Chapter 15: Magnetic Resonance Imaging

Slide set of 242 slides based on the chapter authored by Martin O. Leach of the IAEA publication (ISBN 978-92-0-131010-1):

Diagnostic Radiology Physics: A Handbook for Teachers and Students

Objective:
To familiarize the student with practical issues associated with MRI.

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15.2. Hardware
15.3. Basic image quality issues
15.4. MR Image acquisition and reconstruction
15.5. Artefacts
15.6. Safety and bioeffects
15.2 HARDWARE
Hardware overview

- Several major components
- Components are under control of digital systems that
  - provide instructions
  - monitor system performance
  - acquire and process
    - signals used to create images
    - or spectroscopic signals reporting on a range of tissue states
- Digital systems are coordinated by one or more computers
  - workstations or PCs
  - provide interface to the operator
Computer interface with operator

- Acquisitions
  - planned
  - executed

- Images
  - calculated
  - displayed
  - stored

- Measurement and analysis software
  - for addressing particular clinical questions
Major components of a clinical magnetic resonance imaging system utilising a superconducting magnet
15.2 HARDWARE

15.2.1 THE STATIC MAGNETIC FIELD SUBSYSTEM
15.2 HARDWARE

15.2

Major components

- 15.2.1 The static magnetic field subsystem
- 15.2.2 The radiofrequency (RF) subsystem
- 15.2.3 Gradient coil design and specifications
- 15.2.4 Computer and control systems
- 15.2.5 Common imaging options
Requirements for static magnetic field subsystem

- Must provide a highly uniform and stable magnetic field
  - Larmor resonance condition must be met over the imaging volume to within about 1 part per million (ppm)

- Achieve by
  - main magnet design
  - additional static and electronic shims (adjustments) to correct for
    - imperfections in magnet design
    - effects of nearby static steel structures
    - effects of the patient’s intrinsic magnetic susceptibility
Magnet designs and field strengths

- Resistive solenoid, $< \sim 0.5$ T
- Superconducting magnet
  - clinical use: 0.5 – 3.0 T
  - experimental clinical use: 3.0 – 8 T and above
- Electromagnets, 0.1 – 0.2 T
- Permanent magnets

- Geometry relates directly to the intrinsic orientation of the magnetic field
15.2 HARDWARE
15.2.1 The static magnetic field subsystem

Three different superconducting magnets
- A: Siemens 3T Vario system
- B: Philips 1T Panorama system
- C: General Electric 1.5T Discovery MR450 system.
Resistive solenoid

- Simplest design
- Long solenoid generates uniform magnetic field
- Solenoid reduced to typically 4 or 6 coils, separated by spacers
- Coils may have different diameters
- Uniformity maximised by calculating optimal
  - relative current density
  - number of windings
  - diameter
- Both horizontal and vertical configurations have been built
Resistive solenoid

Advantages
- Relatively cheap

Disadvantages
- Produce considerable heat
  - require water cooling
  - resistance changes with temperature
- Constraints of power supplies
- High current demand
- Maximum field strength 0.5 T
Superconducting magnets

- Design based on similar principles to resistive solenoid
- Usually horizontal bore geometry
- A number of coils in parallel, but wound from superconducting cable
  - niobium/tin encased in copper
  - maintained at liquid helium temperatures (4 K, -269 °C)
- Considerably reduced current requirements compared with resistive solenoid
- Higher field strengths possible 0.5 – 3.0 T or above
Cryostat features

- Coils are encased in a vacuum cryostat
  - designed to limit heat conductance
  - includes a number of thermal layers
    - liquid helium surrounded by
    - helium vapour barrier
    - then vacuum

- Helium vapour is re-liquefied by cryoc ompressors
  - so very little liquid helium is needed during normal operation

- Earlier designs had layers of liquid and gaseous nitrogen instead
  - this needed frequent replenishment to minimise helium boil-off
Cryocompressor failure

- May be caused by fault, loss of chilled water, loss of power
- Remaining liquid helium cryogen will boil off
  - superconducting windings no longer adequately cooled
  - windings become resistive
  - windings heat up rapidly due to large current

- Results in a magnet quench
  - current is rapidly resistively dissipated as heat
  - rapid boil off of any remaining cryogen

- Cryostat is designed to vent resulting release of gas safely to the outside of the building
15.2 HARDWARE
15.2.1 The static magnetic field subsystem

Shielding

- Up to 3.0 T, system usually self-shielded
- A second, reversed, magnetic field is generated
  - cancels much of the field outside the magnet
  - retains strong magnetic field in the magnet bore
- Extent of magnetic field considerably reduced
  - makes site planning and facility management easier
  - reduces area of restricted access
  - reduces effects on nearby equipment
Variations in geometry

- Interventional systems
  - accessible central aperture perpendicular to the magnet axis

- Vertically oriented field
  - signal to noise advantages in receiver coils when patient is horizontal
  - as in Philips I T Panorama system
15.2 HARDWARE
15.2.1 The static magnetic field subsystem

Electromagnets

- Incorporate a ferromagnetic core into resistive design
  - reduces the electrical current requirement of resistive magnets
  - increases stability
  - minimises cooling requirements
- Lower field than superconducting, e.g. 0.1 – 0.2 T
- Typically have vertically oriented field between pole faces
- Increased access to patient compared with most superconducting systems
Permanent magnets

- Predominantly have vertical field format
  - Also horizontal field system, with patient upright, used for examining joints
- Field constrained between top and bottom pole faces
  - design requires a flux return path

- Advantages
  - small stray field
- Disadvantages
  - heavy
  - cannot be switched off
15.2 HARDWARE

15.2.1 The static magnetic field subsystem

Magnetic field homogeneity

- Typically require at least 1 ppm over field of view (FOV)
  - tolerances of magnet design and the environment e.g. structural steel in building
  - adjust magnetic field at installation by shimming
    - steel shims
    - additional magnetic fields from adjustable currents in shim coils

- Some approaches require about 0.1 ppm over FOV
  - fat suppressed imaging and MR spectroscopy
  - adjust magnetic field prior to study using shim coils
  - compensate for distortions in magnetic field caused by magnetic susceptibility of the patient
Siting issues

- Safety issues – section 15.6
- Effect on magnet homogeneity of
  - adjacent steel
  - moving steel objects
  - nearby current carrying cables
- Adequate structural strength
- Effect of magnet on adjacent equipment
Site for static magnetic field - homogeneity

- Contains 0.5 mT field contour within a secure zone with controlled access

Magnet homogeneity

- Self shield to minimise effect of structural steel
  - but it may need replacing with non ferromagnetic stainless steel
- Seek advice from manufacturer regarding
  - Large steel pipes and electrical cables with heavy current load
  - Moving steel from vehicles, trains, subway trains
Site for static magnetic field – structural and other equipment

- Design must account for structural factors
  - floor loading
  - equipment access
  - avoid sources of vibration

- Other sensitive equipment with potential to be affected
  - gamma cameras
  - x-ray systems
  - radiotherapy linear accelerators
  - image intensifiers
  - electron microscopes
15.2 HARDWARE
15.2.2 THE RADIOFREQUENCY (RF) SUBSYSTEM
Major components

- 15.2.1 The static magnetic field subsystem
- 15.2.2 The radiofrequency (RF) subsystem
- 15.2.3 Gradient coil design and specifications
- 15.2.4 Computer and control systems
- 15.2.5 Common imaging options
15.2 HARDWARE
15.2.2 The radiofrequency (RF) subsystem

Requirements for the RF subsystem

- Generation of analogue audio frequency pulses
  - modulate the RF Larmor frequency
  - generated from a digital source and amplified to drive the RF coils

- RF coils transmit and receive RF to and from the patient

- Amplifier may be capable of supplying 15 kW of power
  - to drive a coil that can irradiate the whole body

- Weak detected RF signal
  - provides information that builds images or spectra
  - receive channel(s) must be protected from the transmitted power
  - several stages of amplification
15.2 HARDWARE

15.2.2 The radiofrequency (RF) subsystem

Coil designs

- Volume
  - transmit and receive

- Surface
  - transmit and receive

- Phased array
  - receive
Volume RF coils - transmit

- Main body coil or head coil
  - transmits RF to the patient
  - typically circularly polarised
    - generates a field rotating at the Larmor frequency
    - driven in quadrature
- Coils transmit (and detect) magnetic fields orthogonal to the main $B_0$ static magnetic field
Volume RF coils – Parallel transmit systems

- Overcome the inhomogeneous $B_1$ transmit field that arise as wavelength of RF approaches dimensions of the body
- In 3 T systems and above
- Array of transmit coils
- Each supplied by separate amplifier
- Allows individual amplitude and phase modulation
Volume RF coils - receive

- Main body coil used as a receiver
  - allows imaging of large volumes of the body
  - multi-station body imaging
    - images of different sections of the body are joined together to give a whole body image
- Also head coil, knee coil, extremity coil
- Range of designs, including birdcage
  - based on two circular loops connected by parallel rods
**15.2 HARDWARE**

**15.2.2 The radiofrequency (RF) subsystem**

**Surface RF coils - transmit**
- Smaller than body coil
- Positioned over volume of interest in the body
- Particularly for multi-nuclear measurements

**Surface RF coils – receive**
- Provide increased signal to noise from small volumes
- Flexible designs for many parts of the body
Phased array RF coils – receive

