image quality in an offset FOV.

Axial SE/FSE/incoherent (spoiled) GRE T1

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. As for bilateral examination. Use the body coil and include both hips.

Coronal SE/FSE T1

Thin slices/gap are prescribed from the posterior to the anterior margins of the femoral head and aligned parallel to the femoral neck. The area from the proximal margin of the femoral shaft (below the lesser trochanter) to the greater sciatic notch is included in the image.

Coronal coherent GRE T2*/FSE T2 +/– tissue suppression

Slice prescription as for the coronal T1.

T2* images are particularly good for identifying the labrum and loose bodies in the joint. A FSE T2 may be preferred to provide higher resolution.

Axial FSE T2 +/– tissue suppression

Thin slices/gaps are prescribed from a coronal image to include the articular components of the hip joint. Angle the slices so that they are parallel to the femoral neck.

Axial SE/FSE/incoherent (spoiled) GRE T1

Slice prescription as for axial T2.

Additional sequences

Coronal FSE T2 +/– tissue suppression (both hips)

This may be used as an additional sequence to the unilateral examination, especially to rule out AVN of the asymptomatic hip. Use the body coil to avoid repositioning of the patient. Medium slice/gap is adequate as the contrast sensitivity of the sequence should identify pathology. Position slices to include the bony components of the hip joint and some surrounding musculature.

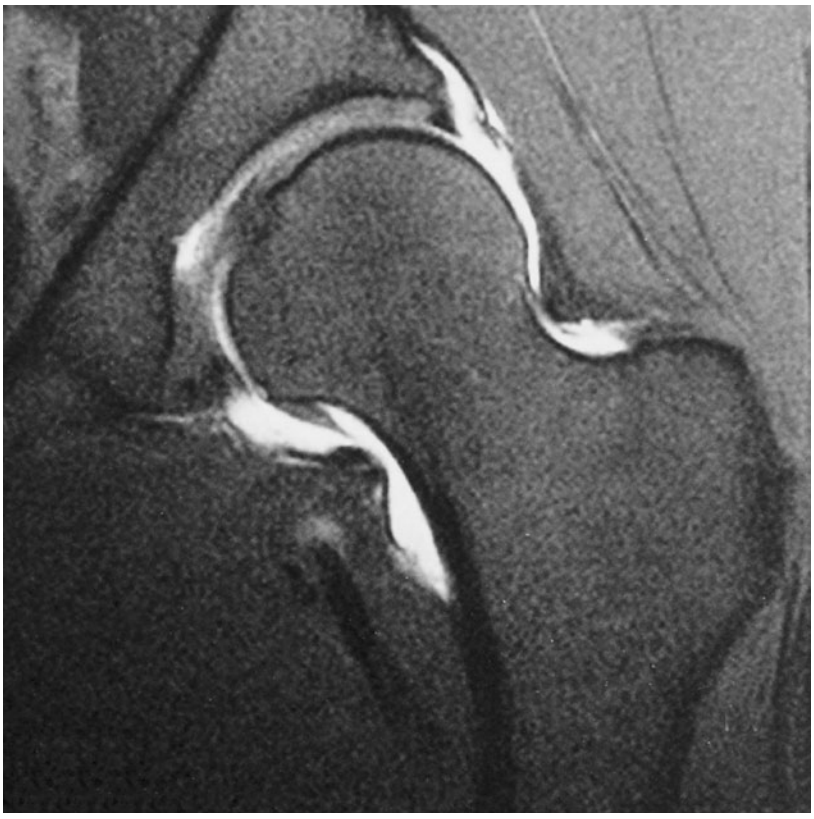

Figure 14.5 Coronal arthrogram.

Coronal/oblique FSE T2 + tissue suppression (both hips)

This sequence, with thin slices/gap and fine matrices, may be used to visualize the labral tears.

SE/FSE/incoherent (spoiled) GRE T1 + contrast (Figures 14.5 and 14.6)

This sequence may be used after intra-articular injection of contrast to visualize labral tears and chondral defects. A very dilute solution of gadolinium contrast agent in saline (1:100) is introduced into the joint capsule, and the single joint is imaged at high resolution with tissue suppression. T1-weighted images in three planes are acquired aligned to the femoral neck and acetabular rim.

Image optimization

Technical issues

The TE influences the signal of the muscle in musculoskeletal imaging. A very long TE produces T2-weighted images in which muscle is hypointense. The SNR is therefore reduced but fluid detection is improved.

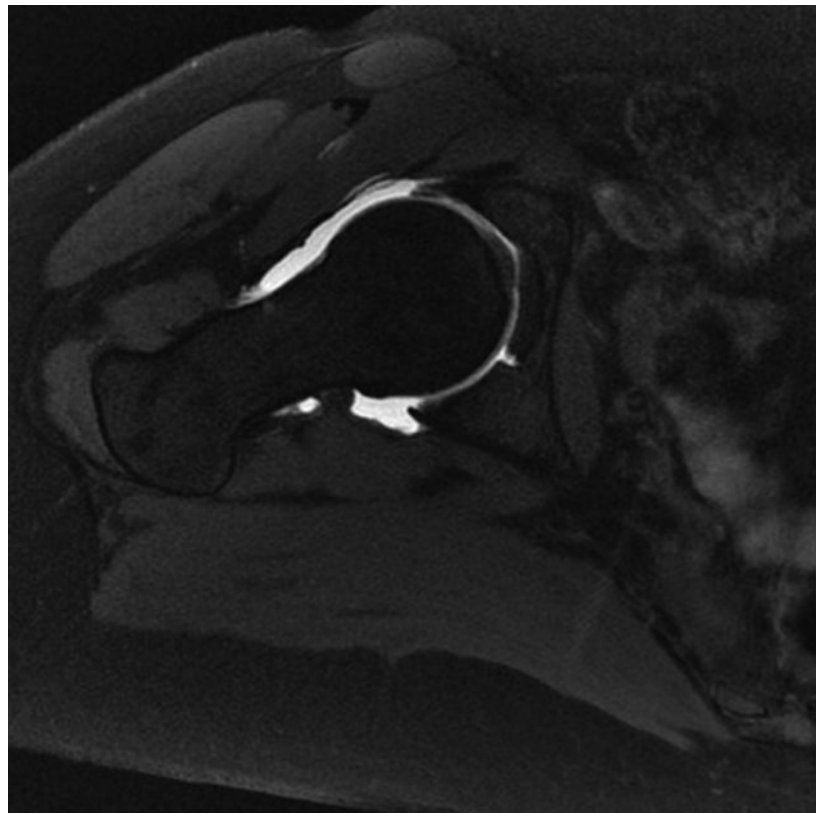

Figure 14.6 Axial arthrogram.

Tissue suppression can also be used to enhance the signal from fluid even further; however, larger voxels may be required to compensate for the inherent drop in SNR. By choosing a moderate TE, muscle still retains signal (a grey-level intensity) and the images are PD weighted. The SNR is however higher and the spatial resolution can be better than a T2-weighted image. This kind of contrast is used to detect fluid and retain an anatomical image. Tissue suppression techniques are recommended with this kind of weighting because signal from fluid is reduced. Cartilage lesions can be better detected when TE is high (at least 30–40 ms) because the signal from normal cartilage decreases.

Spatial resolution is a critical parameter in joint imaging and depends on the clinical indications. For example, when examining small labral tears, resolution is paramount and utilization of thin slices/gap and a fine high matrix is necessary. However, when the lesion is large and CNR is high, resolution can be sacrificed to achieve better SNR or shorter scan times. Volume acquisitions are sometimes valuable as very thin slices with no gap are used, and joint structures may be visualized in any plane. As volume acquisitions are usually performed in order to demonstrate anatomy, an incoherent (spoiled) GRE sequence that produces predominantly T1 weighting is required.

Bilateral and unilateral examinations have been described in this section. Bilateral imaging with a large phased array coil has a number of advantages.

It can provide acceptable resolution for visualizing joint structures when used with a combination of a small FOV and oversampling, but it can also be utilized with a large FOV to provide medium-resolution images of a large area of anatomy. For unilateral examinations, the requirement for fine spatial resolution is paramount. The hip joint structures are comparable in size to the shoulder, requiring high spatial resolution (pixel size less than 0.5 mm). Unfortunately, the relatively bulky musculature and the external morphology of the hip demands physically larger coils. As a result, it may be necessary to use higher NEX/NSA and longer scan times to achieve acceptable SNR.

Flexible selection of a rectangular/asymmetric FOV has greatly helped to tailor hip sequences in the axial and sagittal planes. In addition, flexible application of oversampling allows a small FOV to be used in the coronal and axial planes in conjunction with larger coils, as well as providing finer incremental changes in SNR.

Several sequences are employed in hip examinations. SE sequences usually provide better contrast and resolution in T1-weighted images than FSE. However, the development of high-performance gradients reduces blurring associated with long ETLs. Tissue suppression is an important imaging option in the musculoskeletal system, as the suppression of normal fatty marrow often enhances the visualization of bony pathology. Tissue suppression techniques are usually preferred, but STIR sequences provide very uniform fat suppression (and the degree of the fat suppression can be controlled by altering the inversion time), particularly on older systems and in large FOVs. There is a developing trend to use moderately short TE acquisitions (35–60 ms) for fat-suppressed PD-weighted FSE sequences which yield higher SNR and improve CNR between cartilage and muscle. The efficacy of this approach has not yet been established. Additional shimming may be required before tissue suppression sequences.

While reduced bandwidth sequences offer SNR increases without serious time penalties, the bandwidth should be chosen to limit the chemical shift to one or two pixels for most non-fat-suppressed sequences and particularly when producing high-resolution images. When a tissue suppression technique is used, chemical shift artefact is less problematic and a lower bandwidth can be used. However, because a reduced bandwidth improves SNR, flow sensitivity and therefore flow artefacts are more evident.

Artefact problems

The main source of artefact is from flow within the femoral and iliac vessels. Spatial pre-saturation pulses placed S and I to the FOV reduce this to a large degree. When imaging a single hip for labral tears, bowel motion may be troublesome. Placing a spatial pre-saturation pulse medial to the hip effectively reduces this. GMN further minimizes flow artefact, but as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences. However, GMN can effectively increase contrast (depending on the direction GMN is applied)

in synovial fluid in T2- and T2*-weighted images. For FSE imaging, using a high receive bandwidth and/or shorter ETL reduces flow artefact and motion reduction techniques, such as PROPELLER, are also beneficial. For bilateral coronal acquisitions, fat suppression may not be homogenous due to the use of a large FOV. Therefore, additional shimming may be required before tissue suppression sequences. Alternatively, STIR sequences may be used. Techniques that use the 3-point Dixon method whereby four images are acquired in one sequence (water, fat, in and out of phase), provide robust fat-suppressed images (fat–water separation).

Hip prosthesis or pins produce significant magnetic susceptibility artefact. This can sometimes, but not always, ruin an image. Do not use a GRE sequence as gradients do not compensate for magnetic field inhomogeneities, thereby increasing magnetic susceptibility artefact. To minimize the artefact, select SE or FSE sequences in conjunction with a broad receive bandwidth, a lower TE and a coarser matrix. The artefact can sometimes be shifted away from the ROI by swapping the phase and frequency encoding directions, but this, in turn, may lead to aliasing. However, aliasing can be avoided by oversampling and careful location of the hands away from the side of the body and on to the chest.

Chemical suppression techniques cannot be used when metallic implants are present. Other types of suppression or STIR sequences are recommended. Recently, protocols have been developed for imaging soft tissue in the vicinity of metallic prosthesis. These techniques significantly reduce magnetic susceptibility artefact, and therefore, inflammation can be detected close to the prosthesis.

Patient considerations

Patients with a hip prosthesis may experience warmth during the examination. They have to be warned of this, and an emergency bell has to be provided and used in case of any discomfort. Due to excessively loud gradient noise associated with some sequences, earplugs/headphones must always be provided to prevent hearing impairment.

Contrast usage

IV contrast is virtually never indicated in hip joint imaging unless as an indirect MR arthrography technique (see Shoulder in Upper Limb). Direct MR arthrography of the hip is an important technique in the diagnosis of some hip disorders, especially labral tears. Arthrography techniques include:

- coronal SE/FSE T2 + tissue suppression
- coronal SE/FSE T1 + tissue suppression
- para-axial SE/FSE T1 + tissue suppression
- 3D BGRE or GRE T1 + tissue suppression

Femur

Basic anatomy (Figure 14.7)

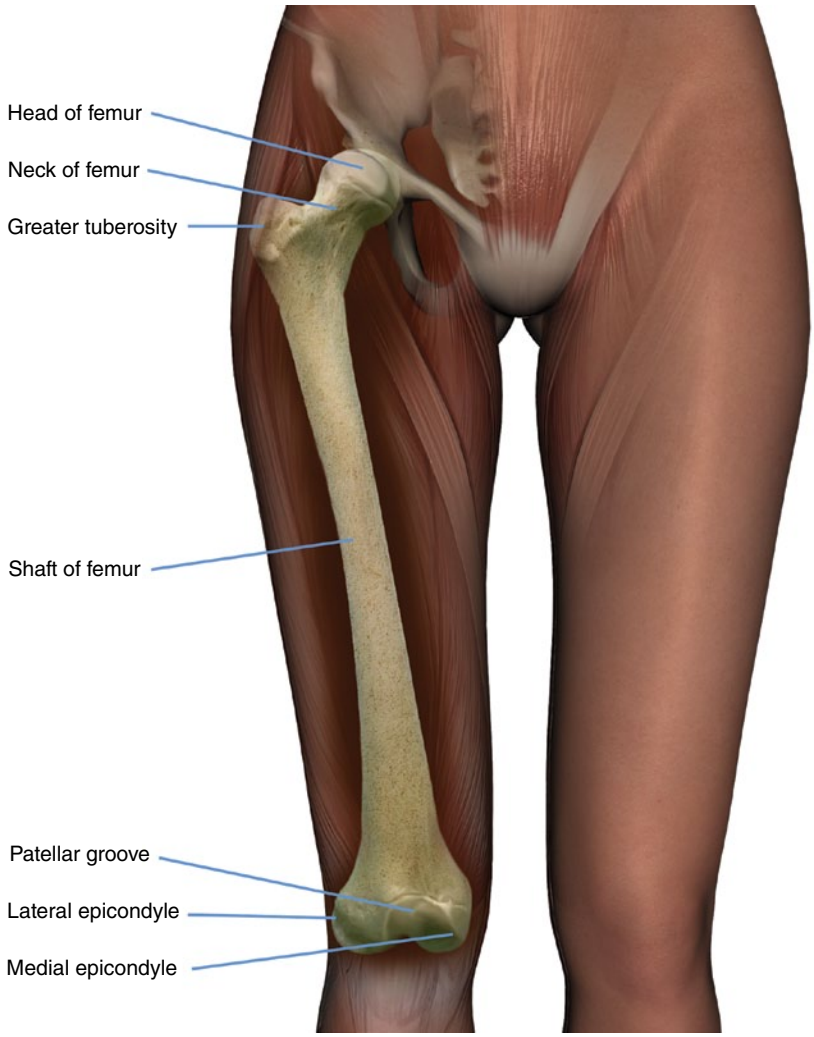

Figure 14.7 Anterior view of the right femur.

Common indications

- Assessment of suspected or known pathology of soft tissues and bone (tumours, infection, muscle tears)

A bilateral examination is recommended for all new cases, but single-sided imaging can be used for follow-up examinations, particularly if an array coil is unavailable.

Equipment

- Body array coil for imaging both femora or one femur (offset the anterior and posterior portions slightly to cover the entire femur)/ body coil for both femora/long surface coil placed under the femur if only one leg is under examination and the ROI is localized posteriorly in the thigh
- Immobilization pads and straps
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with their legs straight and their feet in a comfortable position. The feet are immobilized in this position using pads and straps. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through a point midway between the knee and the hip (or over the ROI if this is known). If only one side is to be imaged, the patient should be moved until the femur is as close as possible to the midline of the bore. Use the plastic ruler to measure from the horizontal alignment light to each joint to ensure the full femur fits within the long axis of the FOV. If not, include either the knee or hip depending on the location of the lesion(s). When a lesion is palpable, place an oil- or water-filled marker over it for easy localization. For large lumps or scars, place a marker at each end.

