# HANDBOOK OF MRI TECHNIQUE

THIRD EDITION

Catherine Westbrook

WILEY-BLACKWELL

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## Third Edition

**Catherine Westbrook**
Anglia Ruskin University
Cambridge, UK

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# Contributors

Catherine Westbrook MSc, DCR(R), PgC (L&T), CT Cert, FHEA
Senior Lecturer and Post-Graduate Course Leader, Radiography, Anglia Ruskin University, Cambridge, UK

John Talbot MSc, DCR(R), PgC (L&T) FHEA
Senior Lecturer, Radiography, Anglia Ruskin University, Cambridge, UK

William Faulkner BS RT(R), (MR) (CT), FSMRT
William Faulkner & Associates, LLC

Carolyn Kaut RT(R), (MR), (CT)(M)(CV),
CEO, Imaging Education Associates

Michael Kean Dip. App. Sci., Grad. Dip. Edu.
Senior Radiographer, Children's MRI Centre, Royal Children's Hospital, Melbourne, Australia
Research Affiliate – Murdoch Childrens Research Institute

# Preface

The *Handbook of MRI Technique* is now an established text for many MRI practitioners around the world. *MRI in Practice* (also published by Blackwell Publishing) provides radiographers and radiologists with a user-friendly approach to MRI theory and how it may be applied in practice. The *Handbook of MRI Technique* is intended to guide the uninitiated through scanning techniques and protocols and to help more experienced technologists 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 second edition, published in 1999, has filled this gap and has proven to be a useful clinical text. In this, the third edition, it has been my intention to continue with the objectives of the second edition but update the reader on recent technical advances in both hardware and software. As previously, technologists and radiographers from the UK, USA and Australia have made large and important contributions to the book and, as a result, I believe the third edition is even more comprehensive than the second.

The *Handbook of MRI Technique* is split into two parts. Part 1 summarizes the main aspects of theory that relate to scanning and also includes practical tips on gating and equipment use, patient care and safety, and information on contrast media. Several useful tables are added for ease of reference and the pulse sequence section has been updated to include newer sequences. Part 2 includes a step-by-step guide to examining each anatomical area. It covers most of the techniques commonly used in MRI as well as paediatric imaging. Under each examination, categories such as indications, patient positioning, equipment, artefacts and tips on optimizing image quality are included. Guidance on technique and contrast usage is also provided. Owing to the variety of imaging systems and differences in radiological preferences, information on protocols is mainly limited to pulse sequence, scan plane and slice prescription. The advice given on protocols is only intended to direct the examination. In addition, a basic anatomy section has been added at the beginning of each examination area.

The *Handbook of MRI Technique* provides a guide to the operation of MR systems and 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, apart from the Paediatric chapter in which several

clinical images are to be found, diagrams and images focus intentionally on scan planes, slice prescriptions and sequencing to reflect the technical thrust of the book.

The third edition of the *Handbook of MRI Technique* should be especially beneficial to those technologists studying for board certification or post-graduate 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**

# Acknowledgements

I must give my heart-felt thanks to the contributing authors: John Talbot, Bill Faulkner, Candi Kaut-Roth and Mike Kean without whom this book could never have been updated. As usual I am extremely impressed with their professional and thoughtful contributions and am very grateful for their valued opinions. In particular I would like to thank my friend and colleague John Talbot for his beautiful illustrations and continued support. Several have contributed towards the gallery of images. I would like to thank the following; Kirk Odders, Chattanooga Imaging, Lawrence Tanenbaum, MD and Philips Medical Systems.

**CW**

# 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 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 (Blackwell Science, 2005, third 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
- paediatric imaging.

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

on 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.

## 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 respiratory compensation 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.
- **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 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. Phased array coils are commonly used in spinal imaging.

- **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, phased array coil, parallel imaging coils or a local coil inserted into an orifice must be utilized (e.g. a rectal coil).
- **Parallel imaging or multi-coils** use the data from multiple coils or channels arranged around the area under examination to either decrease scan time and/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 it is usually a minimum of 2 and maximum of 32. During acquisition each coil fills its own lines of K space (e.g. if 2 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 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/ETL in fast spin echo (*see section on Pulse sequences* in Part 1). Every coil produces a separate image which 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. It has special advantages in brain and body imaging.

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 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 neither the radiologist nor the practitioner knows how to proceed. The