- Extension of surface coil approach
- Set of closely positioned separate coils
  - each connected to a separate parallel receive channel
  - signal is acquired from many surface coils simultaneously
- Improved image quality and faster image acquisition
- Some systems allow body to be covered with such coils
  - optimised imaging of many different body parts with no need to move patient to position additional coils
- Multinuclear measurements
  - coils tuned to required frequency
  - or may operate several coils at different frequencies
15.2 HARDWARE

15.2.2 The radiofrequency (RF) subsystem

- Top row:
  - Siemens 32 channel head coil
  - General Electric torso array coil
  - Philips neck coil

- Bottom row:
  - General Electric cervical, thoracic and lumbar spine coil
  - Four channel flex coils
15.2 HARDWARE

15.2.2 The radiofrequency (RF) subsystem

Siting issues: RF shielding

- RF screened room
- Avoid RF interference to other equipment
  - including radio and television reception
- Prevent interference from external sources
  - interfering with detection of very weak RF signal
15.2 HARDWARE

15.2.2 The radiofrequency (RF) subsystem

Siting issues: RF screened room

- Made of copper, aluminium or stainless steel
- RF screened windows
- RF doors with knife edge brushes to maintain screen integrity
- Attached to good earth point
- All services non-conducting, RF filtered and incorporate non-conducting break
- Wave guide access channels for non-conducting services
15.2 HARDWARE

15.2.3 GRADIENT COIL DESIGN AND SPECIFICATIONS
Major components

- 15.2.1 The static magnetic field subsystem
- 15.2.2 The radiofrequency (RF) subsystem
- 15.2.3 Gradient coil design and specifications
- 15.2.4 Computer and control systems
- 15.2.5 Common imaging options
Requirements for gradient coils

- **Spatial localisation of image information**
  - governed by three orthogonal sets of coils
  - superimpose a field gradient
  - add to, or subtract from, main $B_0$ static magnetic field

- **Larmor frequency changes linearly with position in**
  - x (usually horizontal: orthogonal to $B_0$) direction
  - y (usually vertical: orthogonal to $B_0$) direction
  - z (along $B_0$) direction
15.2 HARDWARE

15.2.3 Gradient coil design and specifications

Gradient coil design

- For standard superconducting magnet
- For x and y direction
  - two pairs of Golay coils
  - shaped like a saddle positioned on a cylinder
- For x direction
  - pair of coils coaxial with magnet windings
- Mounted on a substantial former placed concentrically within the room temperature bore of the magnet
15.2 HARDWARE

15.2.3 Gradient coil design and specifications

Gradient coil design

- Capable of rapid switching
- Carry high currents of order of 600 A
  - as may generate fields up to about 60 mTm\(^{-1}\)
- Require cooling because of high power dissipation
  - often water cooled
- Noise and vibration addressed by
  - high mass and stiff mountings
  - balanced force designs
  - mounting within a vacuum jacket
  - active noise cancellation
15.2 HARDWARE

15.2.3 Gradient coil design and specifications

Gradient amplitude and slew rate (rise time)

- **Large gradients**
  - allow thin slices and high resolution images
  - reduce impact of $B_0$ field inhomogeneities
  - can aid diffusion weighted imaging by allowing larger $b$ values with faster imaging times

- **Fast switching**
  - allows fast imaging sequences
  - is defined in terms of slew rate (or rise time)

- **Slew rate** is the rate of change of the gradient
Maximum slew rate (rise time)

- Maximum slew rate is maximum rate of change of gradient
  - 200 Tm$^{-1}$s$^{-1}$ possible currently
- In practice, maximum used is limited by induction of currents in body that can lead to nerve stimulation
- For large gradients, slew rate may be slower to ensure safe operation
- A given machine may offer a choice of gradient modes
Eddy current effects

- Calculated gradient pulse waveform
  - linear ramp up, maximum value held for a defined period, linear ramp down
  - all within a specified total time

- But, get a non-perfect response arising from
  - inductance of gradient coils
  - presence of currents in adjacent conducting structures resulting from the time varying magnetic field generated by the gradient coils i.e. eddy currents

- Eddy currents can lead to time varying magnetic fields that distort the image information
Compensation for eddy current effects

- **Screened gradient designs**
  - cancel out gradient fields outside magnet bore
  - thus reduce generation of eddy currents that would generate additional magnetic field gradients

- **Design of magnet cryostat and heat shields can minimise generation of eddy currents**

- **Apply pre-emphasis corrections in gradient circuitry**
  - impose additional LC terms on the driving waveform to compensate for eddy current modulation
  - performance tuned by manufacturer
15.2 HARDWARE

15.2.4 COMPUTER AND CONTROL SYSTEMS
15.2 HARDWARE

15.2

Major components

- 15.2.1 The static magnetic field subsystem
- 15.2.2 The radiofrequency (RF) subsystem
- 15.2.3 Gradient coil design and specifications
- 15.2.4 Computer and control systems
- 15.2.5 Common imaging options
15.2 HARDWARE

15.2.4 Computer and control systems

Pulse programmer

- Interprets pulse sequences
- Generates and delivers waveforms to different equipment components
  - gradient amplifiers
  - RF amplifiers
- Receives and digitises signals at appropriate times
- Access to pulse programmer
  - Sometimes user has direct access to generate own sequences
  - More usually, user has access using an interface that allows a limited class of variables to be adjusted for a given sequence
Processor interface

- Allows selection of variables for pulse sequences
- May include specialised equipment for image calculation
- Memory, to store
  - raw time-domain data (i.e. the measured signals)
  - reconstructed data
- Further interfaces to
  - storage facilities
  - hard copy output
  - PACS systems
  - interactive displays for measurement planning and image data analysis
15.2 HARDWARE
15.2.5 COMMON IMAGING OPTIONS
Major components

- 15.2.1 The static magnetic field subsystem
- 15.2.2 The radiofrequency (RF) subsystem
- 15.2.3 Gradient coil design and specifications
- 15.2.4 Computer and control systems
- 15.2.5 Common imaging options
Choice of equipment for clinical requirements

- **MRI systems**
  - core equipment configurations plus
  - packages marketed for clinical applications

- **Steps when choosing a system**
  - Helpful first to develop a clinical specification
  - General considerations
    - lead to choice of magnet configuration
  - Specific equipment considerations
15.2 HARDWARE
15.2.5 Common imaging options

General considerations

- Clinical requirements
- Space
- Budget
- Reliability of power supplies
- Availability of cryogens
- Quality and lifetime cost of engineering support
- Cost of maintenance support
15.2 HARDWARE

15.2.5 Common imaging options

Specific considerations

- Once magnet configuration decided:
- Gradient specification (if an option)
- Clinical packages
- RF coils
15.3 BASIC IMAGE QUALITY ISSUES
Basic image quality issues

Major determinants (there are many other features)

- 15.3.1 $B_0$ field strength, homogeneity and shimming
- 15.3.2 $B_1$ homogeneity and flip angle adjustment
- 15.3.3 Phantoms, equipment assessment and coil loading
- 15.3.4 Signal-to-noise ratio (SNR) and contrast-to-noise ratio
- 15.3.5 Spatial resolution
- 15.3.6 Image acquisition time
15.3 BASIC IMAGE QUALITY ISSUES

15.3.1 $B_0$ FIELD STRENGTH, HOMOGENEITY AND SHIMMING
Basic image quality issues

- 15.3.1 $B_0$ field strength, homogeneity and shimming
- 15.3.2 $B_1$ homogeneity and flip angle adjustment
- 15.3.3 Phantoms, equipment assessment and coil loading
- 15.3.4 Signal-to-noise ratio (SNR) and contrast-to-noise ratio
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- 15.3.6 Image acquisition time
**15.3 BASIC IMAGE QUALITY ISSUES**

**15.3.1 $B_0$ field strength, homogeneity and shimming**

$B_0$ field strength
- Determines signal to noise
- Signal to noise increases approximately linearly with magnetic field strength
B₀ homogeneity and shimming

- Fundamental determinant of the quality of an MRI system
- Determined by design of magnet system
- Governed by
  - type of magnet
  - size of magnet
    - larger (longer) the better the homogeneity
  - optimisation at installation
    - avoid structural steel etc.
  - careful shimming at set up (passive and electronic)
  - demonstration by engineers that meets specification
Changes in $B_0$ homogeneity

- Sudden deterioration could arise from
  - changes in environmental steel
  - small items of steel that have entered vicinity of magnet and been attracted to the magnet

- Investigate these potential causes
**Shimming**

- Operator shimming of $B_0$ for some imaging sequences e.g.
  - frequency dependent fat suppression
  - frequency dependent water excitation
- Performed by adjusting current in a number of room temperature shim coils incorporated into the system
- Shimming required in spectroscopy to compensate for $B_0$ inhomogeneities arising from susceptibility of patient
Other causes of spatial distortion in images

- Gradient non-linearities
- Eddy currents
- Inadequate pre-emphasis correction
15.3 BASIC IMAGE QUALITY ISSUES

