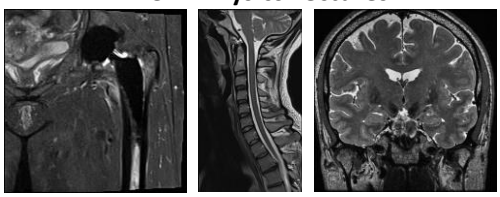
Magnetic Resonance Imaging

F.R.C.R. Physics Lectures



Lawrence Kenning PhD

Magnetic Resonance Imaging

Magnetic Resonance Imaging (MRI) [1]

- Construction, function and operation of a superconducting MRI scanner
- Permanent and resistive magnets
- Radiofrequency receiver coils
- Spatial localisation of the signal
- K-space, image acquisition and image reconstruction

Construction, function and operation of a superconducting MRI scanner

- Key performance criteria for magnet design include:
  - field strength
  - temporal stability
  - field homogeneity
- There are three types of MRI magnets:
  - Permanent
  - Resistive (electromagnet)
  - Superconductive



Permanent

- Two opposing flat-faced magnetised poles (ferromagnetic materials) Iron/ Alloys of aluminium, nickel & cobalt
- Low power consumption
- Low operating cost
- No cryogen
- Small fringe field
- Low field strength (0.064T ~ 0.3T)

Swoop 0.064 Tesla



O-scan 0.31 Tesla field strength



https://www.esaote.com/en-GB/dedicated-mri/mri-systems/p/o-scan/

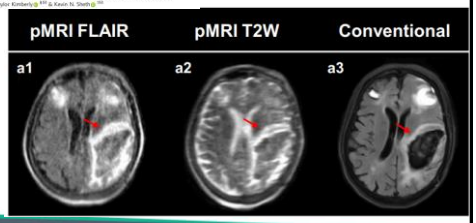
Scanner Construction

Permanent

ARTICLE

OPEN

Portable, bedside, low-field magnetic resonance imaging for evaluation of intracerebral hemorrhage



Remarkable people. Extraordinary place.

Scanner Construction

Resistive

- Large electromagnets
- Magnetic field generated by running a current through loops of wire
- Field strength ~ 0.3T
- Produce a lot of heat, so water cooling
- Light weight
- Can be shut off
- Low cost
- High power consumption
- Large fringe field

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Scanner Construction

Superconductive

- **High magnetic field strengths (>1 T)** requires electromagnet core wires to be superconductive
- Superconductivity is a characteristic of certain metals (e.g., niobium–titanium alloys) that when maintained at extremely low temperatures (liquid helium; **<4°K**) exhibit no resistance to electric current
- Superconductivity allows the closed-circuit electromagnet to be energised and ramped up to the desired current and magnetic field strength by an external electric source
- Superconductive magnets with field strengths of 1.5 to 3.0 T are common for clinical systems, and 4.0 to 7.0 T clinical large bore magnets are currently used for research at present

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Scanner Construction

Superconductive

- High field strength (Required for low sensitivity of MR)
- High field homogeneity
- Low power consumption
- High SNR
- High capital costs (~£1M)
- High cryogen costs (~£6/L & @1500L)
- Technical complexity

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Scanner Construction

Homogeneity

- Important for techniques such as fat-nulling, spectroscopy and steady state imaging
- To obtain most homogeneous magnetic field, magnet must be finely tuned ("shimmed") by adding small corrective fields:
  - Passively (using movable pieces of ferromagnetic material – shim blocks)
- Or
  - Actively, using small electromagnetic coils distributed within the magnet
  - Active shim correction can be made after patient is in scanner as they will cause inhomogeneities
- Active shielding makes the fall-off very rapid (gradient of B)
- Remember the patient will change the B_0!

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Scanner Construction

Quench

- If any part of the windings ceases to be superconducting, electrical energy will be dissipated as heat in the surrounding regions of the magnet
- Subsequently superconductivity is lost
- Rapid lost of the magnetic field results in rapid boiling of the liquid helium
- Gas should leave room by quench pipe
- Failure to vent the gas could result in asphyxia and frostbite
- Oxygen monitor needed in room to give warning

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Scanner Construction

Quench

- Controlled/deliberate quenches are necessary if patient is at risk
- 'Ramp Down' the magnet
- Controlled quench prevents damage to the magnet
- Quenching has the potential to be very costly!



