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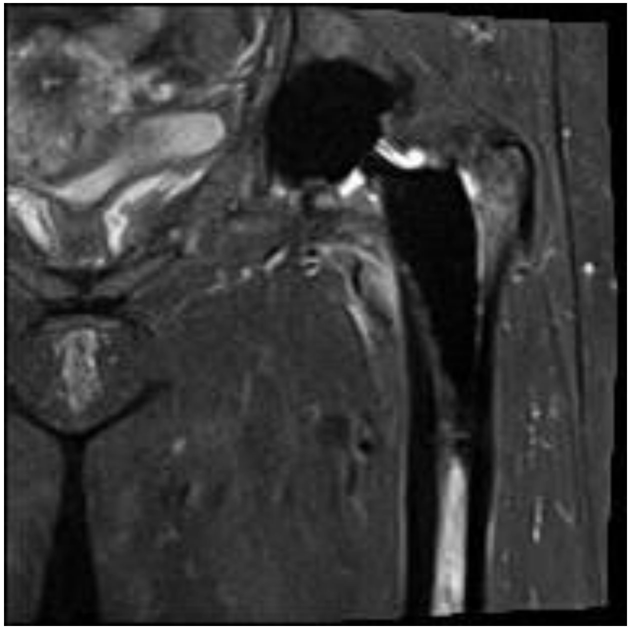
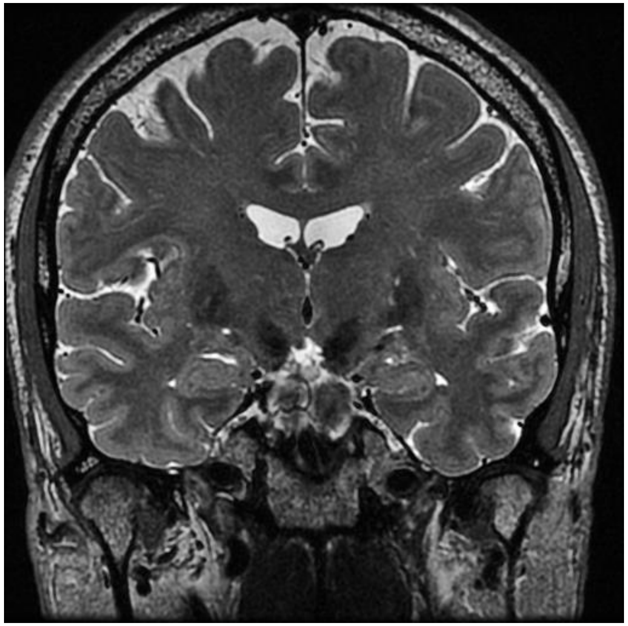
Magnetic Resonance Imaging

F.R.C.R. Physics Lectures





Lawrence Kenning PhD

7.3 Basic MRI sequences & common variants

- Spoiled gradient echo, spin echo
- Multiple echo variants (TSE/FSE, EPI)
- Single shot versus multi shot
- Pulse sequence diagrams *(interspersed throughout lecture)*
- Basics of steady-state sequences

7.3 Basic MRI sequences & common variants

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- Multiple echo variants (TSE/FSE, EPI)
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- Pulse sequence diagrams *(interspersed throughout lecture)*
- Basics of steady-state sequences
- Spoiled gradient echo

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Spin Echo (SE) Pulse Sequences

- Spin echo describes the excitation of the magnetised protons in a sample with a **90° RF pulse** and production of a FID, followed by a refocusing **180° RF pulse** to produce an echo
- The 90° pulse converts M_z into M_{xy} and creates coherent transverse magnetisation that immediately begins to decay at a rate described by T_2* relaxation
- The 180° RF pulse applied at TE/2 inverts the spins and induces phase coherence at TE
- Inversion of the spins causes the protons to experience external magnetic field variations opposite of that prior to TE/2, resulting in the cancellation of the extrinsic inhomogeneities and associated dephasing effects