Suggested protocol

Axial/coronal/multi-planar SE/FSE T1/T2 or SS-FSE or incoherent (spoiled) GRE T1

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. Axial localizers are useful to locate lesions in the SI axis but do not indicate if the full length of the femur will be included in the other planes. Coronal localizers locate lesions situated in the RL axis. Medium slices/gap are prescribed from skin surface to skin surface. In the coronal plane, the entire length of the femur should be included in the image.

Axial localizer: I 100 mm to S 100 mm
Coronal localizer: P 50 mm to A 40 mm

Sagittal STIR

Medium slices/gap are prescribed to include the entire thigh and aligned parallel to the long axis of the femur. If bilateral lesions are suspected, repeat this sequence on the other leg.

Coronal SE/FSE T1

Medium slices/gap are prescribed to include the entire thigh from the anterior to the posterior skin surfaces and aligned parallel to the long axis of the femur. This sequence enables visualization of both femora for comparison and identification of lesions in the marrow space.

Coronal/oblique SE/FSE T2 + tissue suppression bilateral or coronal STIR bilateral

Slice prescription as for coronal SE/FSE T1

Axial SE/FSE T1

Medium slices/gap are prescribed to extend from well below to well above lesions seen on the coronal or sagittal images. Axial images are useful for localizing lesions within significant anatomical compartments. Breach of the marrow space, extension within or through muscle compartments and association with the neurovascular bundle are all significant characteristics.

Axial SE/FSE T2 +/– tissue suppression

Slice prescription as for the axial T1.

Image optimization

Technical issues

The inherent contrast is relatively good in this area due to the apposition of muscle and fat. The TE influences the signal of the muscle in musculoskeletal imaging. A very long TE produces T2-weighted images in which muscle is hypo-intense. The SNR is therefore reduced but fluid detection is improved. Tissue suppression can also be used to enhance the signal from fluid even further; however, larger voxels may be required to compensate for the inherent drop in SNR. By choosing a moderate TE, muscle still retains signal (a grey-level intensity) and the images are PD weighted. The SNR is however higher and the spatial resolution can be better than a T2-weighted image. This kind of contrast is used to detect fluid and retain an anatomical image. Tissue suppression techniques are recommended with this kind of weighting because signal from fluid is reduced. Cartilage lesions can be better detected when TE is high (at least 30–40 ms) because the signal from normal cartilage decreases.

The use of sensitive coils and medium-resolution imaging permits relatively fast examinations in the sagittal and coronal planes. As a result, more time can be spent acquiring higher-resolution axial images when necessary. Lesions close to the neurovascular bundle or subtle cortical bone breaches are examples of when this strategy might be utilized.

A surface coil increases the signal substantially as compared with the body coil, but signal fall-off in the anterior part of the thigh often prohibits its use. The body array coil must be positioned to provide coverage of the entire thigh. Total coverage of both femora is necessary in the evaluation of bony tumours to ensure that additional skip lesions are detected. Good spatial resolution is usually achievable especially if FSE is used, as fine matrices can be selected without unduly lengthening the scan time.

A rectangular/asymmetric FOV can be implemented in the sagittal and axial planes with the long axis of the rectangle either R to L or S to I, respectively. Tissue suppression techniques are commonly utilized, especially in FSE T2-weighted images, where the signal from fat remains bright and may return a similar signal to pathology. Additional shimming may be required before tissue suppression sequences. In T2 FSE, the signal returned from muscle is usually lower than in SE, thereby increasing conspicuity of some lesions. To enable accurate characterization of a new lesion, MRI must be performed before tissue biopsy or partial excision.

Artefact problems

Chemical shift artefact must be kept within one pixel, particularly in axial images, to delineate the interface of marrow and cortical bone and the edges of muscle compartments clearly. Flow artefact from the femoral vessels is the main source of phase ghosting in this area. Spatial presaturation pulses placed S and I to the FOV reduce this effectively. GMN minimizes the artefact, but as it increases the minimum TE, it is not usually beneficial in T1-weighted sequences.

Patient considerations

Patients with a hip prosthesis may experience warmth during an examination of the femur especially if there is a long femoral component. Warn them that this may occur and provide them with an emergency bell in case any discomfort is noticed. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely used in the femur. It may, however, be useful for tissue characterization of certain tumours.

Knee

Basic anatomy (Figure 14.8)

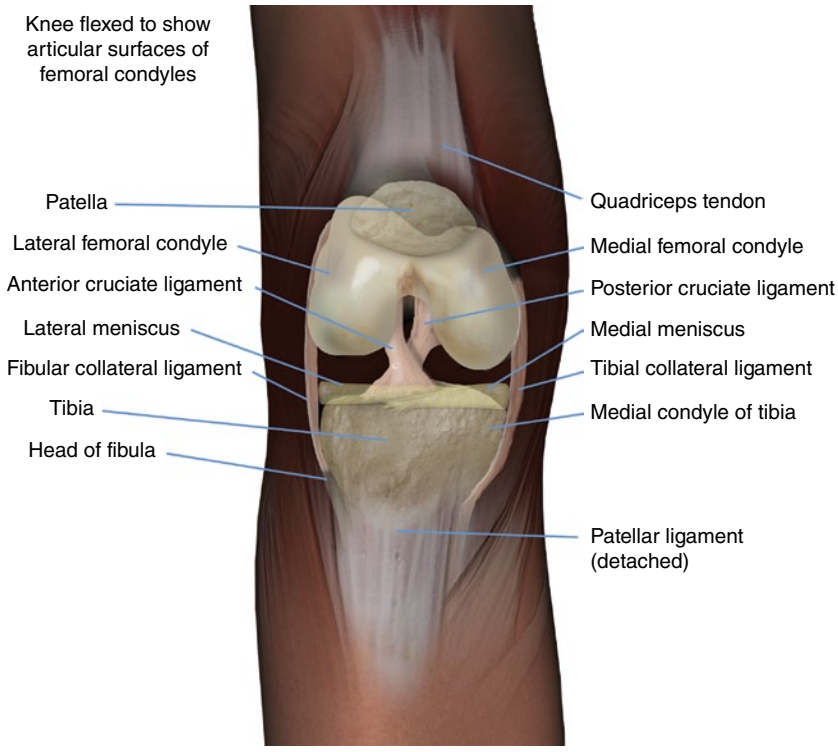

Figure 14.8 Anterior view of the right knee showing joint structures and ligaments.

Common indications

- Internal derangement of the joint (meniscal tears, cruciate ligament tears, post-repair cruciate ligament tears, bursae)
- Chondromalacia patella and patella tracking
- Bone tumours and bony damage within the knee joint
- Almost all other knee disorders can also be visualized

Equipment

- Knee phased array coil/extremity knee coil/pair of small circular coils combined as a phased/multi-coil array/large flexible coil
- Immobilization pads
- Earplugs or headphones

Patient positioning

The patient lies supine on the examination couch with their knee in a relaxed, slightly flexed position within the coil. The knee is well immobilized with pads. The coil can be offset so that the other leg rests comfortably at the side. The patient is positioned so that the longitudinal alignment light lies either along the midline of the leg under examination, or displaced from it if the knee has been offset. The horizontal alignment light passes through the centre of the coil. The knee is placed within the coil so that the centre of the coil corresponds to the lower border of the patella.

A clear display of the anterior cruciate ligament is essential in knee examinations for pain, trauma or suspected joint damage. The ligament is best seen in oblique sagittal scans oriented to the appropriate anatomical plane. If your equipment is not capable of oblique imaging, or oblique scan prescription compromises other significant technical choices, the patient's knee should be positioned with a slight (5–10°) external rotation (under-rotation is better than over-rotation). If the scanner can only employ a single-plane oblique, the sagittal scan plane can be prescribed along the internal margin of the lateral femoral condyle from an axial localizer. A more accurate approach is described within the Suggested protocol section.

Suggested protocol

Axial/multi-planar coherent gradient echo T2* (Figure 14.9) or axial PD with tissue suppression

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. If the knee is not at isocentre, the FOV is offset so that the knee is in the middle of the image. Medium slices/gap are prescribed on either side of the horizontal alignment light to locate the knee and ensure correct positioning.

Axial localizer: I 10 mm to S 10 mm

With an axial localizer, a slice in which the patella is clearly demonstrated is chosen to prescribe the following sequences as this ensures that the knee joint is centred to the FOV. If coronal or sagittal localizers are used, the knee joint should be in the middle of the image.

Sagittal coherent GRE T2* (Figure 14.10) or sagittal/oblique PD +/– tissue suppression

Thin slices/gap are prescribed from the lateral to the medial collateral ligament and aligned parallel with the anterior cruciate ligament which runs at an angle (5–10°). The superior edge of the patella to below the tibial tuberosity is included on the image (Figure 14.11). The sagittal plane is used to detect lesions of the cruciate ligaments, menisci, popliteal cysts

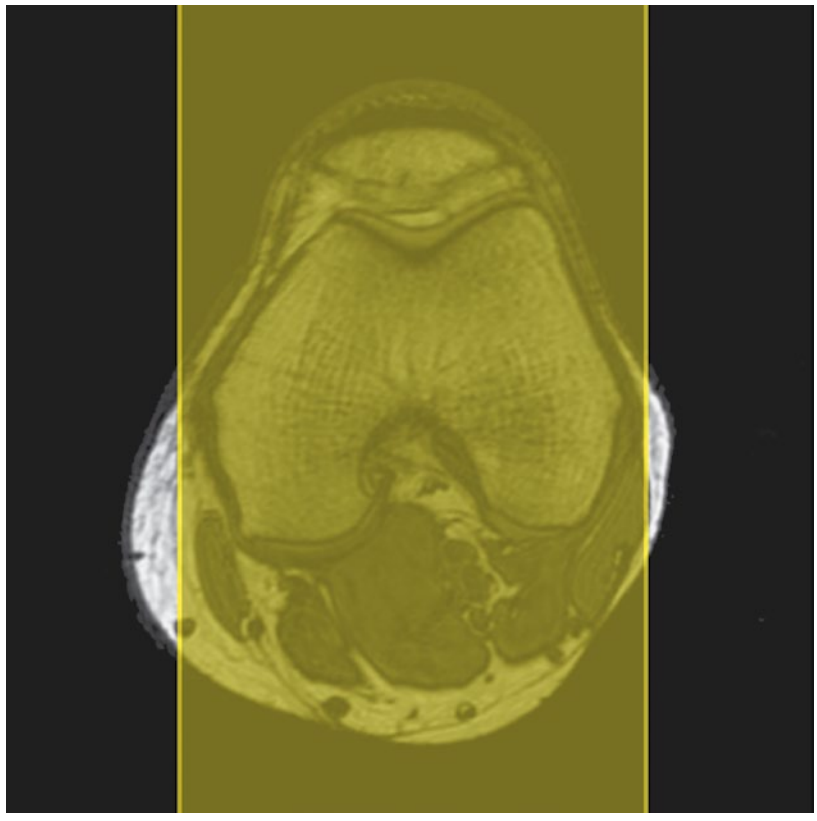

Figure 14.9 Axial T1-weighted localizer of the knee showing slice prescription boundaries and orientation for sagittal imaging.

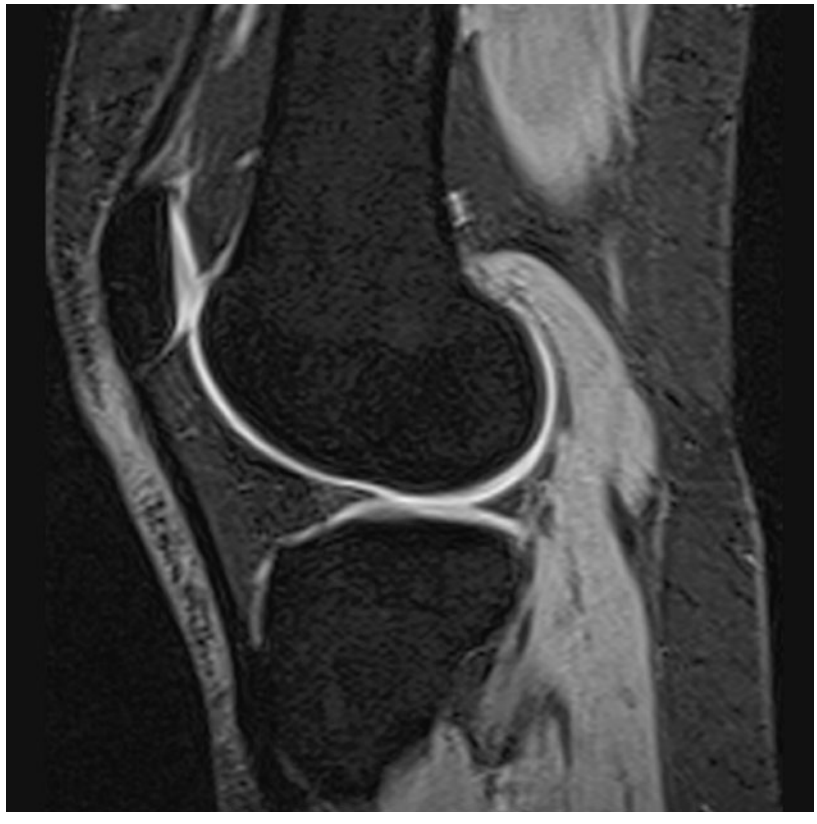

Figure 14.10 Sagittal coherent GRE T2*-weighted image of the knee with tissue suppression.

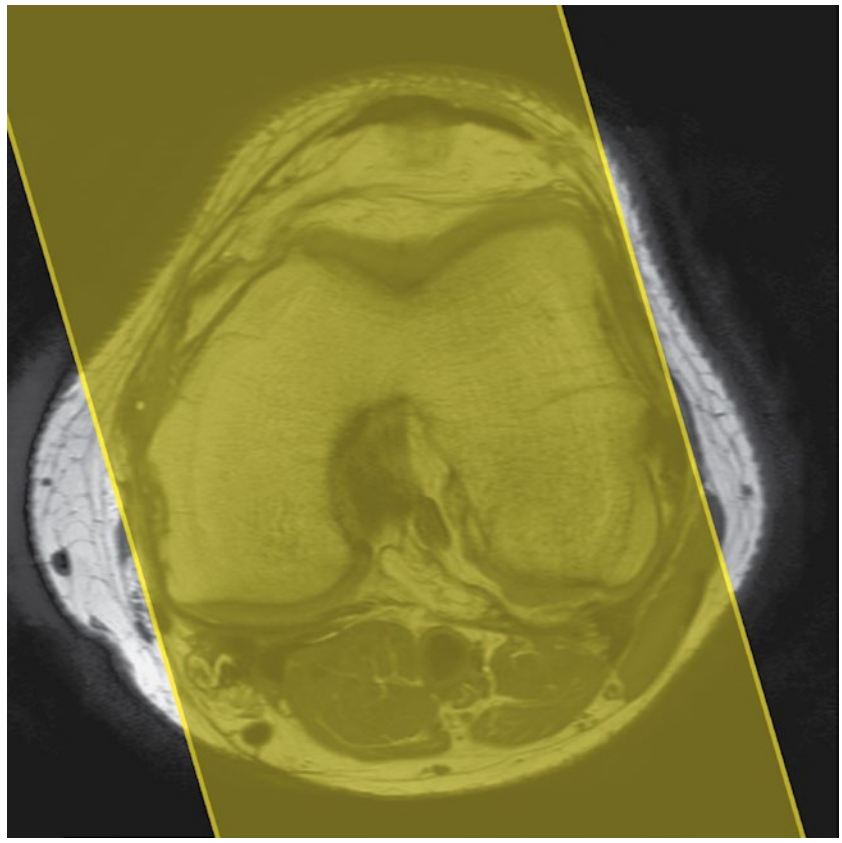

Figure 14.11 Axial T1-weighted localizer of the knee showing angled slice prescription boundaries and orientation for sagittal imaging of the anterior cruciate ligament.

and patella tendon injuries and require a high-resolution imaging (pixel size < 0.45 mm). For ligament imaging, sagittal PD-weighted acquisitions are performed without fat suppression, and ligaments are dark grey and fat bright. For lesion detection of the ligament, TEs between 45 and 65 ms are recommended in order to increase CNR.