Scanner Construction

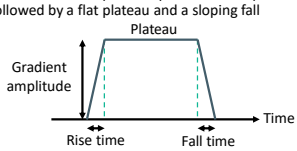
Quench

- A quench will in general be accompanied by a loud bang and the emission of large quantities of cold gas
- The gas outlet for the normal boil-off and the emergency bursting discs should be vented directly to a suitable point on the outside of the building
- A minimum three metre exclusion zone is recommended for the quench vent exhaust
- If there is inadequate venting, cold gas may spread through the patient area. It will form a white fog that eventually clings to the ceiling.
- The patient should be removed at once, since there may be oxygen depletion and the presence of very cold gases may cause a cold burn, frostbite or hypothermia

Scanner Construction

Gradients

- Gradient coils are contained within the scanner bore to produce a linear variation of magnetic field strength across the useful imaging volume
- Spatial localisation of the MR signal requires the use of three orthogonal linear magnetic field gradients
- Gradient pulses in conventional pulse sequences are trapezoidal in shape with a sloping rise, followed by a flat plateau and a sloping fall



Scanner Construction

Gradients

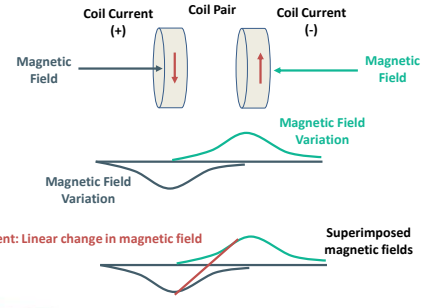
- Strength of a gradient, or how rapidly the magnetic field changes over distance, is expressed in millitesla per metre (mT m^{-1})
  - typical values ~45 mT m^{-1}
- Gradient rise time, or how rapidly the field changes with time from zero to the peak amplitude, is usually expressed in microseconds (µs), with typical values from 1000 µs down to 200 µs
- The gradient slew rate is calculated by dividing the peak gradient amplitude by the rise-time. Typical slew rates are in the range of 150-200 T m^{-1} s^{-1}

Table 3-23: Gradient information

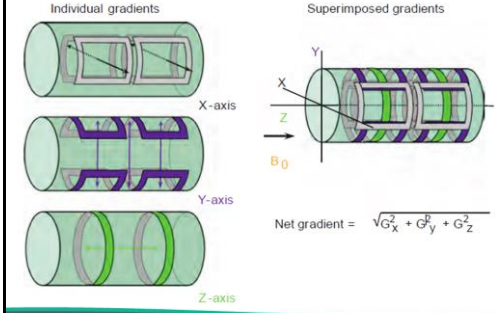
Component	Specification
Gradient type	Non resonant, actively shielded, rapidly switching
Peak Amplitude	80 mT/m
Slew Rate	200 T/m/s
Rise time to Maximum Amplitude	400 microseconds

Scanner Construction

Gradients



Scanner Construction



Scanner Construction

RF Coils

- Radiofrequency (RF) coils exist within the main bore of the magnet to **transmit** energy to the patient as well as to **receive** returning signals
- The RF coils are used to excite the protons produce a uniform field B_1 at right angles to B_0
- Transmit coils are usually large to optimise their uniformity and encompass a significant volume of tissue
- The main transmitting coil is usually the body coil, which surrounds the entire patient.
  - Usually built into the scanner bore and is not visible externally
- Since the coil is large, it has a very uniform transmission field, but is not as sensitive as a receiver coil

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Scanner Construction

RF Coils

- The function of a receiver coil is to maximise signal detection, whilst minimising the noise
- Usually the major source of noise is from the patient's tissue (Brownian motion of electrolytes)
- To minimise the noise, and maximise the SNR, it is necessary to minimise the coil dimensions, i.e. the coil's volume should be filled as much as possible by the sample
- There are two fundamental types of receiver coil: volume & surface.
  - **Volume coils** completely encompass the anatomy of interest and are often combined transmit/ receive
  - **Surface coils** are generally receive only, due to their inhomogeneous reception field

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Scanner Construction

Volume coils

- Radiofrequency coil that surrounds either the whole body, or one specific region, such as the head or a knee
- Volume coils have a better RF homogeneity than surface coils, which extends over a large area
- The most commonly used design is a (birdcage) bird cage coil. This consists of a number of wires running along the z-direction
- It is possible to use the same coil to transmit and receive, or to use two separate coils

T/R Coils Available:

- **GE Artist/Premier:** Integral Body; Knee; Hand-Wrist; Quadrature Head (Birdcage)
- **Siemens Sola/Aera:** Integral Body; Knee; Hand-Wrist

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Scanner Construction

Surface coils

- Placed close to the area under examination
- Consist of a single or double loop of wire
- High signal to noise ratio (SNR)
- However; signal uniformity falls off quickly away from the coil
- Limited Field of View (FOV)