15.3.2 $B_1$ HOMOGENEITY AND FLIP ANGLE ADJUSTMENT
15.3 BASIC IMAGE QUALITY ISSUES

Basic image quality issues

- **15.3.1** $B_0$ field strength, homogeneity and shimming
- **15.3.2** $B_1$ homogeneity and flip angle adjustment
- **15.3.3** Phantoms, equipment assessment and coil loading
- **15.3.4** Signal-to-noise ratio (SNR) and contrast-to-noise ratio
- **15.3.5** Spatial resolution
- **15.3.6** Image acquisition time
**B₁ homogeneity**

- Expectation is that specified flip angle is delivered to imaging volume uniformly and accurately.
- For each new patient MR system performs a calibration:
  - Adjusts voltage delivered to body coil to compensate for:
    - Loading of the coil by the patient (changes coil Q)
    - Particular coil configurations
    - Interaction of RF field with subject leading to standing wave and dielectric effects (at higher fields)
- Calibration allows adjustments for RF pulse lengths, slice thicknesses and so on.
B$_1$ homogeneity in practice

- A number of factors lead to inaccurate pulse angles being delivered to all or part of the volume
  - physical geometry of the transmit coil
  - presence of receiver coils within transmit coil
  - effects of standing waves or dielectric effects
  - imperfect shape of slice select pulses (finite pulse length)

- Conventional diagnostic imaging - useable image information but
  - reduced image contrast and reduced signal to noise ratio

- Quantitative imaging – need to address or compensate in analysis
15.3 BASIC IMAGE QUALITY ISSUES

15.3.3 PHANTOMS, EQUIPMENT ASSESSMENT AND COIL LOADING
Basic image quality issues

- 15.3.1 $B_0$ field strength, homogeneity and shimming
- 15.3.2 $B_1$ homogeneity and flip angle adjustment
- 15.3.3 Phantoms, equipment assessment and coil loading
- 15.3.4 Signal-to-noise ratio (SNR) and contrast-to-noise ratio
- 15.3.5 Spatial resolution
- 15.3.6 Image acquisition time
Phantoms

- Manufacturer provides standard phantoms for basic routine service procedures
  - usually simple
  - allow comparison with manufacturer’s specification and maintenance tolerances
  - but do not fully evaluate scanner performance
Phantoms for equipment assessment

- More sophisticated phantoms than the manufacturer’s
- Some commercially available

Use for

- spatial resolution
- $T_1$ and $T_2$ relaxation time measurements
- spatial distortion assessment
- SNR measurements

Systematic approach valuable
SNR measurements

- Need RF coils to be appropriately loaded
- Achieve by
  - including a conducting (ionic) solution in the phantom or
  - use a separate loading annulus with phantom
- Must check that results accurate and reflect clinical situation
- Valuable to make SNR measurement for each imaging coil
  - controlled and reproducible conditions
  - regularly
  - will demonstrate if equipment is operating outside its specification
If local or surface coil is operating outside its specification

- Repeat measurement with body coil
  - rule out/establish if fault is with coil or main system
- Call manufacturer or
- Undertake further tests to investigate
  - distortion or image artefacts
    - phantom with known structures
  - ghosting or aliasing
    - 3D objects with asymmetries
15.3 BASIC IMAGE QUALITY ISSUES

15.3.4 SIGNAL-TO-NOISE RATIO (SNR) AND CONTRAST-TO-NOISE RATIO
15.3 BASIC IMAGE QUALITY ISSUES

Basic image quality issues

- **15.3.1** $B_0$ field strength, homogeneity and shimming
- **15.3.2** $B_1$ homogeneity and flip angle adjustment
- **15.3.3** Phantoms, equipment assessment and coil loading
- **15.3.4** Signal-to-noise ratio (SNR) and contrast-to-noise ratio
- **15.3.5** Spatial resolution
- **15.3.6** Image acquisition time
Signal-to-noise ratio (SNR)

- Signal is highly dependent on:
  - object
  - imaging sequence
  - parameters chosen

- SNR must be defined for specific:
  - object
  - coil
  - geometry
  - measurement sequence
Distribution of noise in MR image

- Should be distributed uniformly throughout the image
  - uniform distribution of noise expected from use of Fourier transform

- May not be uniform if temporal frequency filter applied in reconstruction or acquisition
  - E.g. with parallel processing or array coils, when distribution of noise may be complex
15.3 BASIC IMAGE QUALITY ISSUES
15.3.4 Signal-to-noise ratio (SNR) and contrast-to-noise ratio

Determination of noise in MR image

- Subtract two identical images
- Not affected by
  - non-uniform distribution of noise
  - directional propagation of artefacts
- Is appropriate MR noise which has a Rician distribution
15.3 BASIC IMAGE QUALITY ISSUES
15.3.5 SPATIAL RESOLUTION
Basic image quality issues

- 15.3.1 $B_0$ field strength, homogeneity and shimming
- 15.3.2 $B_1$ homogeneity and flip angle adjustment
- 15.3.3 Phantoms, equipment assessment and coil loading
- 15.3.4 Signal-to-noise ratio (SNR) and contrast-to-noise ratio
- 15.3.5 Spatial resolution
- 15.3.6 Image acquisition time
Spatial resolution for 2D imaging sequences

Governed by

- In-plane resolution
- Slice width
In-plane spatial resolution – theoretical

- In-plane resolution is a function of
  - the sampling of the time (k-space) signal in the two orthogonal directions $\Delta k_x$ and $\Delta k_y$ and
  - field of view $FOV_x$ and $FOV_y$

- See equations in section 14.5.3
In-plane spatial resolution – in practice also affected by

- Signal power available at higher k-space frequencies
  - depends on order in which k-space data acquired
- Relaxation properties of tissues
- Duration of measurement
In-plane spatial resolution – Reconstruction factors

- Blurring of reconstructed images arises from signal reduction due to
  - relaxation or asymmetrical k-space signal

- Interpolation occurs if images reconstructed at higher resolution than data acquired
  - may be greater interpolation in phase encoding than in the read-out direction, so have asymmetric resolution

- Reduced spatial resolution also arises from
  - reduced sampling schemes designed to speed up acquisition
    - these also introduce phase errors and increase noise
  - spatial filters used in reconstruction
In-plane resolution – theoretical

- For 2-D imaging sequences, spatial resolution is governed by slice width, and by the in-plane resolution, as described in 14.5.3.

\[
\Delta x = \frac{1}{2k_{x,max}} \quad \Delta y = \frac{1}{2k_{y,max}}
\]
Slice width spatial resolution – in practice also affected by

- Slice profile, which depends on
  - RF pulse profiles used to excite pulse and (where relevant) generate echoes
  - relaxation properties of tissues
  - repetition time (TR)
    - non-fully relaxed measurements can result in relative suppression of signal in the centre of the slice compared with tissues at the edge, which receive smaller flip angles
  - pulse sequence
  - sequence parameters
  - excitation pulse bandwidth
  - gradient strength
Slice width spatial resolution – practical points

- Slice profile is best determined experimentally
- Use materials reflecting relaxation times of tissues of interest
- In 2D imaging, may acquire slices
  - contiguous or with inter-slice gaps to reduce overlap of slice profiles
  - serially or in an interleaved fashion
Slice width spatial resolution – 3D imaging

- Slice selection is often used to select thick slices, which are separated into partitions using a phase encoding step.

- Towards edges of slice, the slice profile may affect accuracy of flip angle. Important for quantitative imaging.

- Partition thickness defined in same way as in-plane resolution in the read-out direction. May be subject to interpolation in the same way.
15.3 BASIC IMAGE QUALITY ISSUES

15.3.6 IMAGE ACQUISITION TIME
15.3 BASIC IMAGE QUALITY ISSUES

Basic image quality issues

- **15.3.1** $B_0$ field strength, homogeneity and shimming
- **15.3.2** $B_1$ homogeneity and flip angle adjustment
- **15.3.3** Phantoms, equipment assessment and coil loading
- **15.3.4** Signal-to-noise ratio (SNR) and contrast-to-noise ratio
- **15.3.5** Spatial resolution
- **15.3.6** Image acquisition time
Image acquisition time for simple sequences

\[ \text{Image acquisition time} = TR \times N_{PE} \times NEX \]

where \( TR \) is the repetition time, \( N_{PE} \) is the number of phase encodes and \( NEX \) is the number of signal averages used for each image.