Coronal FSE PD/T2 +/– tissue suppression (Figures 14.12 and 14.13)

Medium slices/gap are prescribed from the femoral condyles posteriorly to the anterior patella, and orientated parallel to the posterior surfaces of the femoral condyles (Figure 14.14). The superior edge of the patella to the inferior edge of the tibial tuberosity is included in the image. The coronal plane is used to detect meniscal lesions using high spatial resolution images (pixel size < 0.45 mm) and high sensitivity to fluid.

Coronal SE/incoherent (spoiled) GRE T1 (Figure 14.15)

Slice prescription as for coronal T2.

This sequence is useful to demonstrate joint anatomy, meniscal tears, musculature and the collateral ligament complexes. Due to great

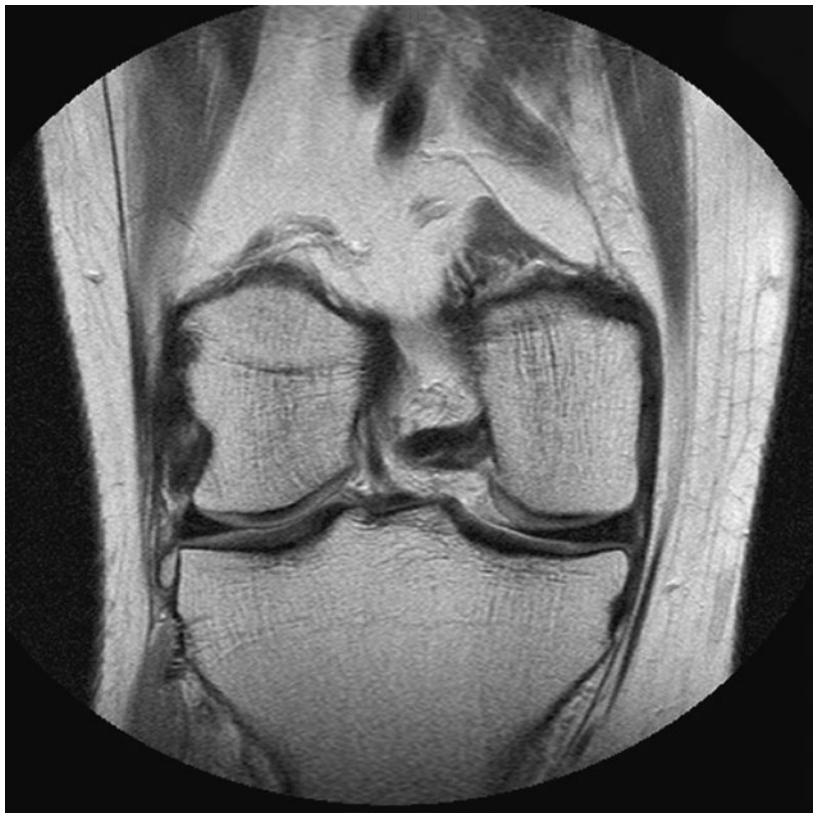

Figure 14.12 Coronal FSE PD-weighted image of the knee.

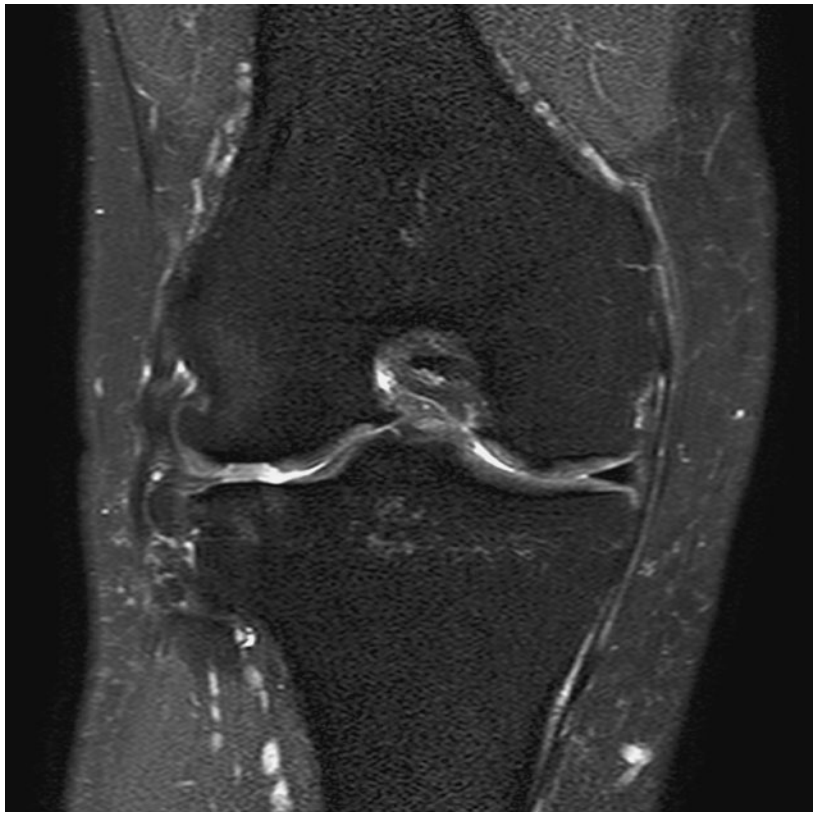

Figure 14.13 Coronal STIR image of the knee.

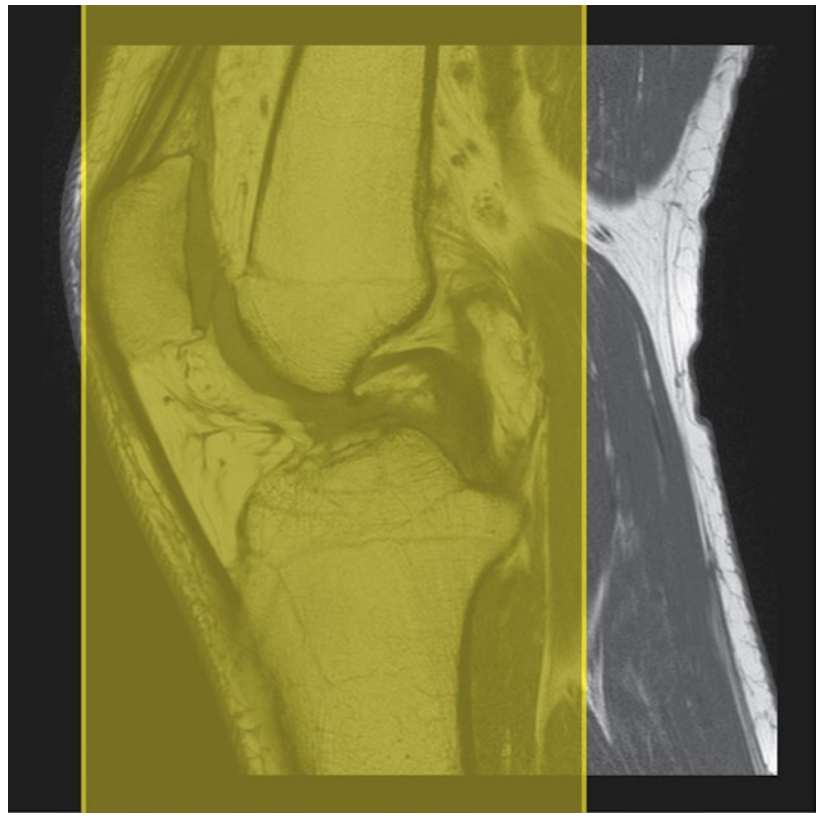

Figure 14.14 Sagittal coherent GRE image showing slice prescription boundaries and orientation for coronal imaging of the knee.

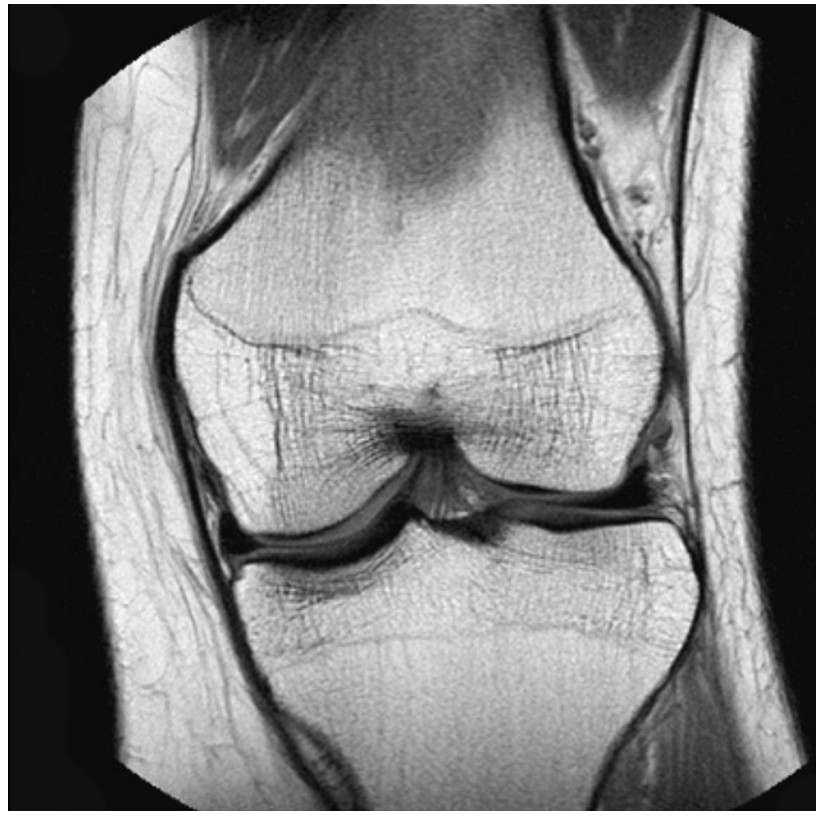

Figure 14.15 Coronal FSE T1-weighted image of the knee.

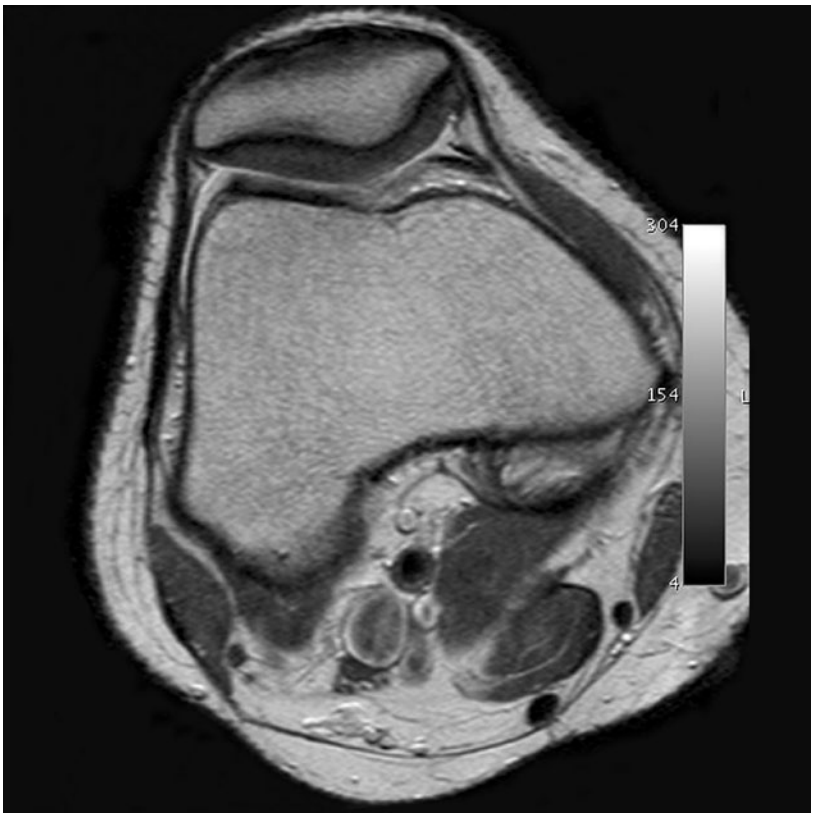

Figure 14.16 Axial FSE PD-weighted image of the knee.

differences in equipment and sequence performance, FSE should not be used in this application unless the ETL is very short and the accuracy of your sequences in identifying meniscal tears, compared with SE or incoherent (spoiled) GRE, has been tested. The receive bandwidth should be selected to reduce chemical shift to less than two pixels otherwise the femoral or tibial cartilage may be obscured.

Axial FSE PD/T2 +/– tissue suppression (Figure 14.16)

Thin slices/gap are prescribed from the superior surface of the patella to the tibial tuberosity. Thin axial slices are essential for patellar tracking problems and to identify chondral damage of the patella and anterior femoral condyles. Images can be repeated with the knee at various degrees of flexion in order to track patella tracking (see *Dynamic imaging* under *Pulse sequences* in Part 1).

Additional sequences

Axial/sagittal SE/FSE T1 +/– tissue suppression

Thin slice, high-resolution imaging is required if patellar tendonitis is suspected. For tumour detection, fat suppression is mandatory.

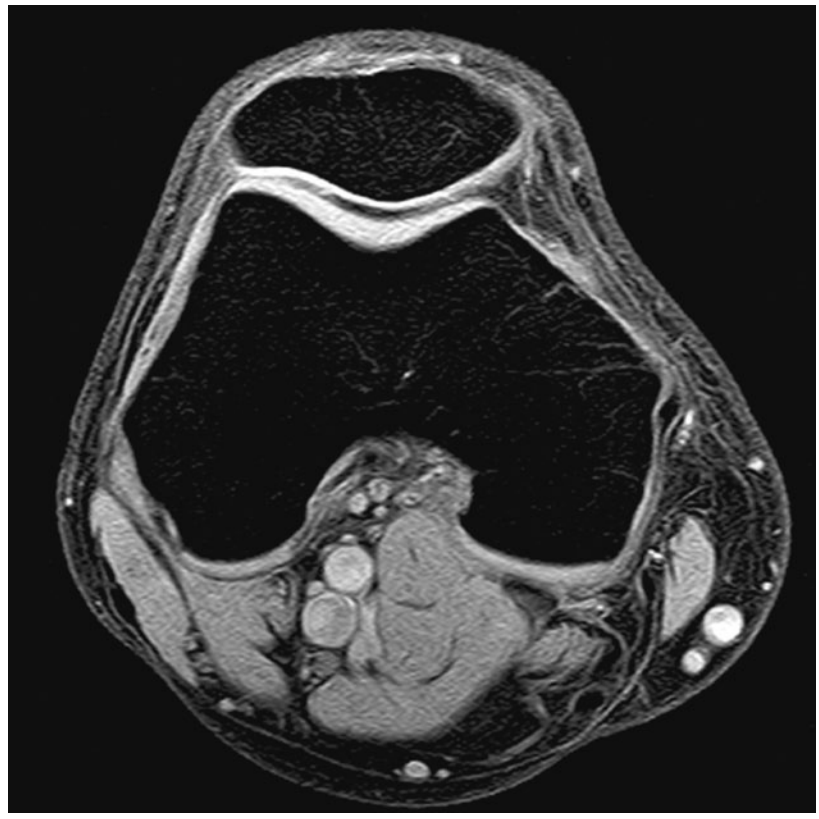

Figure 14.17 Axial slice from a 3D acquisition using tissue suppression.

3D FSE with variable refocus flip angle T2 or PD + tissue suppression

These techniques enable high-resolution, high-sensitivity imaging with the possibility to reformat in any plane. As they use variable refocus flip angles, they benefit from higher SNR, CNR and a shorter acquisition time compared to conventional 3D FSE. For PD weighting with tissue suppression, a TE more than 35 ms decreases signal from normal patella cartilage, thereby improving lesion detection.

3D coherent GRE PD/T2* +/– tissue suppression (Figure 14.17)

Thin slices with a medium to large number of slice locations and an isotropic data set are required to view anatomy in any plane. This is especially useful if evaluation of anatomy and pathology is difficult. Sagittal acquisitions large enough to include the entire knee, from above the patella to below the tibial tuberosity, are necessary.