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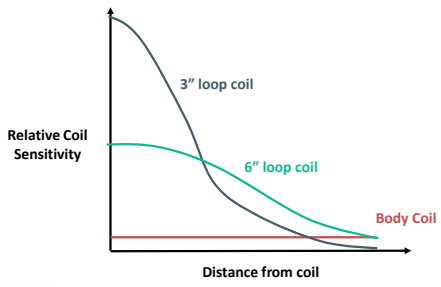
Scanner Construction

RF Coils: Signal Characteristics



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Scanner Construction

Phased Array Coils

- The problem of the limited FOV of surface coils can be solved by using a number of coils simultaneously, known as an array
- Array coils are now available to image most areas, e.g. a spine array coil or a torso array coil.
- These coils need to be constructed very carefully so that the individual coils (also known as elements) do not interact with each other, a phenomenon known as coupling which reduces SNR in the images
- One way of effectively 'decoupling' one element from its neighbours is to geometrically overlap the coils in a particular way
- Each element is connected to an entirely separate preamplifier and receiver which has the advantage that the noise in each receiver is completely different, i.e. uncorrelated, resulting in a higher SNR in the final image

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Scanner Construction

Phased Array Coils

- Images can be produced from the individual elements, but generally they are combined together to produce an image with the large FOV advantage of the array but with the SNR advantage of the small individual elements
- Most common method for combining the signals is the 'sum-of-squares' technique, where the signal in a voxel of the final image is the sum of the squared signals intensities for that voxel measured by each element of the coil
- Phased array coil imaging generates more data than single receive coils, and reconstruction times may be longer due to the additional processing required
- A key advantage of multi-element coils is the possibility of using parallel imaging techniques for acceleration and reduced scan times

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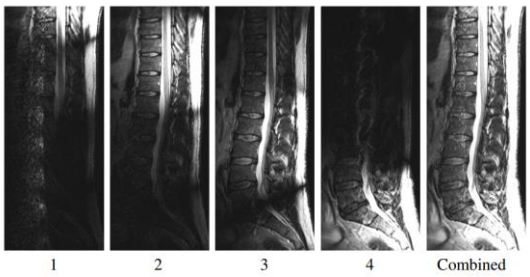
Scanner Construction

Phased Array Coils



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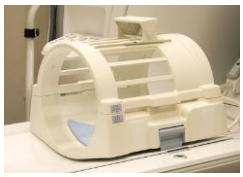
Scanner Construction

RF Coils





T/R Head Coil	Phased Array Head Coil
Local RF Transmission	Body Coil RF Transmission
Volume Coil Design	Phased Array Design
1 Receive Channel	48 Receive Channels
No Parallel Imaging	Parallel Imaging
Uniform signal across imaging volume	Increased signal close to the coils

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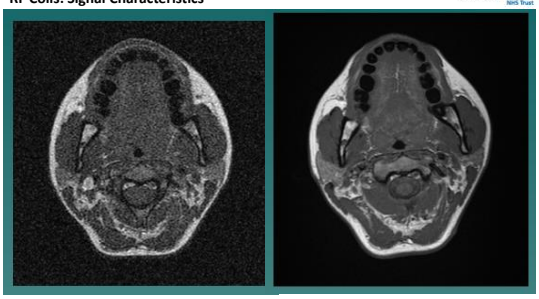
Scanner Construction

RF Coils: Signal Characteristics



Body Coil Receive rSNR=1 **HNS Coil Receive rSNR=25**

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Scanner Construction

- 8-32 element coils are common now
- 64, 128 and even higher channel systems are now available
- Connecting two or more array coils simultaneously provides the possibility of whole body screening where the patient is imaged from head to toe using several stations
- With this technique, a particular FOV is scanned (e.g. the head and neck), then the patient is automatically moved into the magnet by a fixed distance and the next station is scanned (e.g. the upper thorax). This is repeated multiples times to provide complete coverage without having to change coils

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Scanner Construction

Dedicated Scanner Coils

- Head/Neck
- Body
- Breast
- Wrist
- Shoulder
- Knee
- Flex (S/L)
- Per



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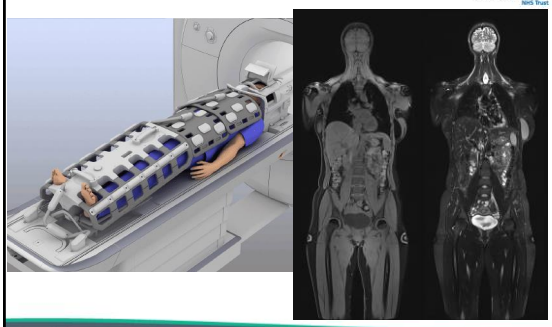
Scanner Construction