- Multiple slices may be acquired during each TR, where TR is long, at no time cost.
15.3 BASIC IMAGE QUALITY ISSUES
15.3.6 Image acquisition time

Image acquisition time, for simple sequences at short TR

For fast sequences, where TR too short for additional slices to be acquired

Image acquisition time =

\[ TR \times N_{PE} \times NEX \times N_{slices} \]

where \( TR \) is the repetition time, \( N_{PE} \) is the number of phase encodes, \( NEX \) is the number of signal averages used for each image and \( N_{slices} \) is the number of slices acquired
Image acquisition time, for complex and 3D sequences

- Extended by
  - preparation pulses
  - inversion or fat suppression pulses
  - acquisition of multiple echoes

- Reduced by
  - employing different echoes to provide some of the different phase encodes (as in fast spin-echo)

- For 3D imaging, governed by
  - product of number of phase steps in each phase encode direction
  - same factors as above will extend or reduce acquisition time
Parallel imaging

- Significant increase in imaging speed
- Share information from arrays of coils
  - use specialised reconstruction algorithms to combine information from each coil (or coil element)
  - spatial sensitivity of each coil is allowed for
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION
MR Image acquisition and reconstruction

Gradient-echo and spin-echo imaging sequences provide the core building blocks of the major families of sequences

- 15.4.1 Gradient-echo sequence (also 14.5.4)
- 15.4.2 Spin-echo sequence (also 14.5.5)
- 15.4.3 Fast spin-echo sequence
- 15.4.4 Inversion recovery sequences
- 15.4.5 Common sequence options
- 15.4.6 Ultra fast imaging sequences
- 15.4.7 MR angiography sequences
- 15.4.8 Flow measurements
- 15.4.9 Cardiac measurements
- 15.4.10 Diffusion measurements
- 15.4.11 Brain activation measurements
- 15.4.12 Dynamic Contrast Enhanced MRI
- 15.4.12 MR spectroscopy
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4.1 GRADIENT-ECHO SEQUENCES
MR Image acquisition and reconstruction

- 15.4.1 Gradient-echo sequence (also 14.5.4)
- 15.4.2 Spin-echo sequence (also 14.5.5)
- 15.4.3 Fast spin-echo sequence
- 15.4.4 Inversion recovery sequences
- 15.4.5 Common sequence options
- 15.4.6 Ultra fast imaging sequences
- 15.4.7 MR angiography sequences
- 15.4.8 Flow measurements
- 15.4.9 Cardiac measurements
- 15.4.10 Diffusion measurements
- 15.4.11 Brain activation measurements
- 15.4.12 Dynamic Contrast Enhanced MRI
- 15.4.12 MR spectroscopy
Gradient-echo sequence

- Small angle slice select pulse (5 - 20°) allows short TR
- Read-out shortened by using larger gradients
- Spoilt gradient echo sequences are widely used
Spoilt gradient-echo sequence

- Any coherent transverse magnetisation destroyed at end of each acquisition
- Destruction of magnetisation by
  - RF spoiling: variations in phase of RF excitation and acquisition
  - dephasing gradients: at the end of the acquisition
- So, before each RF pulse, magnetisation entirely in the longitudinal direction, even for short TR
FLASH sequence

- FLASH (Fast Low Angle SHot) is an example of a spoilt sequence
- Commonly used for 3D sequences
- Short TR allows rapid imaging (many slices within reasonable time)
- T2* weighted: useful for imaging joints
Variations on spoilt gradient-echo sequence

- Turbo FLASH (and other similar sequences)
- Preparation pulses used prior to the acquisition to condition the contrast
  - e.g. inversion pulse
- 2D image can then be read out very quickly with very small flip angles and short TR
Steady state gradient-echo sequences

- Steady state magnetisation maintained
- Achieved by eliminating the spoiling at the end of each repetition
- Image contrast depends on $T_2/T_1$
  - exact contrast dependency includes implementation, TE, TR
- e.g. FISP (Fast Imaging with Steady-state Precession)
- Phase encoding is rewound at end of each repetition by applying reverse of phase encoding gradient pulse
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4.2 SPIN-ECHO SEQUENCE
MR Image acquisition and reconstruction

- 15.4.1 Gradient-echo sequence (also 14.5.4)
- **15.4.2 Spin-echo sequence (also 14.5.5)**
- 15.4.3 Fast spin-echo sequence
- 15.4.4 Inversion recovery sequences
- 15.4.5 Common sequence options
- 15.4.6 Ultra fast imaging sequences
- 15.4.7 MR angiography sequences
- 15.4.8 Flow measurements
- 15.4.9 Cardiac measurements
- 15.4.10 Diffusion measurements
- 15.4.11 Brain activation measurements
- 15.4.12 Dynamic Contrast Enhanced MRI
- 15.4.12 MR spectroscopy
Spin-echo sequence

- Involves relatively high power deposition because of 90° and 180° pulses
  - Limits TR, number of slices or number of echoes achievable
- Typically
  - Long TR (~2 s) to allow signal recovery and minimise $T_1$ weighting
  - TE 70-120 ms for $T_2$ weighted images
  - Employ two echoes and can acquire a short TE proton density weighted image at the same time
- $T_2$ weighting now more commonly obtained using a faster sequence such as fast spin-echo or RARE (Rapid Acquisition with Refocused Echoes)
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4.3 FAST SPIN-ECHO SEQUENCE
### 15.4 MR Image Acquisition and Reconstruction

| 15.4.1 | Gradient-echo sequence (also 14.5.4) |
| 15.4.2 | Spin-echo sequence (also 14.5.5) |
| **15.4.3** | Fast spin-echo sequence |
| 15.4.4 | Inversion recovery sequences |
| 15.4.5 | Common sequence options |
| 15.4.6 | Ultra fast imaging sequences |
| 15.4.7 | MR angiography sequences |
| 15.4.8 | Flow measurements |
| 15.4.9 | Cardiac measurements |
| 15.4.10 | Diffusion measurements |
| 15.4.11 | Brain activation measurements |
| 15.4.12 | Dynamic Contrast Enhanced MRI |
| 15.4.12 | MR spectroscopy |
Fast spin-echo sequence

- Multiple spin echoes are applied
- Each receives a separate phase encoding
  - phase encoding applied prior to 180° pulse and is reversed following read out of the echo
  - further phase encoding pulse for a different line of k-space prior to another 180° pulse and is reversed following read out of the echo
  - repeated for as many k-space lines as are required
- Each line of k-space has a slightly different echo time
- In extreme case, acquire sufficient echoes for entire image, each differently phase encoded
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION
15.4.3 Fast spin-echo sequence

Fast spin-echo sequence
Fast spin-echo sequence

- Diagram shows first three 180° refocusing pulses
- Position in $k_y$ direction depends on
  - phase of the 180° refocusing pulse
  - amplitude of phase encoding gradient
Fast spin-echo sequence – image quality

- Image quality affected by different echo times for each line of k-space
- Except for very long $T_2$ materials results is very little signal in later k-space lines
  - reduced spatial resolution
- So, usual to divide k-space sampling across multiple repetitions of the sequence
  - group together bands of k-space with similar echo times
  - echoes characterised by a narrow range of echo time
- Now a very common approach for $T_2$ weighted imaging
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4.4 INVERSION RECOVERY SEQUENCES AND APPLICATIONS
MR Image acquisition and reconstruction

15.4.1 Gradient-echo sequence (also 14.5.4)
15.4.2 Spin-echo sequence (also 14.5.5)
15.4.3 Fast spin-echo sequence

15.4.4 Inversion recovery sequences

15.4.5 Common sequence options
15.4.6 Ultra fast imaging sequences
15.4.7 MR angiography sequences
15.4.8 Flow measurements
15.4.9 Cardiac measurements
15.4.10 Diffusion measurements
15.4.11 Brain activation measurements
15.4.12 Dynamic Contrast Enhanced MRI
15.4.12 MR spectroscopy
Inversion recovery imaging

- Apply 180° inversion pulse
- Allow recovery of longitudinal ($T_1$) magnetisation
- Select time point during recovery to optimise contrast between chosen different tissues
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION
15.4.4 Inversion recovery sequences and applications

STIR

- **Short TI (Inversion Time) Inversion Recovery (STIR)**
- Common application is to null signal from fat
- Select image read-out at the time recovery of fat signal is passing through null point
- Fat nulling technique
  - depends on $T_1$ relaxation of fat
  - alternative to frequency dependent or selection techniques
- Also applied to null signal from fluid
  - allows monitoring of tissue structures that would otherwise be masked by strong signal from adjacent fluids
STIR imaging read-out by a variety of imaging sequences

- Conventional inversion recovery
  - inversion applied for each line in the image

- Very fast gradient-echo or fast spin-echo
  - single preparation inversion

- Combination
  - apply suitably spaced inversion pulses and acquire several k-space lines around the inversion time
  - e.g. FLAIR (Fluid Attenuated Inversion Recovery), which nulls CSF fluid for CNS imaging, or fluids elsewhere in body

- Double inversion: allows signal from two tissue groups to be nulled
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4.5 COMMON SEQUENCE OPTIONS (SPATIAL AND CHEMICAL SATURATION TECHNIQUES)
MR Image acquisition and reconstruction

- 15.4.1 Gradient-echo sequence (also 14.5.4)
- 15.4.2 Spin-echo sequence (also 14.5.5)
- 15.4.3 Fast spin-echo sequence
- 15.4.4 Inversion recovery sequences

- 15.4.5 Common sequence options
  - 15.4.6 Ultra fast imaging sequences
  - 15.4.7 MR angiography sequences
  - 15.4.8 Flow measurements
  - 15.4.9 Cardiac measurements
  - 15.4.10 Diffusion measurements
  - 15.4.11 Brain activation measurements
  - 15.4.12 Dynamic Contrast Enhanced MRI
  - 15.4.12 MR spectroscopy
Signal suppression using saturation slices or bands

- Select tissues using broad slice defined by a slice select pulse
  - no read out
  - follow by spoiler gradients to null signal in xy plane

- Use to
  - reduce field of view
  - to null signal, which may cause artefacts, from moving tissue

- To plan timing of such bands, consider
  - $T_1$ of tissues concerned
  - TR of the sequence
Signal suppression using saturation of chosen tissue