An alternative is to use BGRE. This sequence enables high-resolution imaging of patella cartilage. In addition, multiple TE FSE based techniques can also be used for better lesion characterization of patellar cartilage, by using T2-mapping (quantification).

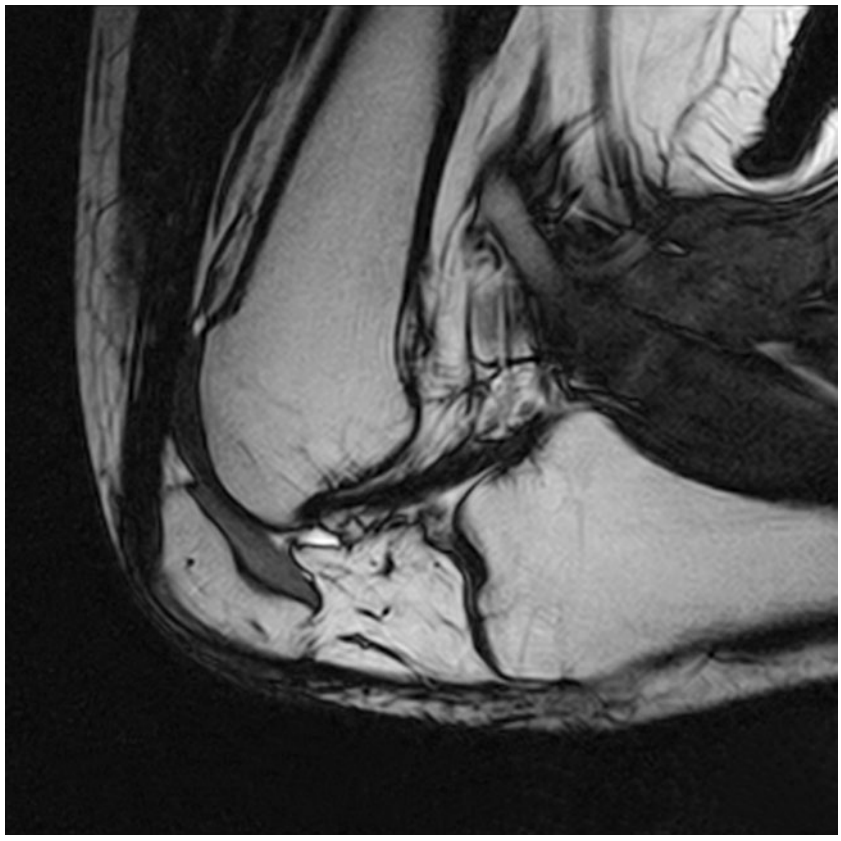

Figure 14.18 Sagittal T1-weighted image of a flexed knee during a dynamic study.

Dynamic imaging (Figure 14.18)

Some open systems, including small-bore magnets designed for orthopaedic imaging, permit dynamic imaging of the joints. In the knee, this is particularly useful for visualizing patellar tracking but may also be used to image other structures during movement.

Image optimization

Technical issues

The TE influences the signal of the muscle in musculoskeletal imaging. A very long TE produces T2-weighted images in which muscle is hypointense. The SNR is therefore reduced but fluid detection is improved. Tissue suppression can also be used to enhance the signal from fluid even further; however, larger voxels may be required to compensate for the inherent drop in SNR. By choosing a moderate TE, muscle still retains signal (a grey-level intensity) and the images are PD weighted. The SNR is however higher and the spatial resolution can be better than a T2-weighted image. This kind of contrast is used to detect fluid and retain an anatomical image. Tissue suppression techniques are recommended

with this kind of weighting because signal from fluid is reduced. Cartilage lesions can be better detected when TE is high (at least 30–40 ms) because the signal from normal cartilage decreases.

Due to the design of most coils, the SNR in the knee is usually good. These often transmit and receive coils and therefore ensure optimum and uniform signal coverage. In addition, the muscle, fluid and fat components of the knee give good inherent contrast. Excellent spatial resolution is usually necessary, especially when meniscal tears are suspected. Therefore, thin slices/gap and fine matrices are required. For assessment of the retropatellar region, a surface coil placed directly over the patella provides very good SNR and permits high-resolution imaging. When utilizing tissue suppression techniques, a reduced bandwidth increases the SNR considerably and should therefore be employed when possible. Additional shimming may be required before tissue suppression sequences.

High-resolution, fat-suppressed images with mild to strong T2 weighting are essential to display occult trabecular fractures, lateral and medial joint effusions and pannus formation. PD fat-suppressed images provide good demonstration of articular cartilage and collateral ligaments, and may adequately visualize meniscal tears (depending on the gradient system's capacity to deliver a short echo spacing). However, coherent GRE T2* sequences are usually necessary to demonstrate meniscal pathology.

A 3D acquisition with an isotropic data set is useful to provide high-resolution visualization of anatomy in any plane. A PD-weighted coherent GRE sequence is most typically employed to demonstrate anatomy and meniscal tears. Dual GRE sequences provide the same weighting but with additional high signal in fluid, which demonstrates joint effusions and provides good contrast with the articular cartilage. These sequences are, therefore, preferred for examining injured joints, despite a significant reduction of meniscal tear conspicuity. An AP phase encoding axis permits the use of a rectangular/asymmetric FOV to reduce scan times.

Artefact problems

The main source of artefact is from popliteal vessel pulsation and patient movement. Pre-saturation pulses placed S and I to the FOV compensate adequately in most cases; however, phase ghosting can sometimes obscure the joint especially in sagittal imaging. Swapping the phase axis so that it lies S to I removes the artefact from the joint. However, in these circumstances, oversampling is necessary to eliminate aliasing from the thigh and the lower leg.

GMN further minimizes flow artefact, but as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences. However, GMN effectively increases the contrast of the synovial fluid on T2- and T2*-weighted images. Volume acquisitions often result in lengthy scan times, and it is quite common for patients to move

during this time. Immobilization with pads and informing the patient of the necessity to keep still are therefore very important.

In the case of metallic implants, chemical fat suppression techniques cannot be used. A STIR sequence is recommended. Recently, new sequences have been developed for soft tissue imaging in the vicinity of metallic prosthesis. For these, magnetic susceptibility artefact is strongly reduced and inflammation detection close to the prosthesis is possible.

Patient considerations

Patients with metal screws or prostheses may experience some discomfort. The patient should be warned to inform the operator if this occurs. Some patients may be unable to extend their knee and place it within the extremity coil. In these cases, a flexible coil wrapped around the knee or a pair of coils placed lateral and medial to the knee, linked together or as a phased array, is often sufficient. Splints and braces should be removed before the examination.

Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

IV contrast is virtually never indicated in knee joint imaging although it may assist in the classification of some pathologies (oncology). MR arthrography is used for the diagnosis of meniscal tears and chondral defects and for identifying residual or recurrent tears in the knee following meniscectomy. It also has a role in identifying loose bodies within the joint. A very dilute solution of gadolinium in saline (1:100) is introduced into the joint capsule, and the single joint is imaged at high resolution with fat-suppressed T1-weighted images in three planes aligned relative to the joint as described.

Tibia and fibula

Basic anatomy (Figure 14.19)

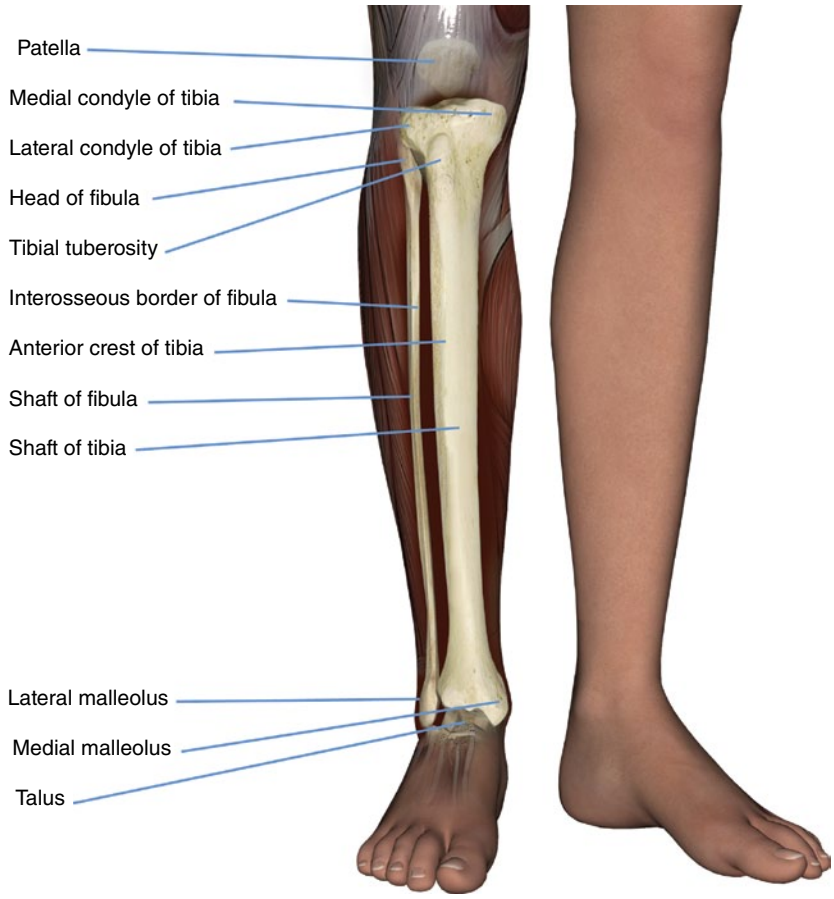

Figure 14.19 Anterior view of the right tibia and fibula.

Common indications

- Assessment of suspected or known pathology of soft tissues and bone (tumours, infection, muscle tears). A bilateral examination is recommended for all new cases, but single-sided imaging can be used for follow-up examinations, particularly if an array coil is not available

Equipment

- Body array coil for imaging both legs or one leg/body coil for both legs/long surface coil placed under the leg if only one leg is under examination and the ROI is localized posteriorly in the calf

- Immobilization pads and straps
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with their legs straight and their feet in a comfortable position. The feet are immobilized in this position using pads and straps. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through a point midway between the knee and the ankle (or over the ROI if this is known). If a rectangular/asymmetric FOV is utilized in subsequent imaging, the vertical alignment light lies midway between the posterior and anterior surfaces of the lower leg. If only one side is to be imaged, the patient should be moved until the leg is as close as possible to the midline of the bore. Use the plastic ruler to measure from the transverse alignment mark to the joints to ensure the full length of the leg will fit within the long axis of the FOV. If not, include either the knee or ankle depending on the location of the lesion(s). When a lesion is palpable, place an oil- or water-filled marker over it. For large lumps or scars, place a marker at each end.

Suggested protocol

Axial/multi-planar SE/FSE/incoherent (spoiled) GRE T1 or Axial SS-FSE T2

Acts as a localizer if three-plane localization is unavailable, or as a diagnostic sequence. The axial plane locates the tibia and fibula in the AP direction but does not indicate if the full length of the tibia will be included on the next series. Coronal images are required for this and may substitute the axial (see the following). Medium slices/gaps are prescribed on the other side of the horizontal alignment light.

Axial localizer: I 50 mm to S 50 mm

Coronal SE/FSE/incoherent (spoiled) GRE T1

Locates lesions in the RL axis and may be used as a localizer, or a diagnostic sequence. Medium slices/gap are prescribed relative to the vertical alignment light from the posterior to the anterior aspects of the lower leg(s) or tibia and fibula. The whole of the tibia and fibula from the ankle to the knee is included in the image.

Coronal localizer: P 50 mm to A 20 mm

Coronal/sagittal STIR or coronal SE/FSE + tissue suppression (Figure 14.20)

Medium slices/gap are positioned and orientated along the line of the leg so that the whole of the tibia and fibula from the ankle to the knee is included in the image. If bilateral lesions are suspected, scan both legs.

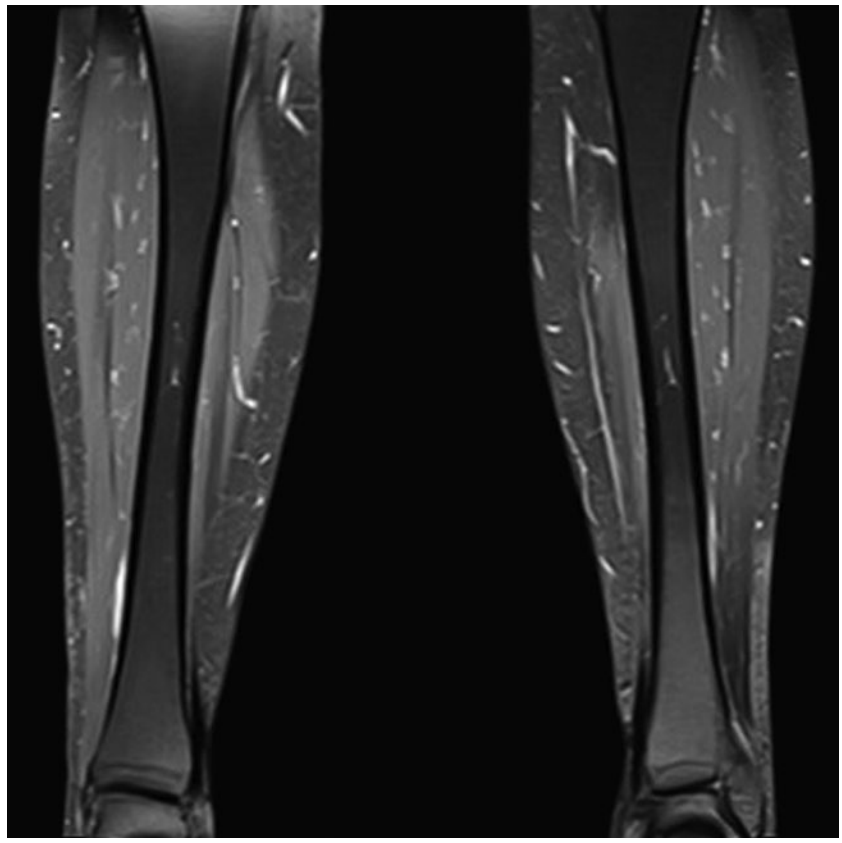

Figure 14.20 Coronal FSE T2 of both tibiae with tissue suppression.

Coronal SE/FSE T1

Medium slices/gap are prescribed and orientated along the line of the leg from the back to the front of the calf. The whole of the tibia from knee to ankle should be included in the image. Both legs should be examined to enable comparison and to identify lesions located in the marrow space.

Axial SE/FSE T1

Medium slices/gap are prescribed to extend well above and below lesions seen in the sagittal and coronal planes. Axial images are useful to localize lesions within significant anatomical compartments. Breach of the marrow space, extension within or through muscle compartments and association with the neurovascular bundle are all significant characteristics.

Axial FSE T2 +/– tissue suppression

Slice prescription as for axial T1.

Sagittal SE/FSE T2 + tissue suppression or STIR unilateral

Sagittal images are useful to localize lesions within significant anatomical regions (three plane visualization of lesions).

Image optimization

Technical issues

The inherent contrast is relatively good in this area due to the apposition of muscle and fat. The TE influences the signal of the muscle in musculoskeletal imaging. A very long TE produces T2-weighted images in which muscle is hypo-intense. The SNR is therefore reduced but fluid detection is improved. Tissue suppression can also be used to enhance the signal from fluid even further; however, larger voxels may be required to compensate for the inherent drop in SNR. By choosing a moderate TE, muscle still retains signal (a grey-level intensity) and the images are PD weighted. The SNR is however higher and the spatial resolution can be better than a T2-weighted image. This kind of contrast is used to detect fluid and retain an anatomical image. Tissue suppression techniques are recommended with this kind of weighting because signal from fluid is reduced. Cartilage lesions can be better detected when TE is high (at least 30–40 ms) because the signal from normal cartilage decreases.