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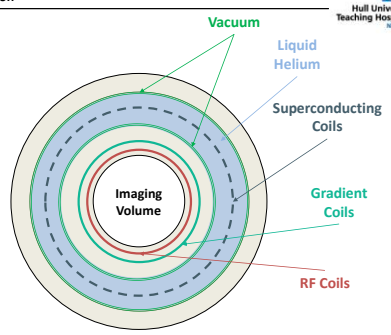
Scanner Construction

System Design



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Scanner Construction

RF (Faraday) cage

- MRI inherently low (RF) signal technique
- RF (Faraday) cage
  - Distributes EM radiation around cage's exterior and cancels it within
  - All 6 sides enclosed in copper
  - Electromagnetic shielding
  - Integrity must be maintained
  - Penetration Panel (contains filters & waveguides for pipes, ducts, cables)
  - Mesh window
  - Closed scan room door

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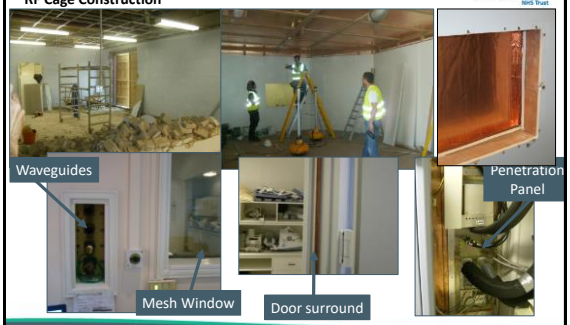
Scanner Construction

RF Cage Construction



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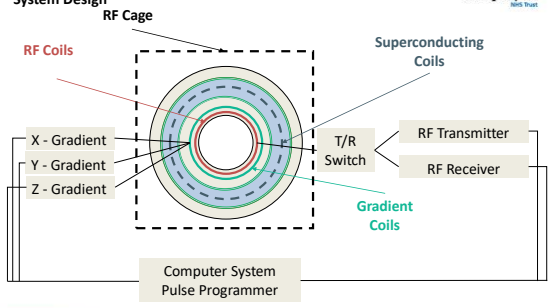
Scanner Construction

System Design



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Scanner Construction

System Design



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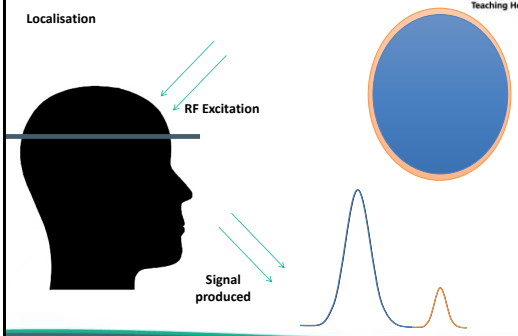
Spatial localisation of the signal

Localisation



Introduction

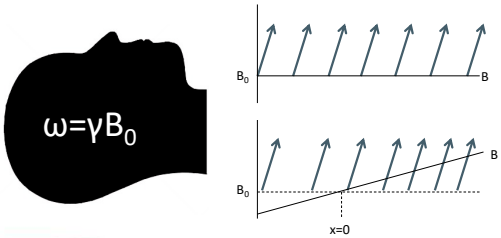
- MR signal localisation utilises **magnetic field gradients**
- 2D slices are produced by the combination of an excitation RF pulse and **simultaneous slice-select gradient**
- the in-plane MR signal is encoded in terms of the spatial frequencies of the object using **phase-encoding** and **frequency-encoding gradients**
- every spatial frequency that exists within the image is sampled prior to Fourier transform (known as 'k-space')
- inadequate or erroneous k-space sampling leads to image artefacts

Localisation

1. Slice selection gradient applied first (Z direction)

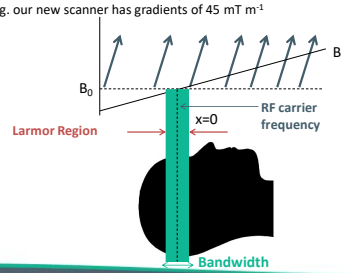
Slice Localisation

- When the term 'gradient' is referred to in MRI, it means the addition of spatially linear changes to the B_0 magnetic field



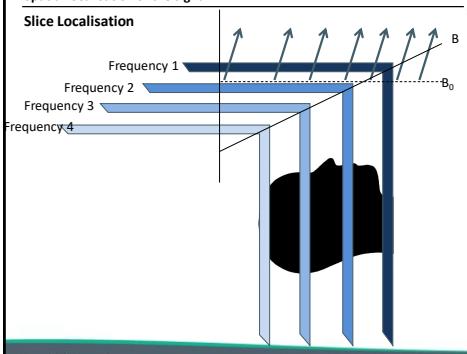
Slice Localisation

- MR scanners have 3 sets of coils which allow slice selection in any plane
- The magnitude of the change to the B_0 magnetic field is measured in mT m^{-1}
  - e.g. our new scanner has gradients of 45 mT m^{-1}