- e.g. CHESS (CHEmically Specific Saturation)
- Frequency selective RF pulse, no slice selection
- Excites fat but not water
- Spoilers dephase fat signal in transverse plane
- Also used in spectroscopy
- Use a tailored range of pulses to better suppress the fat or water signal
  - e.g. WET (Water suppression Enhanced through $T_1$ effects)
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4.6 ULTRAFAST IMAGING SEQUENCES (ECHO PLANAR IMAGING AND SPIRAL TECHNIQUES)
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4 MR Image acquisition and reconstruction

- 15.4.1 Gradient-echo sequence (also 14.5.4)
- 15.4.2 Spin-echo sequence (also 14.5.5)
- 15.4.3 Fast spin-echo sequence
- 15.4.4 Inversion recovery sequences
- 15.4.5 Common sequence options

- 15.4.6 Ultra fast imaging sequences
- 15.4.7 MR angiography sequences
- 15.4.8 Flow measurements
- 15.4.9 Cardiac measurements
- 15.4.10 Diffusion measurements
- 15.4.11 Brain activation measurements
- 15.4.12 Dynamic Contrast Enhanced MRI
- 15.4.12 MR spectroscopy
Echo planar imaging (EPI)

- Independent form of single shot imaging
  - developed by Peter Mansfield (Nottingham, UK)
  - alternative to fast gradient-echo methods

- Slice selective pulse

- Large alternating read-out gradient
  - produces string of echoes

- Phase-encoding by a second gradient
  - small continual gradient or repeated blips
  - origin of k-space adjusted by preparatory phase-encoding offset pulse
Blipped echo planar imaging (EPI) sequence
Blipped echo planar imaging (EPI) sequence

- Initial phase offset
  - dashed line

- Incremented phase for each line of k-space
  - solid lines
Echo planar imaging (EPI)

- Advanced gradient design required
  - but now available on most commercial systems
- Entire image read out in (typically) 50 to 100 ms
- Longer measurement time if build up from interleaved measurements, this approach can
  - reduce $T_2^*$ weighting
  - reduce degree of image distortion
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4.7 MR ANGIOGRAPHY (MRA) SEQUENCES
MR Image acquisition and reconstruction

- 15.4.1 Gradient-echo sequence (also 14.5.4)
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- 15.4.8 Flow measurements
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- 15.4.12 Dynamic Contrast Enhanced MRI
- 15.4.12 MR spectroscopy
MR angiography (MRA) sequences

- Three main approaches used to image and measure vascular structures

1. Measure direction and velocity of flow from the phase encoding that occurs when blood flows in presence of a gradient
2. Obtain high image contrast by exploiting the inflow of unsaturated blood into a saturated slice
3. Obtain high image contrast and increased signal by using a bolus of contrast agent
Contrast enhanced MR angiography

- Preferably use blood pool agent
- Contrast agent is bound to a protein such as albumin which is not rapidly excreted from vascular system
  - avoids tissue blush from leakage of smaller molecules into extracellular space, which can reduce vascular contrast
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4.8 FLOW MEASUREMENTS
MR Image acquisition and reconstruction

- 15.4.1 Gradient-echo sequence (also 14.5.4)
- 15.4.2 Spin-echo sequence (also 14.5.5)
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- 15.4.7 MR angiography sequences
- 15.4.8 Flow measurements
  - 15.4.9 Cardiac measurements
  - 15.4.10 Diffusion measurements
  - 15.4.11 Brain activation measurements
  - 15.4.12 Dynamic Contrast Enhanced MRI
  - 15.4.12 MR spectroscopy
Phase contrast MRI

- Measure direction and velocity of bulk flow of blood
- Spins moving along a magnetic field gradient gain (or lose) phase compared with stationary spins
- Use two sequences
  - one with no flow-encoding gradient
  - one in which phase gain due to flow is encoded by a bipolar pair of gradients
- Compare spatial variation in phase
- Phase gain due to flow calculated and presented as image
Time of flight methods

- Set up slice along the vessel of interest
- Monitor distance travelled by labelled blood in a given time
  - unsaturated
  - or tagged e.g. with an inversion pulse
- Also allows measurement of profiles through a particular vessel
Arterial spin labelling

- For measuring tissue perfusion
- Label blood in a slice outside of the tissue of interest
- Observe delivery of the labelled spins in flowing blood to the tissue of interest
  - saturate tissue in region of interest or
  - invert the labelled inflowing signal
- To avoid magnetisation transfer effects
  - control labelling slice on the opposite side of the sample may also be acquired
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4.9 CARDIAC MEASUREMENTS
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4.1 Gradient-echo sequence (also 14.5.4)
15.4.2 Spin-echo sequence (also 14.5.5)
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15.4.4 Inversion recovery sequences
15.4.5 Common sequence options
15.4.6 Ultra fast imaging sequences
15.4.7 MR angiography sequences
15.4.8 Flow measurements

15.4.9 Cardiac measurements
15.4.10 Diffusion measurements
15.4.11 Brain activation measurements
15.4.12 Dynamic Contrast Enhanced MRI
15.4.12 MR spectroscopy
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION
15.4.9 Cardiac measurements

Cardiac MR imaging – triggering for anatomical images

- ECG triggered acquisitions
- Navigator triggered acquisitions
  - signal profile along a column of tissue measured frequently during imaging
  - dynamics of tissue motion determined
  - pulse sequence may be synchronised or adjusted to compensate for tissue motion
- Obtain excellent anatomical images through the phases of the cardiac cycle
- Direct visualisation of cardiac wall motion
Cardiac MR imaging – additional techniques

- **Motion encoding by phase techniques**
  - measurements of tissue motion, bulk flow of blood, cardiac valve operation

- **Tissue tagging**
  - impose saturation bands on images in one phase of motion
  - map subsequent movement of the tagged bands in any direction

- **Real time imaging**
  - capture and follow irregular cardiac motion

- **Contrast agents**
  - evaluate cardiac muscle perfusion and help to identify areas of cardiac damage
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4

MR Image acquisition and reconstruction

- 15.4.1 Gradient-echo sequence (also 14.5.4)
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- 15.4.8 Flow measurements
- 15.4.9 Cardiac measurements

- 15.4.10 Diffusion measurements
  - 15.4.11 Brain activation measurements
  - 15.4.12 Dynamic Contrast Enhanced MRI
  - 15.4.12 MR spectroscopy
Diffusion

- Random motion of water molecules in unimpeded space in the body

- Measure motion by
  - applying a gradient to cause a phase change
  - wait a set time
  - apply an opposite gradient to rewind the phase gain

- Molecules that
  - have not moved will have no net phase change - no signal loss
  - have moved will experience a change in phase proportional to the distance moved in the direction of the applied gradients - signal loss
Loss of signal in diffusion measurements

- Loss of signal dictated by:
  - strength of gradients
  - duration of gradients
  - interval for movement to have occurred

- Express in terms of the signal at $t=TE$
  - $S(TE)$

- compared with the signal at $t=0$
  - $S(0)$
15.4.10 Diffusion measurements

\[ \ln\left\{ \frac{S(TE)}{S(0)} \right\} = -\frac{TE}{T_2} - \gamma^2 G^2 D \delta^2 (\Delta - \delta/3) \]

where

- \( \gamma \) is the gyromagnetic ratio, \( G \) is the applied gradient, \( D \) is the diffusion coefficient of water, and \( \delta \) and \( \Delta \) are shown on the next slide

- The effects of the pulse sequence parameters are often incorporated into a term \( b \), known as the \( b \)-value, largely driven by the strength of the gradients and their duration
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4.10 Diffusion measurements

Diagram showing the sequence of events in diffusion measurements:
- Slice Select
- 90°
- TE/2
- Refocusing 180°
- TE/2
- Spin Echo

Parameters:
- $G_x$
- $\delta$
- $\Delta$
Diffusion weighted imaging

- Water molecules in fluid spaces can move freely
  * lose signal as a result of diffusion rapidly

- Water molecules in more highly cellular tissues such as tumours
  * can move less freely and lose signal less rapidly

- Approach useful for identifying disseminated cancer
  * sensitive to high cellularity lesions and involved lymph nodes
  * whole body imaging with good fat suppression required to maximise lesion contrast
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION
15.4.10 Diffusion measurements

Apparent Diffusion Coefficient (ADC)

- ADC describes diffusion in a restricted environment
  - D in the equation is the diffusion coefficient of free water
- Acquire set of images with
  - at least two different $b$-values
  - the same TR and TE
- Compute ADC from measured signals and known $b$-values
- If acquire a whole series of $b$-values can identify different components of signal loss
  - one of which is tissue perfusion (IVIM (IntraVoxel Incoherent Motion) technique)
Diffusion Tensor Analysis

- Directional properties of diffusion can be exploited
- In diffusion tensor analysis
  - diffusion is sensitised in many different directions
  - multiple acquisitions required
  - in structured tissue can demonstrate orientation and connectedness of groups of nerve tissues and generate tractograms of neural interconnections to complement functional and structural neurological examinations

- Diffusion anisotropy
  - simpler measure of directional properties
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4.11 BRAIN ACTIVATION MEASUREMENTS
MR Image acquisition and reconstruction

- 15.4.1 Gradient-echo sequence (also 14.5.4)
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- 15.4.3 Fast spin-echo sequence
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- 15.4.5 Common sequence options
- 15.4.6 Ultra fast imaging sequences
- 15.4.7 MR angiography sequences
- 15.4.8 Flow measurements
- 15.4.9 Cardiac measurements
- 15.4.10 Diffusion measurements
- 15.4.11 Brain activation measurements
- 15.4.12 Dynamic Contrast Enhanced MRI
- 15.4.12 MR spectroscopy
BOLD (Blood Oxygen Level Dependent) measurement