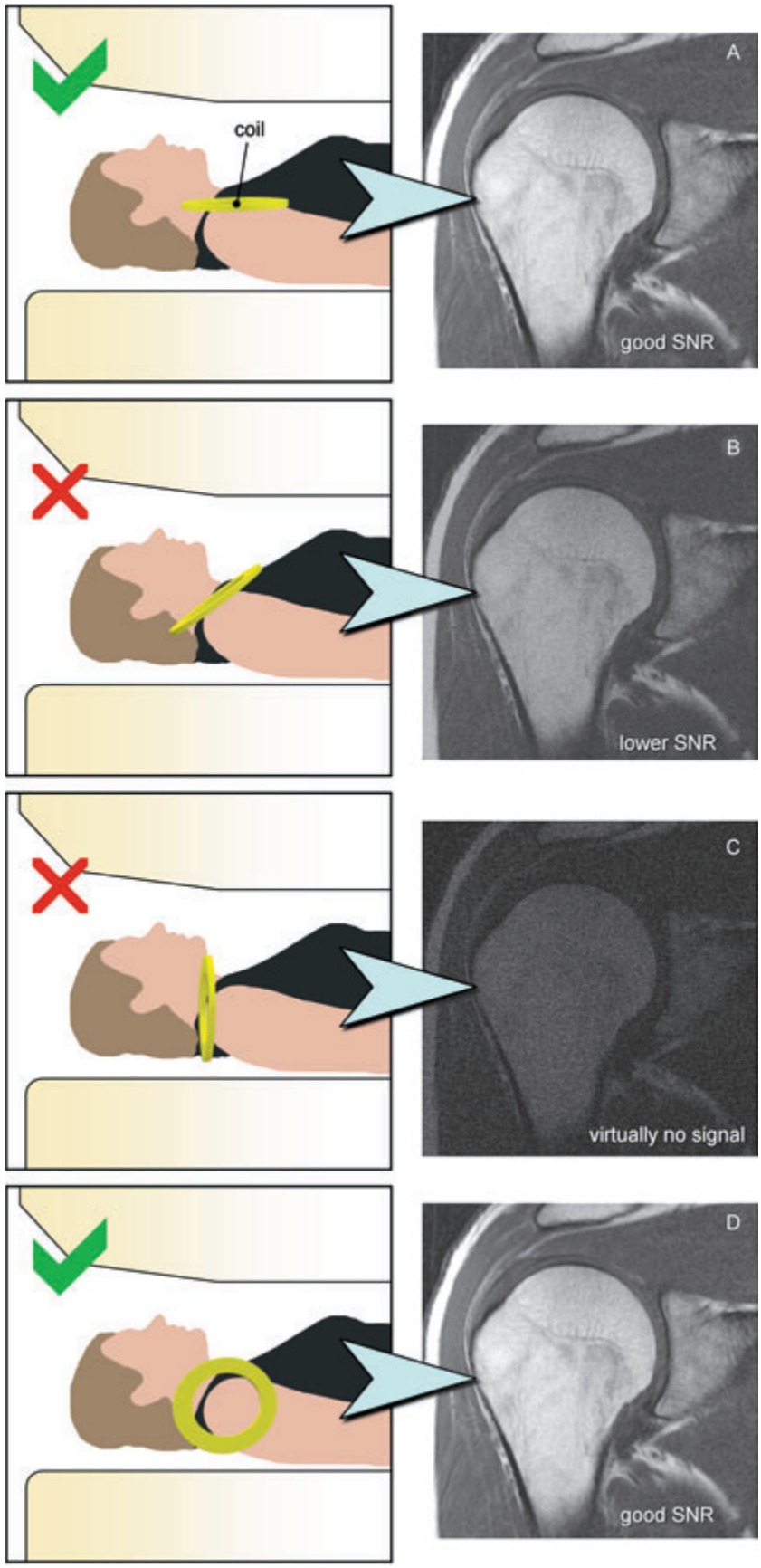


**Figure 1.1** Correct placement of a flat surface coil in the bore of the magnet. The surface of the coil (shaded) area must be parallel to the Z axis to receive signal. The coil is therefore positioned so that transverse magnetization created in the X and Y axes is perpendicular to the coil.

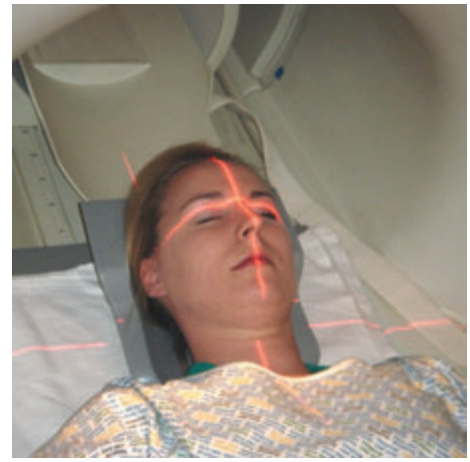

**Figure 1.2** Positioning of the alignment lights.

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 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
- Patient considerations
- Contrast usage.