Spatial localisation of the signal

Slice Localisation



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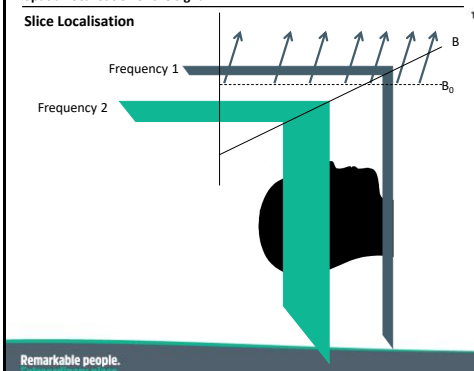
Spatial localisation of the signal

Slice Localisation



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Spatial localisation of the signal

Localisation

1. Slice selection gradient applied first (Z direction)
2. Phase encoding gradient subsequently applied (Y-direction)

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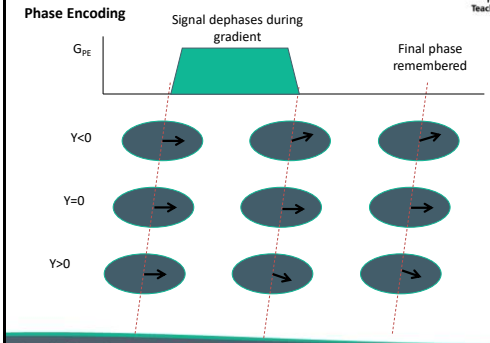
Spatial localisation of the signal

Phase Encoding



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Spatial localisation of the signal

Localisation

1. Slice selection gradient applied first (Z direction)
2. Phase encoding gradient subsequently applied (Y-direction)
3. Frequency encoding gradient applied last (X-direction)

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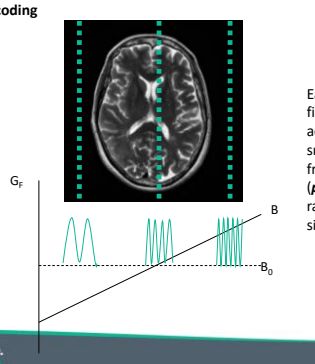
Spatial localisation of the signal

Frequency Encoding



Each pixel has a finite width, so actually contains a small range of frequencies (***pixel bandwidth***) rather than just a single frequency

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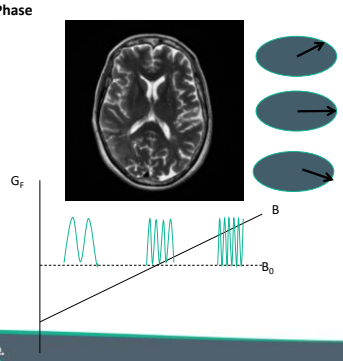
Spatial localisation of the signal

Frequency & Phase Encoding



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Spatial localisation of the signal

Localisation

1. Slice selection gradient applied first (Z direction)
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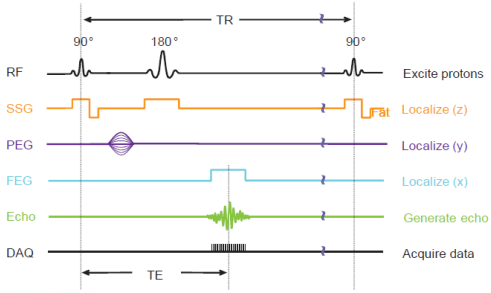
K-space, image acquisition and image reconstruction

Spin Echo Sequence



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K-space, image acquisition and image reconstruction

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K-space, image acquisition and image reconstruction

What is k-space?