- $T_2^*$ weighted images of the brain
- Deoxyhaemoglobin is paramagnetic
- Oxyhaemoglobin is diamagnetic
- Areas of the brain with increased function
  - utilise more oxygen
  - rise in deoxyhaemoglobin
  - change in magnetic susceptibility
  - reduced signal in $T_2^*$ weighted images
  - also increased perfusion
  - affects signal measured
**BOLD (Blood Oxygen Level Dependent) measurement**

- **Paired images**
  - acquired with and without a neural stimulus, such as a visual or mechanical paradigm

- **Difference between the two highlights areas of neural function**

- **Changes in local blood flow as a result of increased demand can also result in changes on these images**

- **Method can be used to map brain functions to localised regions of the brain**
  - higher field strengths useful
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4.12 DYNAMIC CONTRAST ENHANCED MRI (DCE-MRI)
MR Image acquisition and reconstruction

- 15.4.1 Gradient-echo sequence (also 14.5.4)
- 15.4.2 Spin-echo sequence (also 14.5.5)
- 15.4.3 Fast spin-echo sequence
- 15.4.4 Inversion recovery sequences
- 15.4.5 Common sequence options
- 15.4.6 Ultra fast imaging sequences
- 15.4.7 MR angiography sequences
- 15.4.8 Flow measurements
- 15.4.9 Cardiac measurements
- 15.4.10 Diffusion measurements
- 15.4.11 Brain activation measurements
- 15.4.12 Dynamic Contrast Enhanced MRI
- 15.4.12 MR spectroscopy
Dynamic Contrast Enhanced MRI (DCE-MRI)

- Dynamic behaviour of a contrast agent
  - usually a chelate labelled with gadolinium
- Provides information about tissue function that may inform on pathology, especially in cancer
- Non-dynamic methods look at uptake of contrast and appearance of lesion
- Extension to dynamic methods
  - uptake and washout of the contrast agent
DCE-MRI and tumours

- Important feature of tumour development is growth of a highly permeable neovasculature
- Uptake and washout of the contrast agent identify areas of greatest vascular permeability
- Characteristics of washout curves can aid discrimination between benign and malignant lesions for diagnosis
DCE-MRI and pharmacokinetic models

- Quantitative approach
- Calculate concentration of contrast agent
- Fit dynamic change of concentration to a pharmacokinetic model
- Find values of parameters describing
  - the vascular properties of tissue
  - the related exchange of contrast agent
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4.13 MR SPECTROSCOPY (MRS) SEQUENCES
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

MR Image acquisition and reconstruction

- 15.4.1 Gradient-echo sequence (also 14.5.4)
- 15.4.2 Spin-echo sequence (also 14.5.5)
- 15.4.3 Fast spin-echo sequence
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- 15.4.10 Diffusion measurements
- 15.4.11 Brain activation measurements
- 15.4.12 Dynamic Contrast Enhanced MRI
- 15.4.13 MR spectroscopy
MR spectroscopy (MRS)

- Allows chemically specific measurements to be made
- Range of nuclei $^1$H, $^{19}$F, $^{31}$P, $^{13}$C
- Accurately identify chemical shift (or resonance frequency) of resonant lines
  - molecular origin of line can be identified

- $^{31}$P spectroscopy
  - Energy metabolism in muscle using phosphocreatine and adenosine triphosphate
  - Behaviour of phospholipids in tumours (phosphocholine and phosphoethanolamine)
$^1$H MR spectroscopy (MRS)

- $^1$H spectroscopy
  - used to require broadband RF capability and additional amplifiers
  - now provided on many MRI systems

- Principal signals
  - total creatine
  - total choline
  - $n$-acetyl aspartate in the brain
  - citrate in the prostate
  - lipids
  - lactate
Requirements for MR spectroscopy (MRS)

- Optimised field homogeneity over the region of interest
  - to the order of 0.1 ppm
  - automated routines to adjust currents in a number of shim coils

- Suppression of the water signal in $^1$H spectroscopy
  - to avoid saturation of the analogue to digital converter (ADC)
  - some systems have sufficient ADC range to avoid need for suppression

- Localisation of the origin of the signal
  - using a small surface receive coil
  - using a localisation sequence
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION

15.4.13 MR spectroscopy (MRS) sequences

Single voxel localisation

- Sample signal from a well defined region, often cubic
- Two commonly used techniques in $^1$H spectroscopy
  - STEAM (STimulated-Echo Acquisition Mode)
  - PRESS (Point RESolved SpectroSocopy)

- In $^{31}$P spectroscopy
  - can use STEAM and PRESS, but short $T_2$ leads to considerable signal decay
  - ISIS (Image Selected In vivo Spectroscopy)
STEAM

- Stimulated echoes utilised
- Three orthogonal slice-selective 90° pulses
  - 90° pulses have good slice profile, so get sharp definition of volume of interest
- Only 50% of available signal is sampled (intrinsic feature)
- Can deliver short echo times
- Magnetisation is stored along the z axis between the last two pulses, which reduces $T_2$ signal decay
- Can be preceded by water suppression pulses such as CHESS or WET
PRESS

- One slice-select 90° pulse
- Followed by two orthogonal 180° pulses
- Delivers all of the magnetisation
- Less prone to motion artefacts than STEAM
- Short echo times achievable with high performance gradients
- Can be preceded by water suppression pulses such as CHESS or WET
ISIS for $^{31}$P

- Eight separate permutations of three preparation slice-selective inversions
- Each permutation is followed by a 90° read-out pulse which generates a free induction decay (FID)
- Combine the eight FIDs
- Localised signal generated from the space representing the intersection of the planes
- No signal loss from $T_2$ decay
15.4 MR IMAGE ACQUISITION AND RECONSTRUCTION
15.4.13 MR spectroscopy (MRS) sequences

Pre-treatment (temozolomide) images
- Square shows position of voxel for spectroscopy

STEAM spectra - Serial $^1$H spectroscopy
- A: Before treatment
- B: 3 months
- C: 6 months
- D: 9 months
- Cho/Cre ratio decreased
- NAA peak increased

From Murphy et al, Br J Cancer 90, 2004
Spectroscopic imaging

- Single voxel techniques require careful positioning of VOI prior to acquisition, and must be repeated if further voxels are required.
- Spectroscopic, or chemical shift, imaging techniques obtain an array of voxels in 2D or 3D.
- Signal from many voxels obtained simultaneously.
- But
  - voxels not as sharply defined as for single voxel spectroscopy.
  - point spread function is defined by number of sampling points in each dimension.
Spectroscopic imaging

- For $^1$H (proton) spectroscopy
  - select FOV using a stimulated (STEAM) or spin-echo (PRESS) based technique
  - employ phase encoding in 2D or 3D to sample FOV

- For $^{31}$P spectroscopy
  - preselected VOI less commonly used
  - VOI covers entire object space
  - or can establish smaller FOV by using saturation slabs surrounding the desired VOI
15.4.13 MR spectroscopy (MRS) sequences

- Acquired on 1.5 T scanner using $^1$H decoupled $^{31}$P CSI
- Image shows grid used to acquire the array of spectrum
- Green square shows position of selected spectrum

$^{31}$P spectrum

PE: phosphoethanolamine, PC: phosphocholine, Pi: inorganic phosphate, PCr: phosphocreatine, NTPs: nucleotide tri-phosphates
15.5 ARTEFACTS

15.5 ARTEFACTS
Artefacts

Wide variety of factors can lead to image artefacts in MRI

- 15.5.1 Motion
- 15.5.2 Aliasing or “wrap-around”
- 15.5.3 Metal objects
- 15.5.4 Chemical shift
- 15.5.5 Truncation
- 15.5.6 System-related
Artefacts generated by
- behaviour of sample
- imperfections in equipment or its operation
- poorly optimised measurement sequences

Many artefacts can be eliminated or reduced by
- careful attention to quality assurance
- tuning and optimising sequences

Ameliorate effects of others (intrinsic, patient-related) with
- judicious choice of imaging sequence
- choice of orientation of phase-encode direction
- application of saturation bands
15.5 ARTEFACTS

15.5.1 MOTION
15.5 Artefacts

- 15.5.1 Motion
- 15.5.2 Aliasing or “wrap-around”
- 15.5.3 Metal objects
- 15.5.4 Chemical shift
- 15.5.5 Truncation
- 15.5.6 System-related
Tissue motion

- Motion during MR acquisition results in additional phase gains that lead to incorrect phase-encoding
- Results in characteristic artefacts propagated in the phase encode direction
  - ghosted, displaced, lower intensity images of fat in the body particularly from lower abdomen
  - multiple repeat copies of major vessels aligned in the phase direction with major arteries or veins
15.5 ARTEFACTS

15.5.1 Motion

Reduction or mitigation of tissue motion artefacts

- Ghosted, displaced, lower intensity images of fat in the body particularly from lower abdomen
  - signal averaging
  - respiratory gating or navigator triggered acquisitions
  - rotation of phase encode direction
  - fat suppression
  - saturation band placed over source tissue