Medium slices and resolution, combined with sensitive coils, allow a fast examination with the potential for higher-resolution images if required. A surface coil substantially increases the signal compared with the body coil, but signal fall-off in the anterior part of the leg sometimes prohibits its use. Whenever a tumour is suspected, the entire leg must be examined to ensure that additional skip lesions are detected. This can be achieved with the body coil or by offsetting the top and bottom parts of the body array coil. Good spatial resolution is achievable, especially if FSE is used, as fine matrices can be selected without unduly lengthening the scan time.

When imaging a single leg, a rectangular/asymmetric FOV is used effectively in the coronal and sagittal planes with the long axis of the rectangle parallel to the long axis of the tibia and fibula. In axial imaging of both legs, a rectangular/asymmetric FOV can be used with the long axis of the rectangle R to L. Ensure that the legs are raised so that the vertical alignment light passes through the middle of the lower leg in the vertical axis. In this way, both tibiae and fibulae are included in the image. This strategy is not essential if the rectangular/asymmetric FOV can be offset or if a variable FOV is available, as with these options the size of the FOV along the shorter, phase axis can be extended to include all anatomy. On FSE T2-weighted images, signal from fat remains bright, so that fat suppression techniques are often helpful to distinguish fat from pathology. When utilizing tissue suppression techniques, a reduced bandwidth increases the SNR considerably and should therefore be employed when possible. Additional shimming may be required before tissue suppression sequences.

Artefact problems

Phase artefact originates from flow motion in the popliteal and posterior tibial arteries and saphenous veins. Spatial pre-saturation pulses placed S and I to the imaging volume reduce this effectively. On axial FSE and sagittal imaging, however, flow artefact is often troublesome. GMN minimizes the problem, but as it also increases the signal from vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences.

Chemical shift artefact must be kept within one pixel, particularly in axial images, to clearly delineate the interface of marrow and cortical bone and the edges of muscle compartments. Fat suppression techniques are commonly used, especially in FSE T2-weighted images where the signal from fat remains bright and may return a similar signal to pathology. In T2 FSE, the signal returned from muscle is usually lower in FSE than in SE imaging, thereby increasing conspicuity of some lesions. To enable accurate characterization of a new lesion, MRI must be performed before tissue biopsy or partial excision.

Patient considerations

Patients should be immobilized adequately to avoid motion artefact. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely used in the tibia and fibula. It may, however, be useful for tissue characterization of certain tumours.

Ankle

Basic anatomy (Figure 14.21)

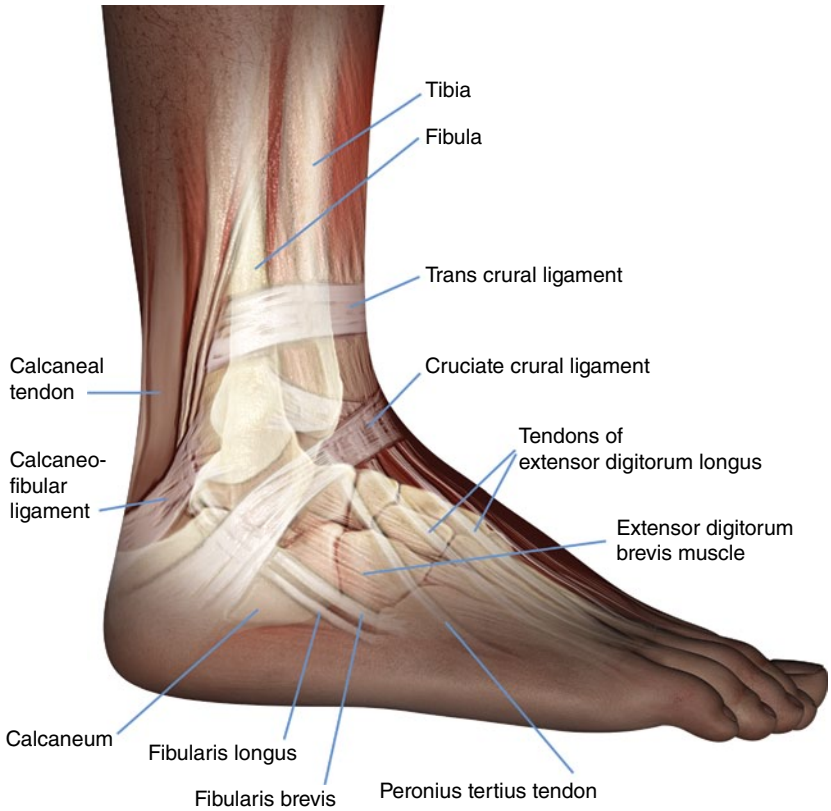

Figure 14.21 Sagittal view of the foot and ankle showing ligaments on the lateral aspect.

Common indications

- Assessment of ankle pain of unknown cause
- Tendonitis (especially posterior tibial)
- Exclusion of osteochondritis dissecans
- Achilles tendon rupture or tear
- Avascular necrosis of the talus
- Evaluation of the ankle joint following trauma
- Soft tissue abnormalities
- Possibly useful for evaluation of lateral ligament complex

Equipment

- Knee phased array coil/extremity coil/pair of small circular coils combined as a multi-array/flexible coil
- Immobilization pads and straps
- Earplugs or headphones

Patient positioning

The patient lies supine on the examination couch with their foot and ankle within the coil. The foot is dorsiflexed so that the dorsal aspect of the foot is perpendicular to the examination couch and it is immobilized in this position with pads. The foot and ankle can also be raised so that the vertical alignment light lies at the level of the malleoli. This ensures that the ankle is at isocentre along the vertical axis. The patient is positioned so that the longitudinal alignment light lies in the midline, and the horizontal alignment light passes through the level of the malleoli that corresponds to the centre of the coil. The other foot is usually placed next to the coil and immobilized with pads and straps.

Suggested protocol

Sagittal/multi-planar SE/FSE/incoherent (spoiled) GRE T1

Acts as a localizer if three-plane localization is unavailable or, if the ankle has been centred correctly, as a diagnostic sequence. Medium slices/gap (thin slices necessary for Achilles tendon) are prescribed on either side of the longitudinal alignment light, from the lateral to the medial aspects of the ankle. The area from the inferior border of the calcaneum to the distal portion of the tibia is included in the image. The sagittal plane enables correct positioning of AP and SI offsets.

Sagittal localizer: L 25 mm to R 25 mm

Axial SE/FSE T1

Thin slices/gap are prescribed to include from the origin of the Achilles tendon to the bottom of the calcaneum, and may require two sequences to provide adequate coverage (Figure 14.22). This sequence provides a clear anatomical display of the tendons of the ankle as well as the vasculature, nerves and musculature. SE sequences are preferred for evaluating tendon damage as FSE sequences mix early and later echoes and, therefore, make it difficult to distinguish tendonitis from partial tears.

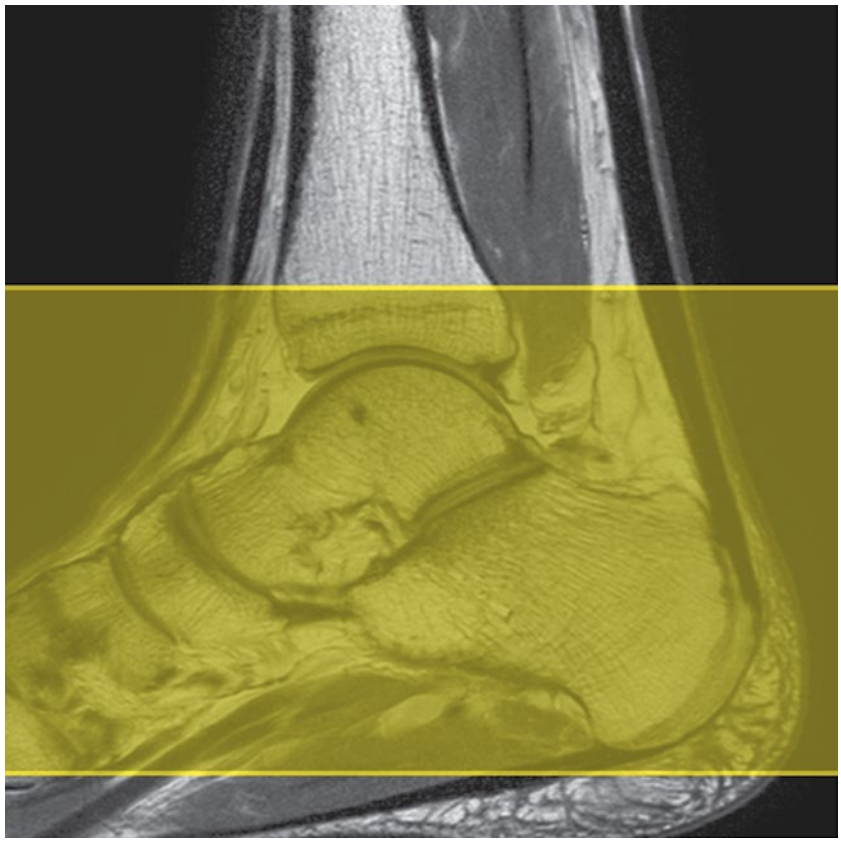

Figure 14.22 Sagittal PD-weighted image showing slice prescription boundaries and orientation for axial imaging of the ankle.

Axial FSE PD/T2 +/– tissue suppression

Slice prescription as for axial T1.

This sequence is useful to classify tendon injury and identify joint effusions. Tissue suppression techniques often demonstrate subtle trabecular damage and cartilage.

Sagittal SE/FSE T1/PD (Figure 14.23)

Thin slices/gap are prescribed from the lateral to medial aspects of the ankle. The whole of the foot and ankle from the sole of the foot to the distal tibia is included in the image. This sequence is necessary to visualize the tendons and permit assessment of the bony components of the ankle.

Sagittal FSE/coherent GRE T2/T2* +/– tissue suppression or STIR (Figure 14.24)

Slice prescription as for sagittal T1.

Demonstrates joint effusion tendonopathy and calcaneal or tarsal fractures.

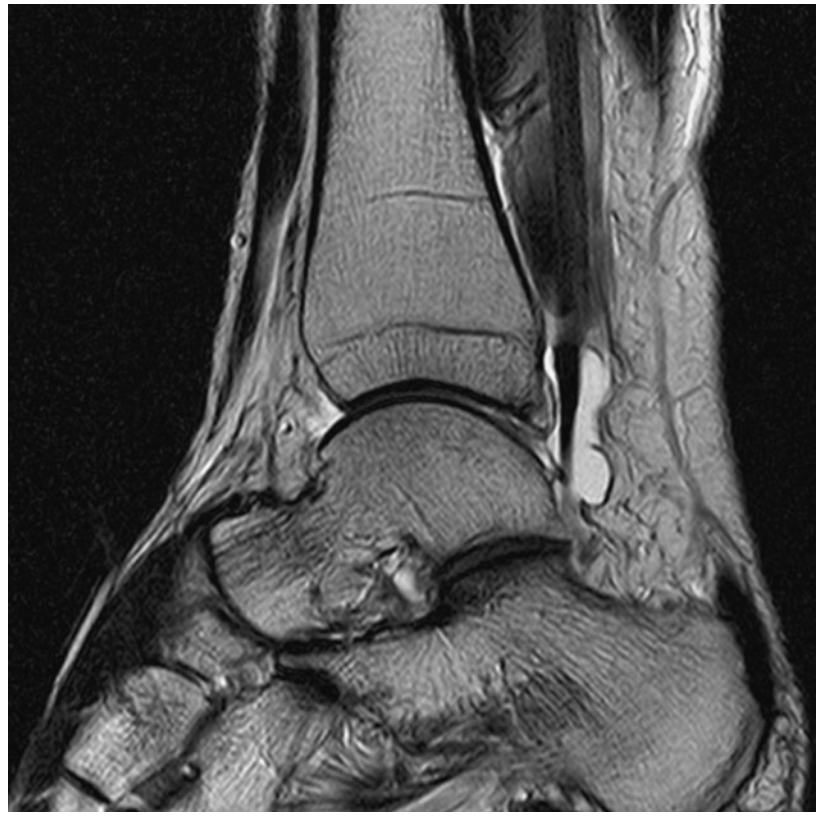

Figure 14.23 Sagittal PD-weighted image.

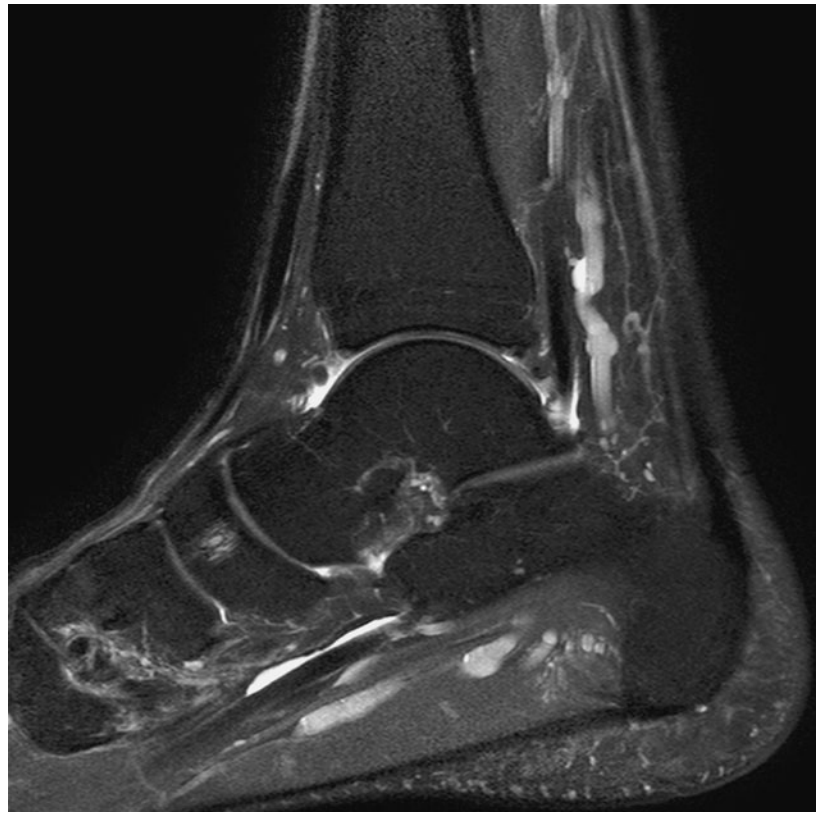

Figure 14.24 Sagittal FSE T2-weighted image of the ankle with tissue suppression.

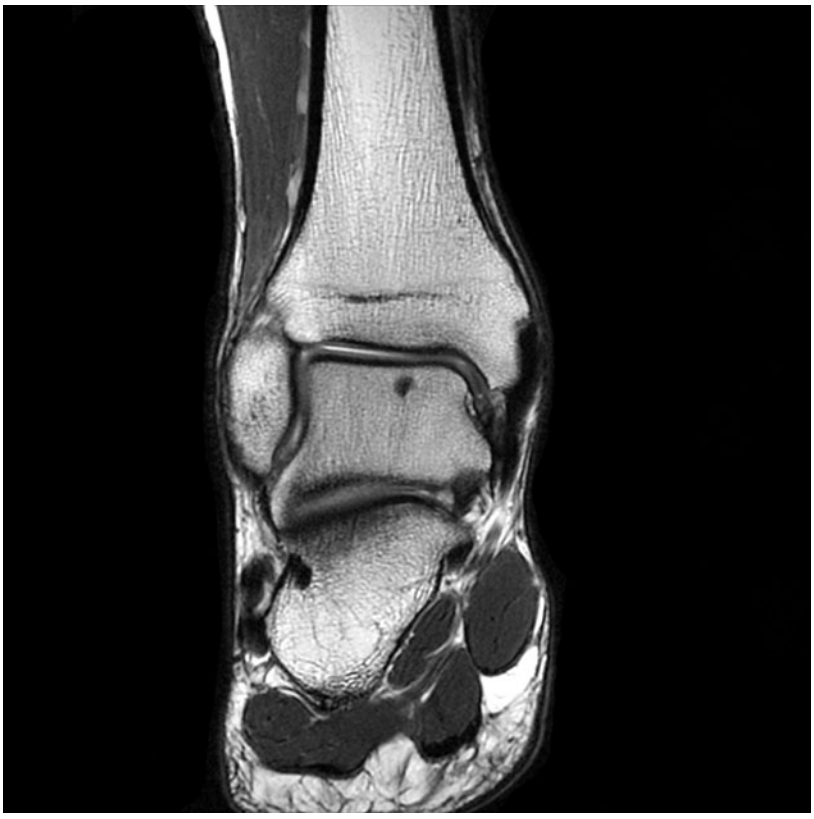

Figure 14.25 Coronal FSE PD-weighted image of the ankle.