- k-space is an array of digitised MR echoes in the "frequency domain"
- array of numbers representing all the spatial frequencies of the MR image (same size as the final image)
- The readout MR signal is a mixture of RF waves with different amplitudes, frequencies and phases containing spatial information
- To go from k-space to an image requires a 2D inverse Fourier Transform (2DFT)
- The individual points in k space do not correspond to individual pixels in the image
- Each k-space point contains spatial frequency & phase information about **every** pixel in the final image
- Conversely, each pixel in the image maps to **every** point in k-space

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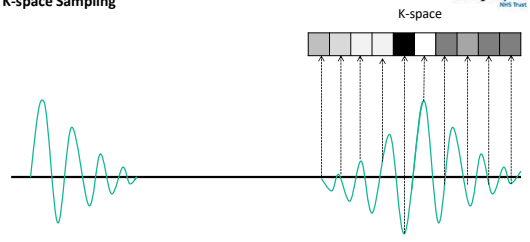
K-space, image acquisition and image reconstruction

K-space Sampling



- In MRI, the echo rather than the FID is sampled for k-space

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K-space, image acquisition and image reconstruction

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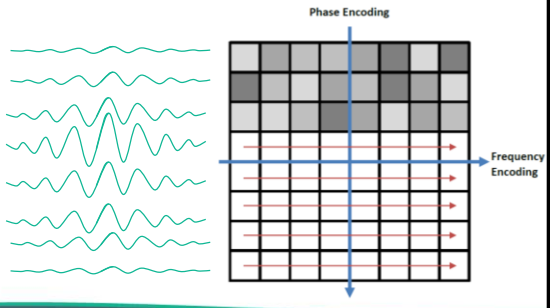
K-space Sampling



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K-space, image acquisition and image reconstruction

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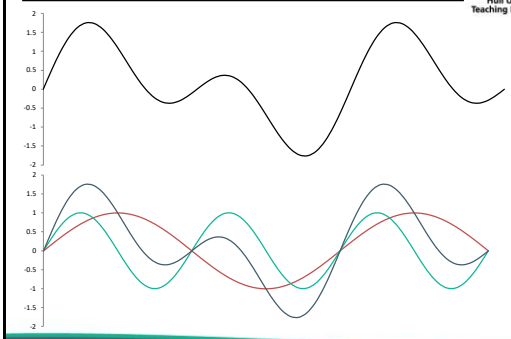

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K-space, image acquisition and image reconstruction

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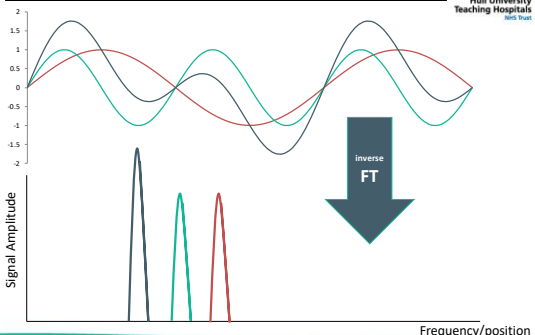

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K-space, image acquisition and image reconstruction

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- Spatial frequency is related to the periodicity with which the image intensity values change.
- Image features that change in intensity over **short** image distances correspond to **high** spatial frequencies.
- Image features that change in intensity over **long** image distances correspond to **low** spatial frequencies.
- To decompose a 2D image we need to perform a 2D Fourier Transform

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K-space, image acquisition and image reconstruction

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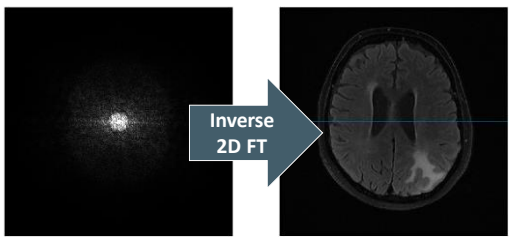
2D Fourier Transforms



Frequency Domain (k-space)

Spatial Domain (image)

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K-space, image acquisition and image reconstruction

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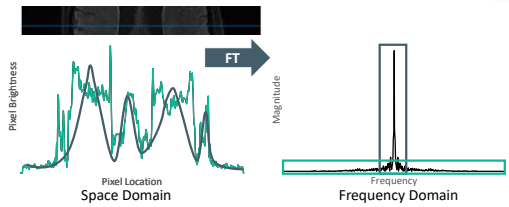

- Low spatial frequencies (change in intensity over long distances) are prevailing
- Low spatial frequencies have greatest change in intensity
- High spatial frequencies (change in intensity over short distances) have lower amplitudes
- General shape of the image is described by low spatial frequencies

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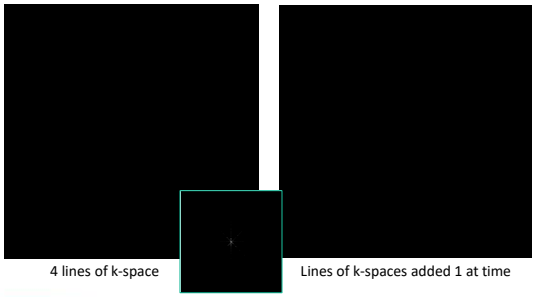
https://www.imaios.com/en/e-Courses/e-MRI/The-Physics-behind-it-all/2D-Fourier-transform