- Multiple repeat copies of major vessels aligned in the phase direction with major arteries or veins
  - out of plane suppression of inflowing blood
  - include motion rephasing gradient lobes in sequences
15.5 ARTEFACTS

15.5.2 ALIASING OR “WRAP-AROUND”
15.5 Artefacts

Artefacts

- 15.5.1 Motion
- 15.5.2 Aliasing or "wrap-around"
- 15.5.3 Metal objects
- 15.5.4 Chemical shift
- 15.5.5 Truncation
- 15.5.6 System-related
Aliasing or “wrap-around”

- Occurs when sample extends outside the imaging field of view
- E.g. areas at the side of the body folded into the FOV
- Reconstruction process cannot discriminate between
  - tissues positioned within one edge of FOV
  - tissues on the other side that are an equal distance outside the FOV
- Problem increased in areas where gradients are nonlinear, so several areas have same gradient strength although at different positions
Reduction or mitigation of aliasing or “wrap-around”

- Alter the phase-encode direction
- Use saturation slabs
- Use RF suppression blankets
15.5 ARTEFACTS

15.5.3 METAL OBJECTS
15.5 Artefacts

Artefacts

- 15.5.1 Motion
- 15.5.2 Aliasing or “wrap-around”
- 15.5.3 Metal objects
- 15.5.4 Chemical shift
- 15.5.5 Truncation
- 15.5.6 System-related
Metal objects

- Ferromagnetic material can cause major distortions on the local magnetic field

- Results in
  - displacement of signals in position
  - loss of signal

- Minimise by using spin-echo sequences with short TE

- Small effects from other metallic materials
  - susceptibility artefacts leading to local distortion and loss of signal
  - conduction of currents induced by switched gradients
15.5 ARTEFACTS

15.5.4 CHEMICAL SHIFT
Artefacts

- 15.5.1 Motion
- 15.5.2 Aliasing or “wrap-around”
- 15.5.3 Metal objects
- 15.5.4 Chemical shift
- 15.5.5 Truncation
- 15.5.6 System-related
Chemical shift

- Water and fat resonate as different frequencies
  - difference is 3.4 ppm
- MRI systems adjust their reference frequency to that of water. So, in slice selection and frequency encoding, where localisation depends on frequency
  - fat signal is spatially displaced from the water signal
  - produces a shifted image
  - areas of signal void, or brighter signal due to overlap of water and fat signals in the read-out direction
- Effect greater at higher field where greater separation of frequencies in Hz
Reduction or mitigation of chemical shift artefacts

- Ensure bandwidth per pixel is of order of the frequency separation between fat and water
  - increasing bandwidth per pixel like this can result in increased noise per pixel compared with a narrower frequency range per pixel

- Fat suppression
- Water excitation
15.5 ARTEFACTS

15.5.5 TRUNCATION
15.5 Artefacts

Artefacts

- 15.5.1 Motion
- 15.5.2 Aliasing or “wrap-around”
- 15.5.3 Metal objects
- 15.5.4 Chemical shift
- 15.5.5 Truncation
- 15.5.6 System-related
Truncation

- Signal digitisation involves sampling echo with a predetermined number of samples (typically 128 or 256)
  - each sample takes a specified time
- Evolution of echo, so there may
  - be a finite signal at the beginning and end of sampling
  - be an asymmetrical echo shape
- Similar effect in phase encoding direction where signal has not reduced to zero at the maximum gradient values
- Effect is equivalent to multiplying signal with a square function
15.5 ARTEFACTS

15.5.5 Truncation

Effect of truncation

- Fourier transforms are used to reconstruct images from the acquired signals
  - square function is the Fourier transform pair of a sinc function
  - so multiplication by square function for the signal is equivalent of convolution with a sinc function for the image
- Results in ringing at sharp edges in the image
- Usually seen as parallel bands
  - in the frequency or phase encoding direction
  - or in both directions
15.5 ARTEFACTS

15.5.6 SYSTEM-RELATED
Artefacts

- 15.5.1 Motion
- 15.5.2 Aliasing or “wrap-around”
- 15.5.3 Metal objects
- 15.5.4 Chemical shift
- 15.5.5 Truncation
- 15.5.6 System-related
System-related artefacts

- Intrinsic to MR hardware
- May not be adjustable without major hardware changes or tuning
- Arise from
  - Distortions
  - RF coil problems
  - RF interference
Distortions
- Spatial distortions resulting from design of gradient coils
- Difficult to maintain linearity of the gradients towards edges of FOV
  - i.e. where physically close to gradient windings
  - particularly relevant for short magnet bore, where gradient coils are close to edge of FOV
- Reduce distortion by increasing bandwidth per pixel
  - but this increase image noise
RF coil problems and RF interference

- Transmit RF coil dictates uniformity of $B_1$ irradiation field and thus consistency of pulse angle over volume of interest
- Consistency largely governed by design of coil
- But dielectric interactions between RF field and patient lead to sample dependent variations in $B_1$
  - i.e. RF interference
  - effects increase with RF frequency ($B_0$ field strength)
  - result is flip angle variations across sample
  - i.e. variations in excitation and inversion efficiency
Reduction or mitigation of RF interference

- Use a circularly polarised transmit coil
- Use adiabatic pulses
  - above a certain threshold voltage these are power independent
  - but, range of applications of adiabatic pulses very limited
15.6 SAFETY AND BIOEFFECTS
Safety and bioeffects

Safety issues in MR can be divided into **acute** hazards (with immediate risk of injury) and **biological** effects (with longer term effects).

Safety concerns arise from four sources:

- 15.6.1 Static field considerations
  - projectiles, effects on implants, physiological effects
- 15.6.2 RF field considerations
  - tissue heating, specific absorption rate, burn injuries
- 15.6.3 Gradient field considerations
  - peripheral nerve stimulation, sound pressure levels
- 15.6.4 Common MR contrast agents
Acute hazards
- Immediate risk of injury from interactions between patient, staff or extrinsic objects with the fields produced during an MR examination
- Aspects of most concern and importance in the design and in day to day operation of MR facilities

Biological effects
- Interactions between MR fields and biological processes
- Could cause longer term effects
Guidance and regulation

- Exposure of patients, staff and general public
- Covered by standards, guidance and regulations
  - continually updated
  - vary from country to country
- In absence of local guidance prudent to follow guidance/regulation from elsewhere
Guidance and regulation: examples

- MHRA (UK) publishes guide summarising recommendations of different bodies and provides practical advice

- American College of Radiology guidance on procedures to ensure patient safety
Patient exposures

- Three levels of exposure adopted by IEC, ICNIRP, HPA
  - Normal operating mode
    - routine scanning of patients
  - Controlled mode
    - for specific examinations above normal operating mode level
    - carried out under medical supervision
    - based on clinical decision balancing potential adverse effects against foreseen benefits
  - Experimental operating mode
    - carried out at levels above the controlled operating mode
    - for which local ethical approval has been obtained
15.6 SAFETY AND BIOEFFECTS

15.6.1 STATIC FIELD CONSIDERATIONS
15.6 SAFETY AND BIOEFFECTS

15.6.1 Static field considerations
- projectiles, effects on implants, physiological effects

15.6.2 RF field considerations
- tissue heating, specific absorption rate, burn injuries

15.6.3 Gradient field considerations
- peripheral nerve stimulation, sound pressure levels

15.6.4 Common MR contrast agents
Static field considerations – projectiles and implants

Static field affects

- ferromagnetic materials
- magnetic storage devices
- magnetically operated switches
- sensitive sound receivers
- sensitive electronic equipment (especially those using accelerated electrons such as linear accelerators and photomultiplier tubes)

Two major areas of concern

- Potential for equipment and objects containing ferromagnetic materials to be attracted into magnet (projectiles)
- Effect on implants that are sensitive to magnetic fields
15.6 SAFETY AND BIOEFFECTS

15.6.1 Static field considerations

Static field considerations – projectiles

- Equipment and objects to be used close to the magnet must be tested

- For magnet room or a defined inner controlled zone
  - rigorous exclusion of ferromagnetic materials
  - access only for
    - trained and approved staff
    - appropriately screened subjects
Static field considerations – implants

- Certain implants may
  - be ferromagnetic or become ferromagnetic in the field
    - attraction leading to projectile effect
    - torque on implanted object leads to force seeking to align object with the field
  - be damaged or malfunction in the field

- Cardiac pacemakers (should not be allowed in field > 0.5 mT), hearing aids and other magnetically controlled or programmable implants

- Steel clips (some grades of stainless steel can become magnetic when worked or adjusted)
Static field considerations – implants

- Should obtain details of exact make and model of implant
- Check before scanning with
  - manufacturer
  - Dr F Shellock’s website [www.mrisafety.com](http://www.mrisafety.com)
Static field considerations – physiological effects

- At higher fields (> 2 T) static field can cause a degree of dizziness or disorientation if the head moves quickly in the field.
- Believed to be due to currents in the vestibular system interfering with normal sensory perceptions.
- At high field:
  - move slowly in the magnetic field
  - avoid abrupt motion of the head
Static field considerations – biological effects

- ICNIRP guidance limits patient exposure to 4 T for normal and to 8 T for controlled operating modes
- At fields used in clinical practice few verified biological effects
- A moving conductor, such as blood, in a magnetic field can result in an induced current
- At 8 T the level of currents produced are below levels of concern
15.6 SAFETY AND BIOEFFECTS