- Subsequent 180° RF pulses during the TR interval produce corresponding echoes with peak amplitudes that are reduced by intrinsic T_2 decay of the tissues, and are immune from extrinsic inhomogeneities
- Digital sampling and acquisition of the signal occurs in a time window symmetric about TE, during the evolution and decay of each echo
- **Spin Echo sequences can produce T_1, T_2 and P.D. weightings**

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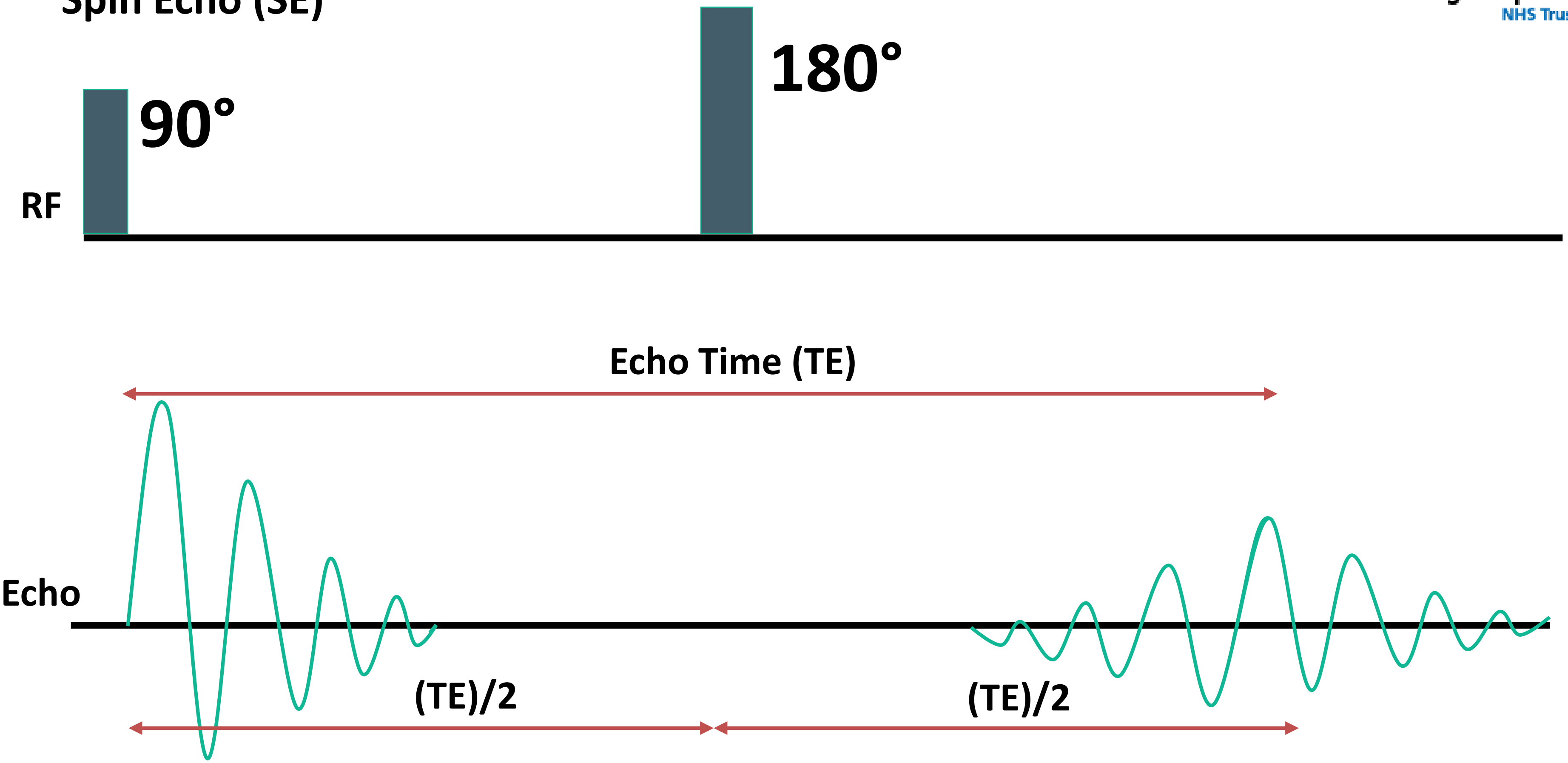
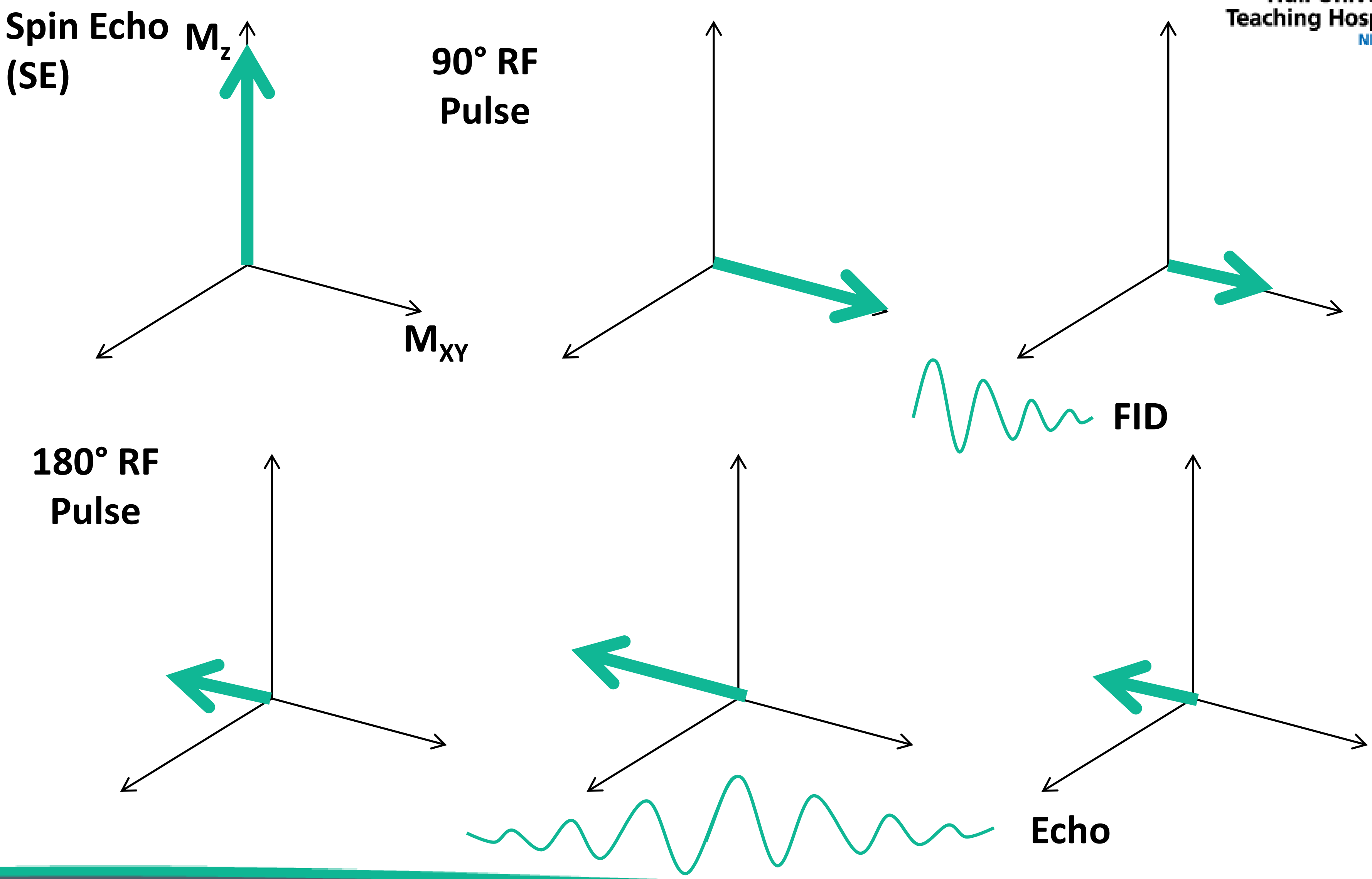
Spin Echo (SE)