K-space, image acquisition and image reconstruction

2D Fourier Transforms



4 lines of k-space

Lines of k-spaces added 1 at time

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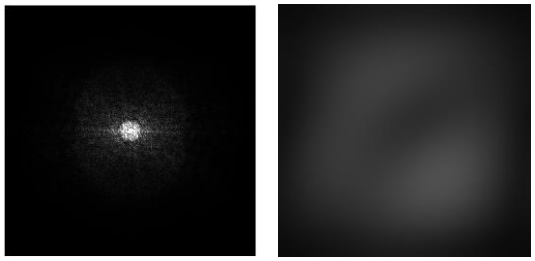
K-space, image acquisition and image reconstruction

2D Fourier Transforms



Concentric circles of k-space from the centre

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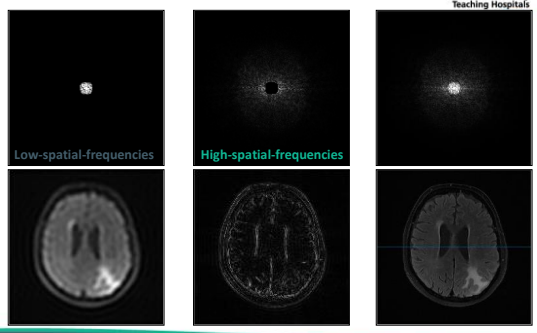
K-space, image acquisition and image reconstruction



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K-space, image acquisition and image reconstruction

k-space continued…

- The location of the data in k-space depends on the strength and duration of the gradients.
  - If no gradient applied, the location is at the centre of k-space
- The higher the gradient strength or duration, the further from the centre of k-space the data will be located
- Simplest way to fill k-space is line-by-line
- One line of k-space is fully acquired at each excitation (containing low and high horizontal spatial frequency information)

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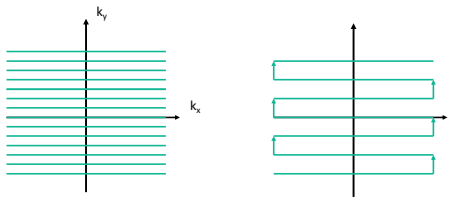
K-space, image acquisition and image reconstruction

k-space trajectories



GRE or SE: one line of k-space per TR (usually 256, 512 lines)
Image time = $N_{phase} \times TR$

EPI: all lines of k-space per TR (typically 64 or 128)
Image time = TR

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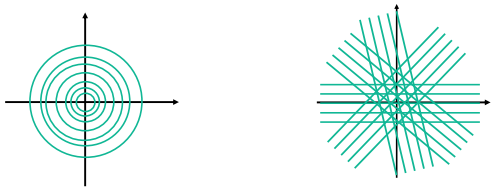
K-space, image acquisition and image reconstruction

k-space trajectories



Spiral:
more efficient single shot
Centre of k-space is filled first

Radial:
Centre oversampled
Motion compensation

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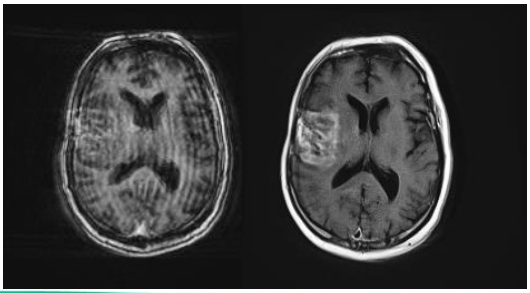
K-space, image acquisition and image reconstruction

PROPELLER/BLADE



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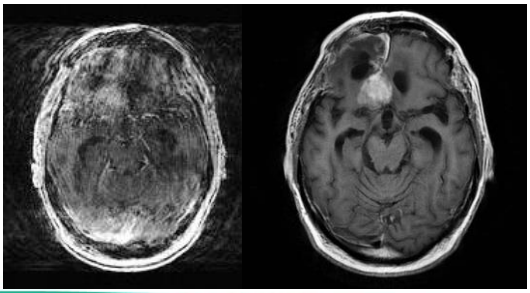
K-space, image acquisition and image reconstruction

PROPELLER/BLADE



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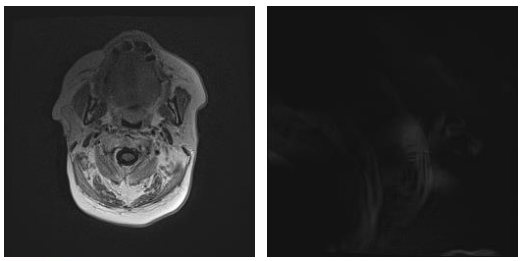
K-space, image acquisition and image reconstruction