Coronal SE T1 or FSE PD/T2 +/– tissue suppression (Figure 14.25)

Thin slices/gap are prescribed from the Achilles tendon to the base of the proximal metatarsals (Figure 14.26). This sequence demonstrates the collateral ligaments and can be extended into the foot to visualize the distal portions of the posterior tibialis tendon. T1 weighting is preferred for tendon injuries or chronic pain. The dual echo sequence is useful for acute injuries and suspected osteochondral defects.

Additional sequences

3D incoherent (spoiled)/coherent GRE T1/PD/T2* (Figure 14.27)

Thin slices and a medium number of slice locations are prescribed through the joint, from above the distal tibia to below the sole of the foot.

Fast incoherent/coherent GRE/SS-FSE/GRE-EPI/SE-EPI

For dynamic imaging of the ankle to assess subluxation and other injuries.

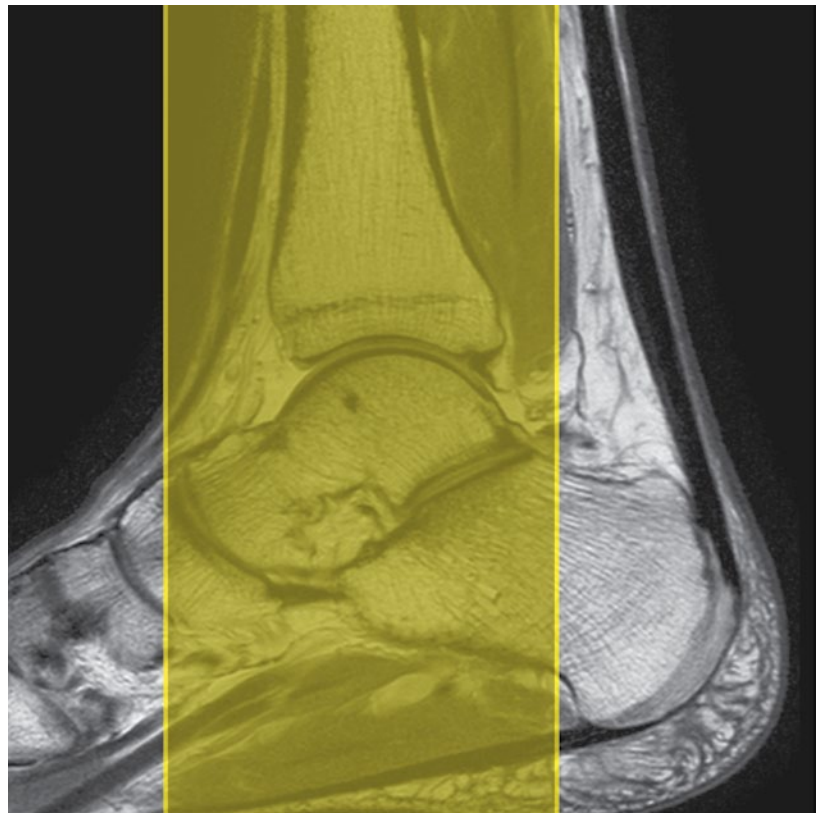

Figure 14.26 Sagittal PD-weighted image showing slice prescription boundaries and orientation for coronal imaging of the ankle.

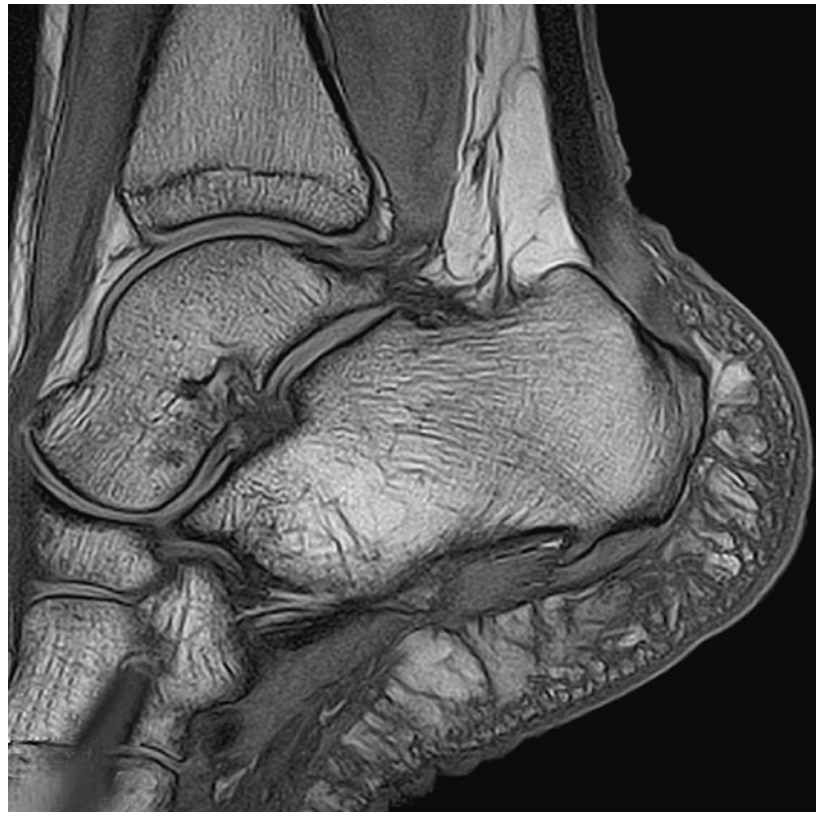

Figure 14.27 High-resolution sagittal incoherent (spoiled) T1-weighted image of the ankle.

Image optimization

Technical issues

The TE influences the signal of the muscle in musculoskeletal imaging. A very long TE produces T2-weighted images in which muscle is hypointense. The SNR is therefore reduced but fluid detection is improved. Tissue suppression can also be used to enhance the signal from fluid even further; however, larger voxels may be required to compensate for the inherent drop in SNR. By choosing a moderate TE, muscle still retains signal (a grey-level intensity) and the images are PD weighted. The SNR is however higher and the spatial resolution can be better than a T2-weighted image. This kind of contrast is used to detect fluid and retain an anatomical image. Tissue suppression techniques are recommended with this kind of weighting because signal from fluid is reduced. Cartilage lesions can be better detected when TE is high (at least 30–40 ms) because the signal from normal cartilage decreases.

The SNR in the ankle is usually high, mainly due to the design of most coils. These often transmit and receive coils and therefore ensure optimum and uniform signal coverage. In addition, the muscle, fluid and fat components of the ankle give good inherent contrast. Excellent spatial resolution is usually necessary, especially when examining small structures such as the Achilles tendon. Therefore, thin/medium slices/gap and fine matrices are required.

A 3D acquisition with an isotropic data set is useful to provide high-resolution visualization of anatomy in any plane. A PD-weighted coherent GRE sequence is most typically employed. Dual GRE sequences provide the same weighting but with additional high signal from fluid which demonstrates joint effusions and provides good contrast with the articular cartilage. They are therefore preferred for injured joints. An AP phase encoding axis permits the use of a rectangular/asymmetric FOV to reduce scan times.

Artefact problems

The main source of artefact is from the posterior tibial vessels. Spatial pre-saturation pulses placed S and I to the FOV are efficient at reducing this. Swapping the frequency/phase directions results in flow artefact along the arteries and not the joint (Note: need of phase oversampling). GMN further minimizes flow artefact, but as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences. However, it effectively increases the contrast of the synovial fluid in T2- and T2*-weighted images.

If the phase direction is AP, aliasing from the toes that are situated within the coil but outside the FOV may obscure relevant anatomy in sagittal imaging. Spatial pre-saturation pulses placed A to the FOV or oversampling reduce this problem. Additional shimming may be required before tissue suppression sequences. If fat suppression is not optimal,

additional shimming may be required before tissue suppression sequences. Otherwise STIR is more convenient. Techniques like the 3-point Dixon technique achieve uniform water–fat separation.

A phenomenon known as the 'magic angle' causes increased signal intensity in tendons in short TE sequences when tendons are orientated at an angle of 55° to the main field. Normally, tendons produce little or no signal on conventional MRI sequences because tendons consist of parallel ordered bundles of collagen fibres. This structural anisotropy causes a local static magnetic field which, when superimposed on to the static field, increases spin–spin interactions and therefore shortens T2 relaxation rates so much that the tendon has a low signal intensity. However, the rate at which spin dephasing is increased is proportional to the angle between the main field and the long axis of the tendon. Because of this relationship, additional spin dephasing caused by the structural anisotropy of tendons decreases to zero when this angle is 55°. Therefore, at this angle, the T2 relaxation time increases, causing a high signal intensity when using short TEs. The increased signal can mimic pathology such as tendonitis in normal tendons. It is seen in many tendons especially supraspinatus and Achilles tendon as well as in the wrist. The magic angle effect can be eliminated by repositioning the tendon (ankle at 90°) or increasing the TE (but not too high as signal from muscle decreases with a very long TE).

Patient considerations

Patients with metal screws or prostheses may experience some discomfort. The patient should be warned to inform the operator if this occurs. Splints and braces are removed before the examination. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

IV contrast is not used to assess joint disease although it may be useful for the classification of tumours. Direct MR arthrography is sometimes used in the ankle to identify ligament tears and for increasing the sensitivity for ankle impingement syndromes. It also has a role in assessing the stability of osteochondral lesions and delineating loose bodies.

Foot

Common indications

- Evaluation of bony and soft tissue abnormalities (tumour, infection)
- Diagnosis of bone trauma not seen with conventional radiography
- Bony tumours
- Morton's neuroma
- Tarsal coalitions
- Diabetic foot

Equipment

- Extremity coil/head coil/flexible surface coils/small coil configured as a multi-coil array
- Foam immobilization pads and straps
- Earplugs/headphones

Patient positioning

Due to the non-orthogonal axis of the feet, true coronal and sagittal imaging can be difficult to obtain without oblique scan prescription. With the feet dorsiflexed, true sagittal imaging is possible, but due to the curvature of the tarsal bones, coronal imaging is sometimes difficult. It is probably advisable to examine the patient as for an ankle if the tarsal bones are the ROI, and reserve specific imaging of the foot if the toes and metatarsals are under investigation. The patient is usually positioned as for an ankle in the extremity or head coil. When using these coils, ensure that the toes do not protrude beyond the coil anteriorly. This may happen if the patient has large feet and, under these circumstances, a surface coil is required to provide adequate coverage. The forefoot can be examined effectively and comfortably using a flexible surface coil or a two-coil array with the patient prone and the foot plantar flexed. Immobilization of the foot and the coil using crossed straps and sponges is essential in both cases.

If the prone position is used, raise the foot and coil so that the long axis of the foot is at the level of the horizontal alignment light. If the feet are flat down on the surface coil, raise the coil and foot so that the vertical alignment light lies through the middle of the foot in the vertical axis. This enhances patient comfort and ensures that every part of the foot is at isocentre, which simplifies subsequent imaging as no offsets are needed. The patient is made as comfortable as possible and immobilized with pads and straps if necessary.

Suggested protocol

Scan plane alignment

These protocols refer to the following anatomical planes. The axial plane is perpendicular to the long axis of the foot, showing the metatarsals in cross section. A coronal plane is analogous to the AP X-ray view, with the metatarsals adjacent to each other.

Note: These planes may not coincide with terminology used in other texts and, depending on patient positioning, may not correspond to your scanner's orthogonal plane labelling.

Axial SE/FSE/incoherent (spoiled) GRE T1

Acts as a localizer if three-plane localization is unavailable so that the curvature of the tarsals and metatarsals can be evaluated. Medium slices/gap are prescribed on either side of the horizontal alignment light.

I 20 mm to S 20 mm

Axial SE/FSE T1

Thin slices/gaps are prescribed to include from the end of the toes to the tarsal bones, with good resolution to provide a clear anatomical display of the anatomy of the foot (Figure 14.28). SE sequences are preferred for

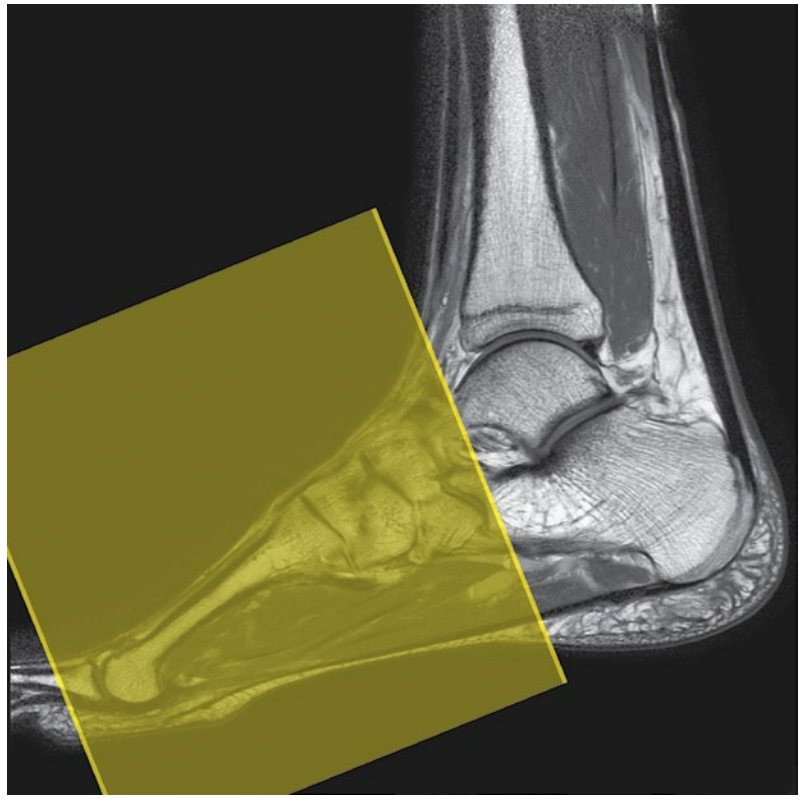

Figure 14.28 Sagittal FSE PD-weighted image showing slice prescription boundaries and orientation for axial imaging of the foot.

evaluating tendon damage, but short ETL FSE sequences can be used to achieve higher spatial resolution in an acceptable scan time.

Axial FSE PD/T2 +/– tissue suppression

Slice prescription as for axial T1.

These sequences demonstrate joint effusions, mass lesions and collections. The addition of fat suppression enables visualization of subtle trabecular damage in stress fractures of the metatarsal bones.

In soft tissue imaging (i.e. Morton's neuroma), T2W images are used (TE > 65 ms).

Sagittal SE/FSE T1/PD (Figure 14.29)

Thin slices/gaps are prescribed from the lateral to the medial aspects of the foot and should include the sole of the foot to the distal tibia (Figure 14.30).

Sagittal FSE PD T2/STIR/coherent GRE T2/T2* + tissue suppression (Figure 14.31)

Slice prescription as for sagittal T1.

For demonstration of fluid collections, infection, and metatarsal or tarsal fractures.