15.6.1 Static field considerations

Static field considerations – biological effects

- No serious or permanent health effects found from human exposures up to 8 T
- But there has been only limited scientific investigation

15.6 SAFETY AND BIOEFFECTS

15.6.2 RF FIELD CONSIDERATIONS
15.6 SAFETY AND BIOEFFECTS

15.6.1 Static field considerations
  - projectiles, effects on implants, physiological effects

15.6.2 RF field considerations
  - tissue heating, specific absorption rate, burn injuries

15.6.3 Gradient field considerations
  - peripheral nerve stimulation, sound pressure levels

15.6.4 Common MR contrast agents
15.6 SAFETY AND BIOEFFECTS

15.6.2 RF field considerations

RF field considerations

- Tissue heating
- Specific absorption rate (SAR)
  - amount of energy deposited by an RF field in a certain mass of tissue
  - units of watts per kilogram (W kg\(^{-1}\))
- Burn injuries
- Non-heat induced long term effects
RF field considerations – tissue heating

- Electromagnetic field used to manipulate sample magnetisation is usually applied by the body coil
  - body coil has large volume to enclose body
  - driven by high voltages generated by powerful amplifier, typical output 15 kW

- RF field can give rise to heating in the body
- Equipment designed to limit temperature rise to 0.5 – 1 °C
- Achieved by limiting the specific absorption rate (SAR)
- Tables on next two slides
### Basic restrictions on the maximum temperature for the body

<table>
<thead>
<tr>
<th>Operating mode</th>
<th>Spatially localised temperature limits</th>
<th>Body core temperature</th>
<th>Local tissue temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Head</td>
<td>Trunk</td>
<td>Extremities</td>
</tr>
<tr>
<td>Normal</td>
<td>38°C</td>
<td>39°C</td>
<td>40°C</td>
</tr>
<tr>
<td>Controlled</td>
<td>38°C</td>
<td>39°C</td>
<td>40°C</td>
</tr>
<tr>
<td>Research</td>
<td>&gt;38°C</td>
<td>&gt;39°C</td>
<td>&gt;40°C</td>
</tr>
<tr>
<td>Research</td>
<td>39°C</td>
<td>40°C</td>
<td>41°C</td>
</tr>
</tbody>
</table>

From these temperature rise limits, specific absorption rates can be derived. These are usually implemented in the software and hardware of clinical scanners.

15.6 SAFETY AND BIOEFFECTS

15.6.2 RF field considerations

Patient and volunteer SAR limits (W kg\(^{-1}\)) for RF field exposure

<table>
<thead>
<tr>
<th>Mode</th>
<th>Volume transmit coil</th>
<th>Local transmit coil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Whole body</td>
<td>Head</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Not head(^a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>1,2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1,2</td>
<td>1</td>
</tr>
<tr>
<td>Normal</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2-10</td>
<td>10</td>
</tr>
<tr>
<td>Controlled</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4-10</td>
<td>10</td>
</tr>
<tr>
<td>Restricted</td>
<td>&gt;4</td>
<td>&gt;3</td>
</tr>
<tr>
<td></td>
<td>&gt;3.2</td>
<td>&gt;10</td>
</tr>
</tbody>
</table>

\(^a\) Head not including ears

\(^b\) Reference 1: ICNIRP 2004, 2: IEC 2010
Tissue heating – modes of operation

- **Normal operating mode**
  - exposure to extended volumes of the body should be such as to avoid a rise of more than 0.5 °C in body temperature of patients and volunteers, including those compromised with respect to their thermoregulatory ability

- **Controlled operating mode**

- **Experimental operating mode**
Tissue heating – modes of operation

- **Normal operating mode**

- **Controlled operating mode**
  - a relaxation of the basic restrictions on the rise in body temperature to 1 °C can be envisaged if the patient or volunteer is monitored medically and with appropriate physiological monitoring
  - consider restricting the use of controlled mode for infants, pregnant women, febrile patients, others with reduced thermoregulatory ability or with compromised peripheral circulation (HPA 2008)

- **Experimental operating mode**
Tissue heating – modes of operation

- Normal operating mode
- Controlled operating mode
- **Experimental** operating mode
  - requires ethical committee approval
  - may result in whole body rise in temperature above 1 °C
  - medical, thermal and physiological monitoring required
  - absolute limits for core and regional temperatures
  - slightly different limits in different publications (see table)
RF field considerations – burn injuries

- Receiver coils should be decoupled from the transmit field to avoid deposition of RF power
- But
  - fault conditions in coils
  - incorrect set up
  - incorrect positioning of connection leads
- Can give rise to
  - local coupling
  - deposition of excessive local RF power
- And result in heating and RF burns
15.6 SAFETY AND BIOEFFECTS

15.6.2 RF field considerations

Burn injuries

- RF burns are the most common form of accident in MR
- Operators must keep in communication with patients and volunteers ready to stop examination if there is any concern about discomfort
- Follow manufacturer’s guidance on use of conducting materials in the magnet, such as ECG leads
RF field considerations – non-heat induced long term effects

- Effects of RF power in producing heat are well established
- However, evidence less clear regarding non-heat induced long term effects
- No clear evidence of such effects at exposures of up to 4 Wkg$^{-1}$

15.6 SAFETY AND BIOEFFECTS

15.6.3 GRADIENT FIELD CONSIDERATIONS
15.6.1 Static field considerations
   • projectiles, effects on implants, physiological effects

15.6.2 RF field considerations
   • tissue heating, specific absorption rate, burn injuries

15.6.3 Gradient field considerations
   • peripheral nerve stimulation, sound pressure levels

15.6.4 Common MR contrast agents
15.6 SAFETY AND BIOEFFECTS
15.6.3 Gradient field considerations

Gradient field considerations

- Switched gradient fields used for localisation give rise to two major effects
- Both can produce acute effects
- Induction of currents in conducting materials in the body
  - involuntary nerve stimulation
  - muscles twitch, or pain at higher levels of stimulation
- Vibration
  - depending on pulse sequence can be loud enough to cause transient loss of hearing, always provide ear protection
- Also biological effects
Gradient field considerations – nerve stimulation

- Likelihood depends on
  - local strength of the gradient
  - rate of change of the gradient
  - individual's susceptibility to stimulation

- Strength of gradient depends on position in bore of magnet and design of gradients
  - so, hard to predict probability of stimulation even for a given individual and a particular sequence
Nerve stimulation – limits

- Gradient levels usually set to avoid stimulation
  - based on a threshold for peripheral nerve stimulation (PNS) defined as the onset of sensation
  - next slide

- Mild stimulation can be acceptable

- In principle, much higher gradients can give rise to sufficiently high cellular potentials to induce cardiac fibrillation

- Threshold for this is a factor of 10 above that for nerve stimulation
Nerve stimulation – modes of operation

- Guidance provided by both IEC and ICNIRP
- Normal operating mode
  - the gradient system shall operate at a level that does not exceed 80% of the directly determined PNS, where the threshold PNS is defined as the onset of sensation
- Controlled operating mode
  - the gradient system shall operate at a level that does not exceed 100% of the directly determined mean threshold PNS
- Additionally, IEC has a limit set to prevent cardiac stimulation
Gradient field considerations – biological effects

- HPA has summarised literature on effects of low frequency time varying fields typical of those used in MRI.
- No consistent evidence of harm following short term exposures was found.
- Some subtle biological effects were reported.
- Subjects with epilepsy, or taking drugs that reduce seizure activity, may exhibit increased sensitivity to stimulation by electric fields induced in the cortex and should be imaged with caution.
15.6 SAFETY AND BIOEFFECTS

15.6.4 COMMON MR CONTRAST AGENTS
15.6 SAFETY AND BIOEFFECTS

15.6.1 Static field considerations
- projectiles, effects on implants, physiological effects

15.6.2 RF field considerations
- tissue heating, specific absorption rate, burn injuries

15.6.3 Gradient field considerations
- peripheral nerve stimulation, sound pressure levels

15.6.4 Common MR contrast agents
Paramagnetic contrast agents

- Paramagnetic agents have unpaired electrons leading to a strong local magnetic field and a strong net electronic magnetic moment.
- In the raw state, paramagnetic materials are highly reactive and therefore potentially toxic.
- To prevent direct interactions between ions and biological molecules, the paramagnetic nucleus has to be bound within a chelate.
Effects of paramagnetic contrast agents

- Agents relax nearby water molecules, decreasing the relaxation time
- The $T_1$ relaxation process is the predominant mode of relaxation
- The degree of relaxation is also affected by ease of access to water molecules, which is governed by structure of the molecules
Gadolinium

- Gadolinium is the most common contrast agent ion
- Can be bound to a number of different chelates
- Two groups of chelates
  - charged and uncharged linear chelates
  - charged and uncharged macro cyclic chelates
- A common chelate is DTPA (diethylenetriamine pentacetic acid)
- So contrast agent is Gd-DTPA
Nephrogenic systemic fibrosis (NSF)

- Rare condition associated with exposure to certain gadolinium-based contrast agents
- Only in patients with severely impaired renal function, which leads to prolonged exposure to the agent
- Guidelines (ACR 2007) on use of Gd agents to avoid NSF

15. BIBLIOGRAPHY
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