PROPELLER/BLADE



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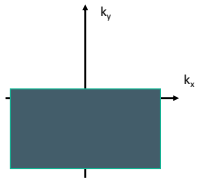
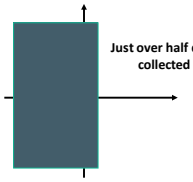
K-space, image acquisition and image reconstruction

Partial k-space

These techniques acquire part of k-space and 'fill-in' the rest using ***conjugate symmetry***





Partial Fourier:
Also called fractional NEX
Collects half of phase-encode steps and speeds up imaging

Partial Echo:
Collects half of echo reducing the shortest possible TE

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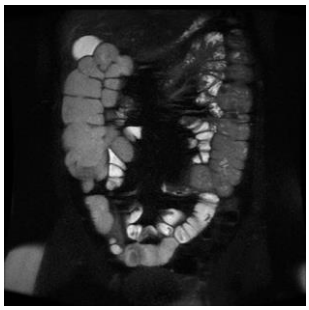
K-space, image acquisition and image reconstruction

Partial k-space



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K-space, image acquisition and image reconstruction

Spin Echo Image acquisition

- **Narrow band RF excitation** pulse simultaneously applied with **the slice select gradient** causing a specific slab of tissue to be excited
- **Transverse magnetisation (M_{xy}) is produced** with amplitude dependence on the saturation of the protons and the angle of excitation
- **Phase encoding gradient is applied briefly**, introducing a phase difference among the protons along the phase encode direction

Spin Echo

- A **refocusing 180-degree RF pulse** is delivered at TE/2 to invert and re-establish the phase coherence of the transverse magnetisation at time TE
- During the echo formation, the **frequency encoding gradient is applied**, generating spatially dependent changes in the precessional frequencies of the protons

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K-space, image acquisition and image reconstruction

- **Data sampling and acquisition** of the signal occurs simultaneous to the **frequency encoding gradient**
- Data is deposited in the k-space matrix at a row location determined by the strength of the phase encoding gradient
- For each TR, an incremental change of the phase encoding gradient strength sequentially fills each row
- Following the **complete filling of k-space, an inverse Fourier transform** decodes the frequency domain variations in phase for each of the columns of k-space to produce the spatial domain representation - an image!

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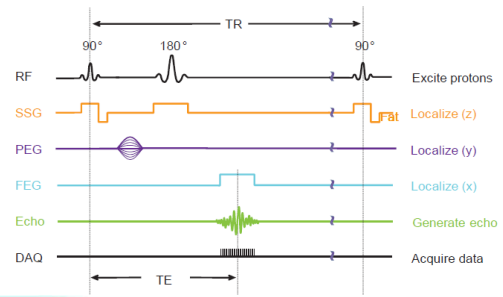
K-space, image acquisition and image reconstruction

Spin Echo Sequence



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Questions

Question

- The outside of K-space contains spatial frequencies relating to?

A. image resolution
B. image contrast
C. image detail
D. image size

- Which type of coil produces more SNR at the surface of a patient?

A. Volume Coil
B. Phased Array Coil

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Questions

Question

In magnetic resonance imaging the following are true:

A. Slice selection must always be applied to the z-axis

B. In a standard SE sequence, frequency encoding is applied during the signal acquisition

C. In a standard SE sequence all of the information for a single slice is obtained with one TR

D. The steeper the slice selection gradient, the thinner the slice

E. In a standard SE sequence the image be built up line by line during acquisition

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Questions

Question

In magnetic resonance imaging the following are true:

A. Slice selection is applied simultaneously with the initial RF excitation

B. A row of phase encoding data in K-space takes less time to acquire than a column of frequency encoding data

C. The centre of a K-space contains the data relating to high spatial resolution

D. Slice thickness can be reduce by decreasing the RF bandwidth for each slice (assuming the gradient remains the same)

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Questions

Question

In magnetic resonance imaging the following are true:

A. The main system magnet must be a superconducting electromagnet

B. Superconductivity requires cooling near to 0°C

C. Resistive electromagnets should ideally not be switched off

D. Gradients for spatial encoding are provided by altering the main magnet

E. The main magnetic field is normally define to be along the Z-direction

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Questions

Hull University Teaching Hospitals NHS Trust

Question

In magnetic resonance imaging the following are true:

A. A 0.5T superconducting magnet produces a greater field strength than a 0.5T resistive magnet

B. A permanent magnetic may be rapidly shut down in an emergency

C. Shim coils are coils that are fine tuned to make the main magnetic field as uniform as possible

D. Surface coils are placed directly on the patient

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