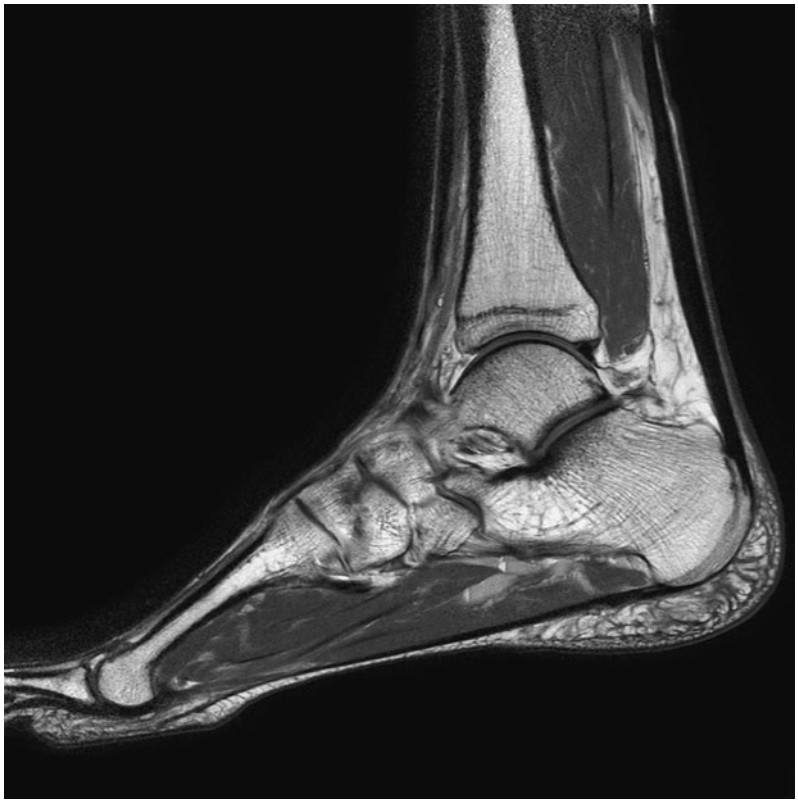

Figure 14.29 Sagittal FSE PD-weighted image of the foot.

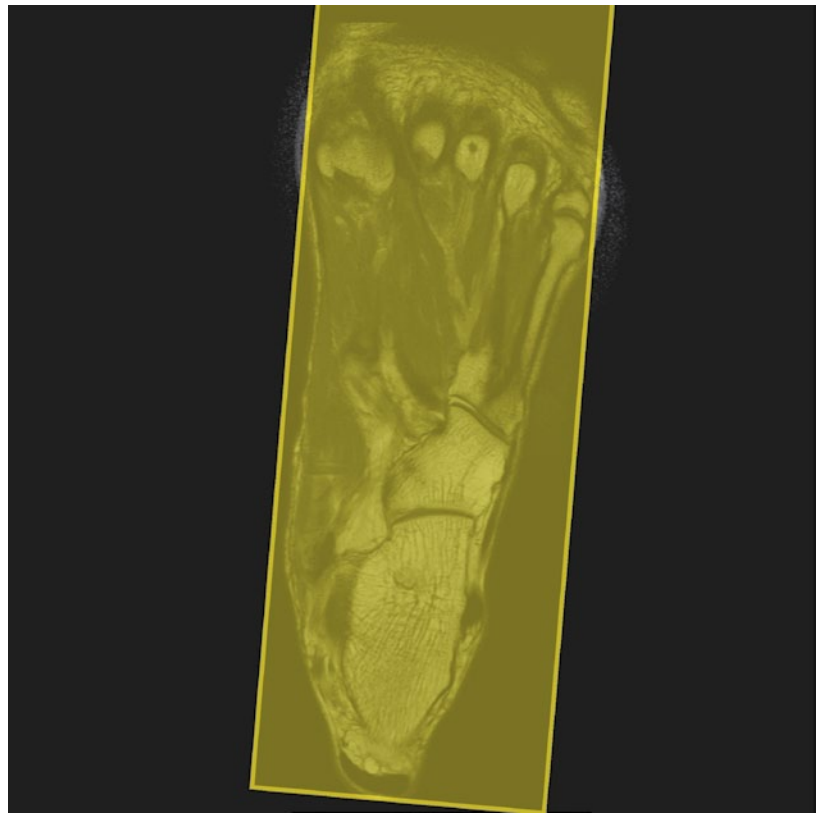

Figure 14.30 Coronal FSE PD-weighted localizer of the foot showing slice prescription boundaries and orientation for sagittal imaging of the foot.

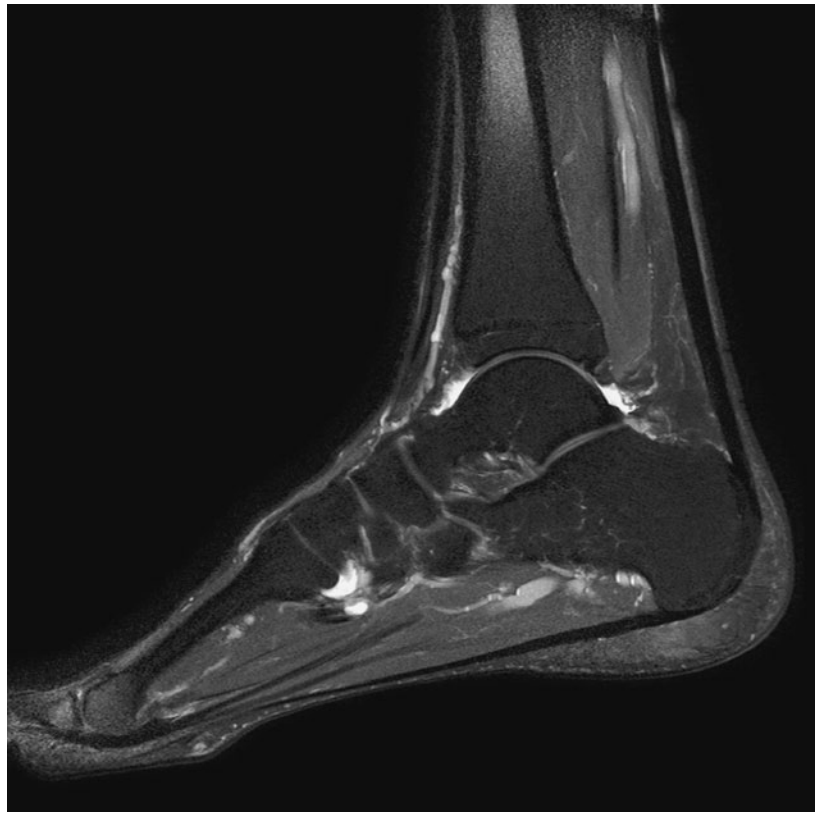

Figure 14.31 Sagittal FSE PD-weighted image of the foot with tissue suppression.

In soft tissue imaging (i.e. Morton's neuroma), T2W images are used (TE > 65 ms).

Additional sequences

Coronal SE T1 or FSE PD/T2 + tissue suppression

This scan plane is used in preference to the sagittal where the axial images show significant pathology extending between the metatarsal bones (Figure 14.32).

Sagittal 3D coherent GRE PD/T2*

Acquired as an isotropic data set, this sequence may be useful to assess anatomy and pathology in any plane. Sagittal slices should include the whole of the foot from the sole to the distal tibia.

3D FSE with variable refocusing flip angle

Provides high resolution and good SNR in a shorter acquisition time than conventional 3D FSE.

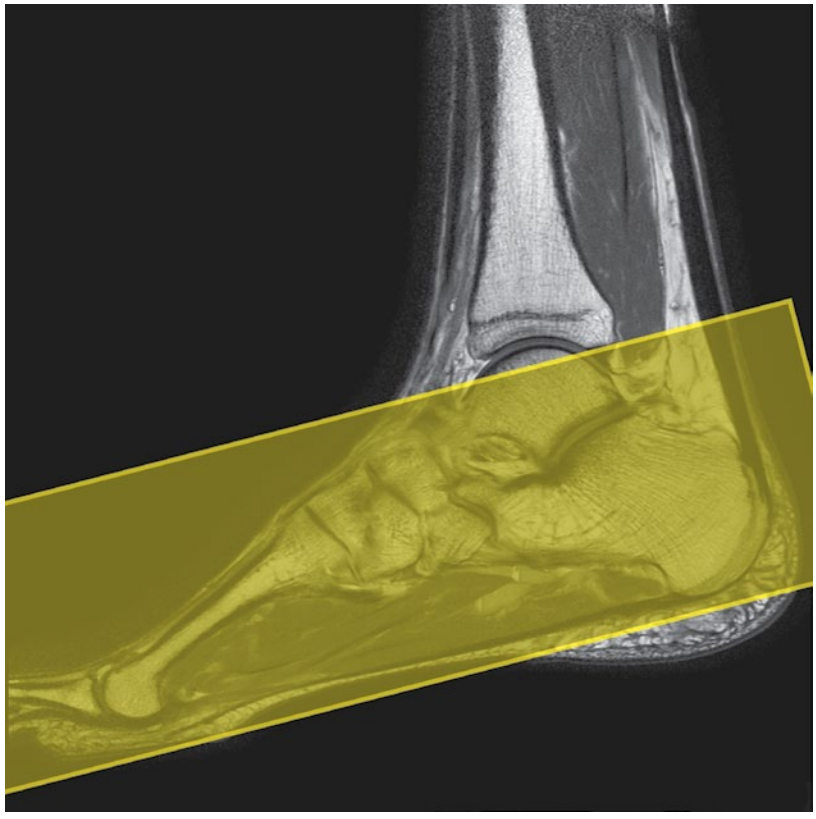

Figure 14.32 Sagittal FSE T2-weighted image of the foot showing slice prescription boundaries and orientation for coronal imaging of the foot.

Image optimization

Technical issues

Foot imaging can be demanding as the foot is small compared with the available coils, compromising SNR and resolution. Flexible coils, simple arrays and dedicated coils can compensate for these inherent difficulties. Multiple NEX/NSA are often required to optimize the SNR. Excellent spatial resolution is necessary, especially when examining small structures such as the metatarsals and phalanges. Therefore, thin slices/gap and fine matrices are required. Additional shimming may be required before tissue suppression sequences.

Artefact problems

There is little flow artefact in this area, but it is advisable to place a spatial pre-saturation pulse S to the FOV to reduce any flow originating in the distal vessels. GMN minimizes flow artefact, but as it increases the signal in vessels and the minimum TE, it is not usually beneficial in T1-weighted sequences. However, GMN can effectively increase contrast (depending on the direction the GMN is applied) in synovial fluid in T2- and T2*-weighted images. For small areas like the toes, motion artefacts can occur and no motion-/flow-sensitive FSE techniques like PROPELLER can be used. Due to the complexity of this anatomy, the fat suppression can be non-uniform. Additional shimming may be required before tissue suppression sequences. Otherwise STIR is preferred.

Patient considerations

Patients are carefully immobilized to reduce motion artefact. The position of the foot is important for subsequent imaging in orthogonal planes, and the use of pads and tape to support the foot is advised. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

Contrast is not routinely used in the foot but is sometimes indicated in the diabetic foot, Morton's neuroma and some tumours.

Vascular imaging

Basic anatomy (Figures 14.33 and 14.34)

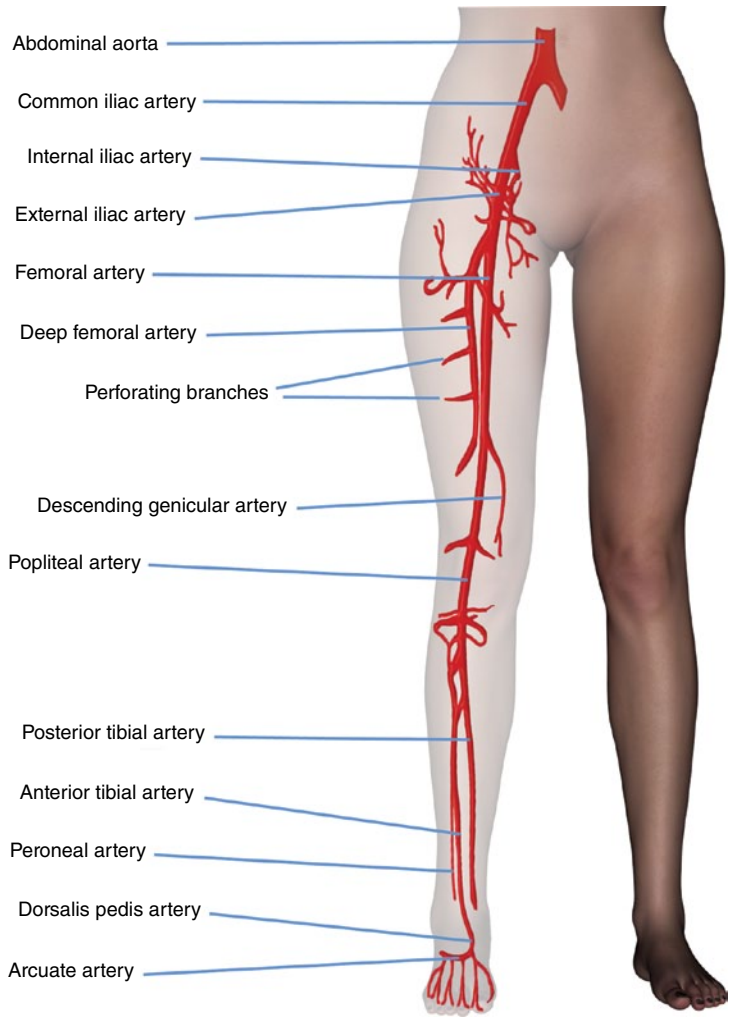

Figure 14.33 Vascular supply of the right leg.

Common indications

- Evaluation of peripheral vascular disease including stenosis and occlusion
- Location of run-off vessels or site for arterial bypass of occlusion
- Evaluation of normal venous vasculature (prior to coronary artery bypass surgery to determine the optimal graft site)

It is essential to determine the objectives of the examination before commencing. For example, if the aim is to survey the entire peripheral

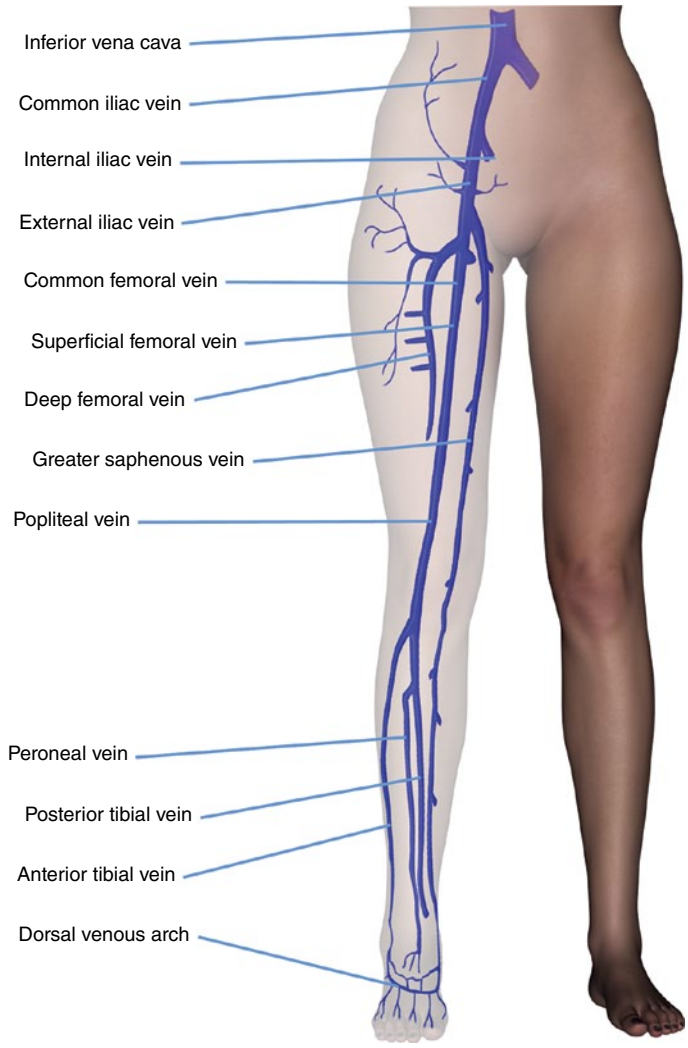

Figure 14.34 Venous drainage of the right leg.

vasculature, speed is more important than resolution and multiple FOVs, and sequences, adjusted to display arterial or venous flow, may be appropriate. However, if the aim is to find a tibial run-off vessel for grafting, the appropriate coils and techniques are different. The technique described here is for a full leg arteriogram. Use these key elements and your experience to develop more specialized techniques.