- **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 ten point plan for good radiographic practice:

- Review all cases carefully and select appropriate protocols.
- Have flexible protocols that can reflect the needs of each individual clinical case.
- Regularly review your procedures and benchmark them against current best practice.
- Have clear diagnostic goals including the minimum accepted sequences necessary to obtain a useful diagnostic/clinical outcome.
- Regularly review your protocols and procedures.
- Understand the capabilities of your system.
- Recognize your limitations and if necessary refer to another site rather than risking an incomplete or diagnostically unacceptable procedure.
- Educate all levels of staff to new procedures and/or system capabilities.
- Be safety paranoid to ensure your unit does not fall victim to the dreaded MRI incident.
- 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:

- **Chemical/Spectral presaturation:** fat suppression techniques such as fat saturation (FAT SAT), spectrally selective inversion recovery (SPIR).
- **Gradient moment nulling (GMN):** gradient moment rephasing (GMR) and flow compensation (FC).
- **Oversampling:** no phase wrap, anti-aliasing 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 later 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 above 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 | Arterio-venous malformation |
| AVN | Avascular necrosis |
| BFFE | Balanced fast field echo |
| BGRE | Balanced gradient echo |
| BOLD | Blood oxygenation level dependent |
| CDH | Congenitally dislocated hips |
| 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 |
| FIESTA | Free induction echo stimulated acquisition |
| FID | Free induction decay signal |
| 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 SE |
| I | Inferior |
| IAM | Internal auditory meatus(i) |
| 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:

- signal to noise ratio (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)

The 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:

- spin echo (SE) and fast spin echo (FSE) pulse sequences
- a long repetition time (TR) and a short echo time (TE)
- a flip angle of 90°
- a well-tuned and correctly sized coil
- a coarse matrix

**Table 2.1** Summary of parameters. The figures given are general and should be adjusted according to the system used

**Spin echo (SE)**

| | |
|---|---|
| short TE | min to 30 ms |
| long TE | 70 ms + |
| short TR | 300–600 ms |
| long TR | 2000 ms + |

**Fast spin echo (FSE)**

| | |
|---|---|
| short TE | min–20 ms |
| long TE | 90 ms + |
| short TR | 400–600 ms |
| long TR | 4000 ms + |
| short ETL | 2–6 |
| long ETL | 16 + |

**Inversion recovery (IR) T1**

| | |
|---|---|
| short TE | min–20 ms |
| long TR | 3000 ms + |
| medium TI | 200–600 ms |
| short ETL | 2–6 |

**STIR**

| | |
|---|---|
| long TE | 60 ms + |
| long TR | 3000 ms + |
| short TI | 100–175 ms |
| long ETL | 12–20 |

**FLAIR**

| | |
|---|---|
| long TE | 60 ms + |
| long TR | 3000 ms + |
| long TI | 1700–2200 ms |
| long ETL | 12–20 |

**Slice thickness**

| | | |
|---|---|---|
| 2D | thin | 2–4 mm |
| | medium | 5–6 mm |
| | thick | 8 mm |
| 3D | thin | ≤ 1 mm |
| | thick | ≥ 3 mm |

**FOV**

| | |
|---|---|
| small | ≤ 18 cm |
| medium | 18–30 cm |
| large | ≥ 30 cm |

**NEX/NSA**

| | |
|---|---|
| short | ≤ 1 |
| medium | 2–3 |
| multiple | ≥ 4 |

**Coherent GRE**

| | |
|---|---|
| long TE | 15 ms + |
| short TR | ≤ 50 ms |
| flip angle | 20°–40° |

**Incoherent GRE**

| | |
|---|---|
| short TE | min–5 ms |
| short TR | ≤ 50 ms |
| flip angle | 20°–40° |

**Balanced GRE**

| | |
|---|---|
| TE | minimum |
| TR | minimum |
| flip angle | ≥ 40° |

**SSFP**

| | |
|---|---|
| TE | minimum |
| TR | 40–50 ms |
| flip angle | 20°–40° |

**Slice numbers**

| | | |
|---|---|---|
| Volumes | small | ≤ 32 |
| | medium | 64 |
| | large | ≥ 128 |

**Matrix (frequency × phase)**

| | |
|---|---|
| coarse | 256 × 128 or 256 × 192 |
| medium | 256 × 256 or 512 × 256 |
| fine | 512 × 512 |
| very fine | ≥ 512 × 512 |

**PC-MRA**

| | | |
|---|---|---|
| 2D and 3D | TE | minimum |
| | TR | 25–33 ms |
| | flip angle | 30° |
| VENC venous | | 20–40 cm/s |
| VENC arterial | | 60 cm/s |

**TOF-MRA**

| | | |
|---|---|---|
| 2D | TE | minimum |
| | TR | 28–45 ms |
| | flip angle | 40°–60° |
| 3D | TE | minimum |
| | TR | 25–50 ms |
| | flip angle | 20°–30° |

- a large FOV
- thick slices
- the narrowest receive bandwidth available
- as many excitations and signal averages (NEX/NSA) as possible.

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 (CNR)

The contrast to noise ratio (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.
- Selection of magnetization transfer (MT) sequences.
- Suppression of normal tissues via chemical/spectral presaturation, or sequences that null signal from certain tissues: short TI inversion recovery (STIR), fluid alternated inversion recovery (FLAIR), magnetization-prepared sequences).

## 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 $256 \times 128$ or $256 \times 192$
- a medium matrix is $256 \times 256$ or $512 \times 256$
- a fine matrix is $512 \times 512$
- a very fine matrix is any matrix greater than $512 \times 512$
- 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 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, e.g. 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, e.g. 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 presaturation 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 number of signal averages/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, i.e. 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 $256 \times 256$ 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 over-prescribe 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