Equipment

- Body phased array/multi-coil array/surface coil/body coil
- Immobilization pads and straps
- Localization markers if required
- Earplugs/headphones

Patient positioning

The patient lies supine on the examination couch with the legs extended into the magnet as far as possible. The legs and feet are immobilized using foam pads. Several series are acquired at different positions in the leg starting either at the feet or the pelvis. If the vasculature of the feet is important, place the feet flat down on to the coil and support this position with foam pads under the knees. This ensures that the vessels within the feet are perpendicular to the axial plane, which is necessary to optimize image contrast in TOF-MRA sequences. The patient then extends the legs again for imaging of the rest of the lower limb vasculature.

The patient is positioned so that the longitudinal light lies in the midline of the patient, and the horizontal alignment light is centred to the ROI. It is important to ensure that there is overlap between each series of images. Copper sulphate or oil markers may be taped on to the patient's lower limbs to achieve this or advance the table by 50 mm less than the longitudinal coverage of each set of sequences. Alternatively, when the first set of images has been acquired, return the patient to the landmark position. Move the table to the location of the most superior slice in the imaging stack of the completed series. Mark this position on the patient using tape, and then reposition the coil so that this mark corresponds to the most distal end of the useful area of the coil. Landmark to the new centre of the coil ensuring that there is an overlap of at least 2.5 cm between each series. Switch to the body coil for imaging of the femora and pelvis.

Suggested protocol

Coronal incoherent GRE T1

Acts as a localizer if three-plane localization is unavailable. Use a large FOV to achieve maximum coverage. Medium slices/gap are prescribed on either side of the vertical alignment light.

P 40 mm to A 40 mm

Axial 2D TOF-MRA

Developing a workable 2D TOF sequence for peripheral MRA is a complex task, as many conflicting factors must be taken into account. Most manufacturers provide suggested protocols optimized for their operational methods and post-processing software. It is probably advisable to start with these protocols and modify them when you completely understand the technique rather than start from scratch. Thin overlapping sequentially acquired GRE slices are obtained with a travelling spatial pre-saturation band positioned distal to the slice for arteriography, or proximal for venography. The slices are prescribed through the useful volume of the coil. It is vital to set the acquisition order to run against the direction of blood flow (e.g. from feet to head for leg arteries). Several

series are performed moving the coil to a new location until the required vasculature has been visualized. There must be overlap between each series to avoid missing important pathology. The images are post-processed to provide oblique and AP views analogous to those collected in X-ray angiography (Figures 14.35, 14.36 and 14.37).

Image optimization

Technical issues

The use of a good surface coil enhances the SNR in the lower leg. When utilizing the body coil to image the pelvis, the inherent SNR and CNR are generally adequate due to the use of a larger FOV. However, because of the length of the examination, a coarse matrix is often selected to try to minimize scan times, and resolution sometimes suffers as a result. To enhance vascular contrast, axial slices are selected so that the direction of flow is perpendicular to the slice. The use of GMN improves vessel enhancement even further. MT is rarely used as it increases the relative signal of fat, which then interferes with the post-processed images. Travelling spatial pre-saturation bands placed between the origin of flow

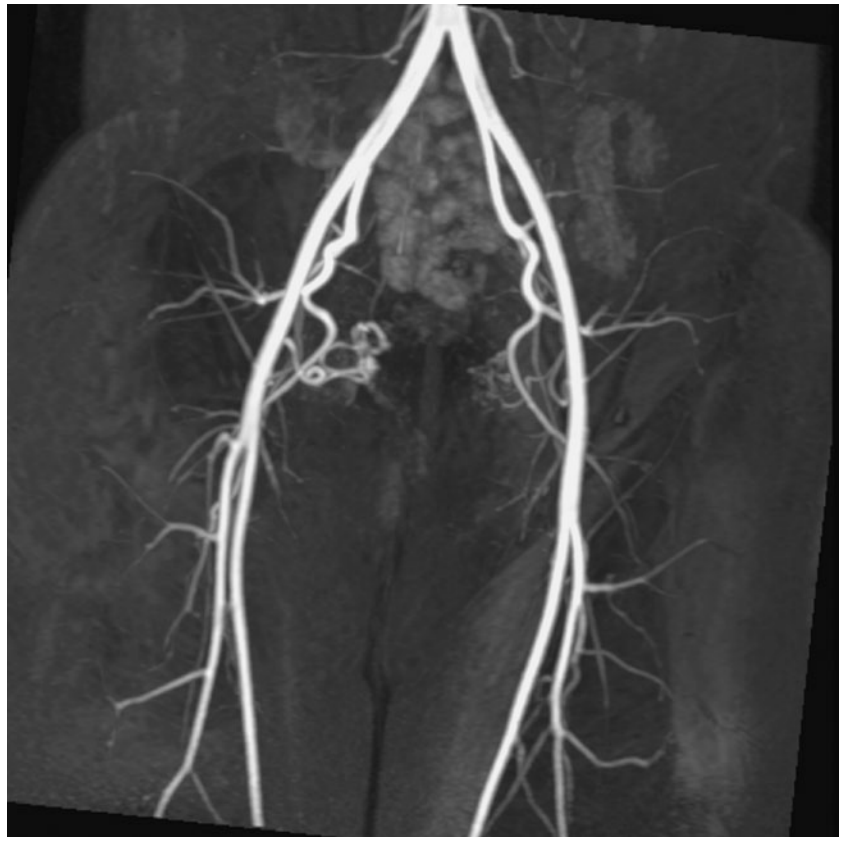

Figure 14.35 Sequential CE-MRA of the iliac vessels showing an arterial venous malformation (first pass).

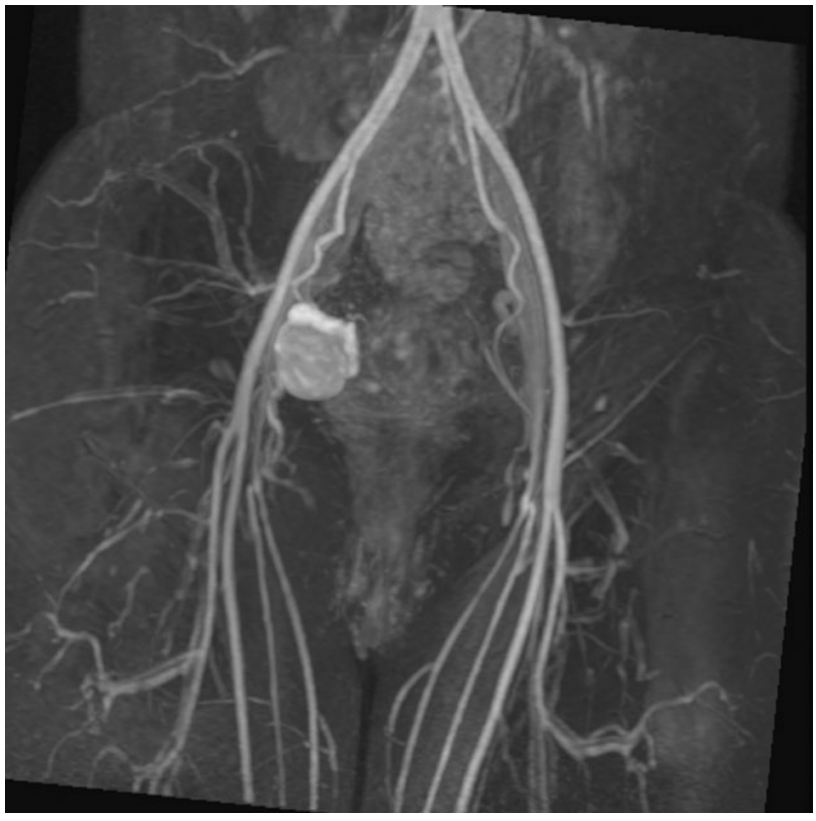

Figure 14.36 Sequential CE-MRA of the iliac vessels showing an arterial venous malformation (second pass).

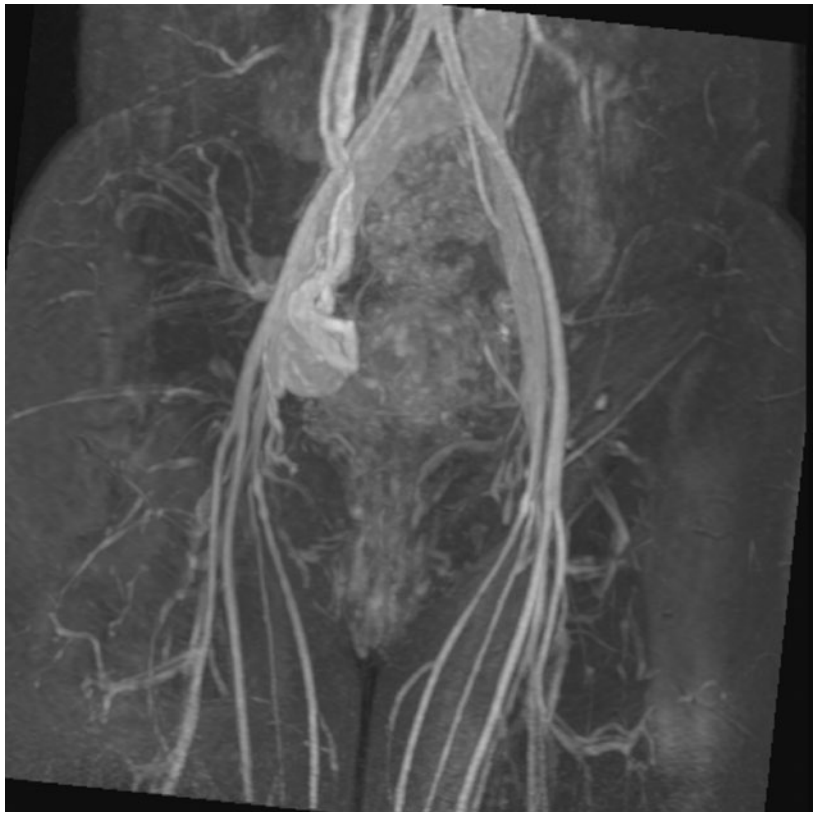

Figure 14.37 Sequential CE-MRA of the iliac vessels showing an arterial venous malformation (third pass).

and the imaging stack nullify unwanted signal. These are placed S to the FOV to saturate arterial flow and demonstrate venous anatomy, and I to the FOV to saturate venous flow and demonstrate arterial anatomy. It is very important to locate the travelling pre-saturation bands correctly. Incorrect placement of these saturation bands leads to poor image quality and perhaps imaging of the wrong vessels.

In 3D FSE sequences, good imaging of calf veins requires careful positioning of the patient to avoid pressure on the calf that may restrict blood flow in the veins. Prone positioning is an alternative to reduce pressure on the calves. In addition, since the flip angle strongly influences the flow sensitivity of the sequence, it should be optimized to better depict the vessels. Large vessels, such as the popliteal artery, are seen well with a high flip angle, whereas smaller branch vessels are better depicted at lower flip angles.

ECG triggering can enhance the quality of peripheral 2D sequential TOF-MRA images by eliminating pulsatile flow ghosts and locking acquisition to the period of maximum distal flow rate. Flow is tri-phasic in peripheral vessels and will reverse direction through the cardiac phase.

Artefact problems

Motion of the body causes vessels to appear in different locations on sequential axial images and results in stepping in the post-processed images. Phase ghosting is also occasionally troublesome and is minimized by reducing the TE or using ECG triggered sequences. Fat signal is often inadequately suppressed during TOF-MRA sequences and may interfere with the image. Tissue suppression pulses could reduce this unwanted signal, but the time penalty is often unacceptable. Using a TE when the fat and water signals are out of phase with each other usually adequately suppresses background signal.

Vessel signal may appear to vary regularly along the line of a vessel creating a 'Venetian blind' artefact similar to that seen in large slab 3D TOF-MRA. However, in peripheral 2D TOF-MRA, the mechanism for this appearance is quite different. It usually results from the travelling pre-saturation slab being too close to the scan plane. During the reversal of flow, blood slips back into the saturation band before being imaged. The same effect may result from blood upstream, which was imaged during previous slice acquisitions, flowing back into the current slice location. It also occurs if the slice acquisition order is not opposite to the direction of flow.

2D TOF-MRA sequences demonstrate reduced vessel signal where the vessel loops backwards or where there is a reversed flow direction. This latter situation is common distal to an arterial occlusion. Reverse flow in the distal limb of an occluded artery is provided from collateral supply but will not be shown with this technique. If the aim of the examination is to visualize the length of an occlusion accurately (e.g. consideration of angioplasty or surgical repair), PC-MRA, which is not flow direction sensitive, should be used.

New high-resolution isotropic 3D non-CE-MRA sequences are often used. They employ ECG triggering and contrast depends on arterial signal difference between end diastole and end systole. At the end of the diastolic phase, arterial blood is stationary and produces signal like static tissues and veins. At the end of the systolic phase, arterial blood is flowing and does not produce signal because of turbulence (i.e. only static tissues and veins provide signal since the blood in veins does not undergo such turbulence artefacts). At the end of the non-CE-MRA acquisition, a subtraction between end-of-diastolic volume and end-of-systolic volume is performed in order to produce an arterial-only volume. One advantage of this kind of acquisition is larger coverage than the 2D and 3D TOF acquisition.

Patient considerations

As the whole of the vasculature of the lower limb is imaged with an overlap of slices, the examination can take over 1 h to perform. It is therefore important to make patients as comfortable as possible and to warn them of the length of the study. It is wise to send the patient to the toilet before the examination begins! Ensure that the lower limbs are adequately immobilized, as any motion during the study causes artefact. Due to excessively loud gradient noise associated with some sequences, earplugs or headphones must always be provided to prevent hearing impairment.

Contrast usage

A small dose of contrast (0.25–1 mmol/kg) shortens the T1 of the blood and therefore increases the signal of the flowing blood in TOF-MRA sequences. An extension of this technique, time-resolved MRA or dynamic imaging during contrast injection, is now well accepted in examining peripheral vasculature. A range of approaches are under development with the required coils, sequences and coordination measures ranging from those that can be performed with most high-performance systems to those requiring extensive hardware and software modifications.

The technique is directly analogous to X-ray angiography. Extremely short TR sequences result in saturation of signal from most tissues except those with very short T1 times, such as the mixture of blood and gadolinium. In this way, the vessel lumen is outlined. Short TEs (1–2 ms) are employed to minimize the effects of flow that generate signal void in arteries where turbulence is prominent. Acquisition of the central portions of k-space, relative to the IV injection, is timed to image the first pass of the contrast bolus through the arterial system. Subsequent acquisitions display the bolus in veins. 3D coronal GRE sequences with very short TRs and TEs are used with high-performance array coils. The coronal plane enables a fast sequence with large coverage, and images are then post-processed. A ‘mask’ scan is often acquired prior to injection for

subtraction from the contrast images. This further reduces background signal and is essential if multiple injections are employed (especially for the detection of popliteal artery entrapment syndrome using neutral position / plantar flexion in feet imaging). Subtraction of the first pass arterial data from later acquisitions provides better isolation of the venous circulation. Timing of the scan to the bolus arrival is critical. This can be achieved with interactive scan initiation via navigator scans, by prior timing of a small dose in conjunction with a single location axial fast sequential scan, or by simple empirical estimation.

Key points

- The TE is a very important parameter in MSK imaging. The TE determines T2 contrast, influences the signal in muscles and determines the cartilage contrast (>30–40 ms).
- To reduce motion artefacts in MSK imaging, use sandbags, straps or BLADE/PROPELLER sequences.
- Inhomogeneity of fat suppression can be a problem in MSK imaging. To reduce this, use additional shimming, STIR or 3-point Dixon techniques.
- To reduce artefacts from metal implants, do not use GRE sequences, and instead use higher receive bandwidth; short TE, SE or FSE sequences; 3-point Dixon techniques; or metal artefact reduction sequences (MARS).
- In MSK imaging, to reduce chemical shift artefact, alter the receive bandwidth and frequency matrix so that the bandwidth per pixel is >0.44 at 3 T or >0.22 at 1.5 T.
- To reduce flow artefacts, use pre-saturation bands, swap frequency/phase, or use GMN.

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Note: Page numbers in *italics* refer to Figures; those in **bold** to Tables.

Handbook of MRI Technique, Fourth Edition. Catherine Westbrook.

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