FID signal gradually decays with rate constant T_2*

Spin echo peak amplitude depends on T_2


Spin Echo
(SE)
Mz
90° RF
Pulse
MXY
FID
180° RF
Pulse
Echo

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

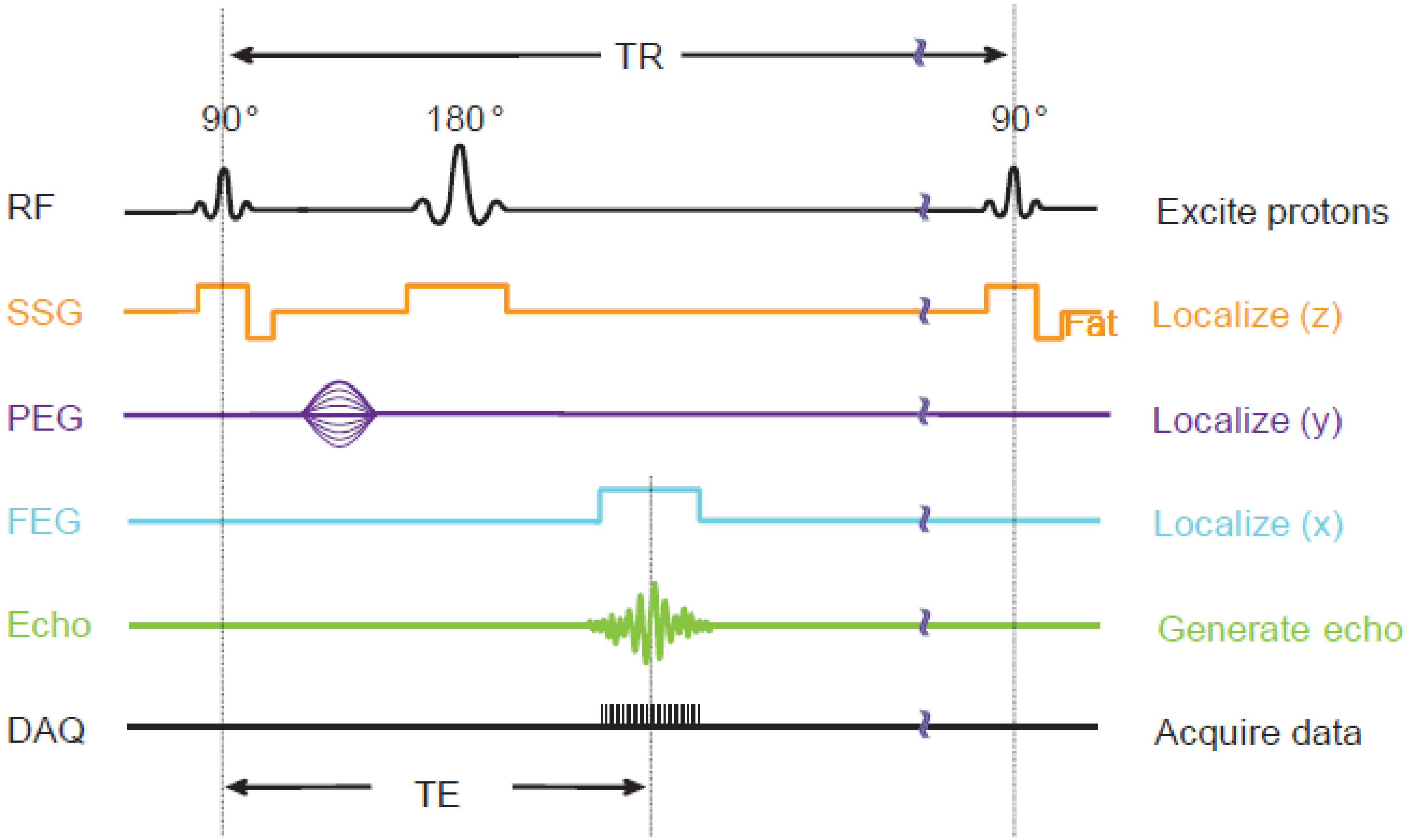
- **Data sampling and acquisition** of the signal occurs simultaneous to the **frequency encoding gradient**

- 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!

Spin Echo Sequence

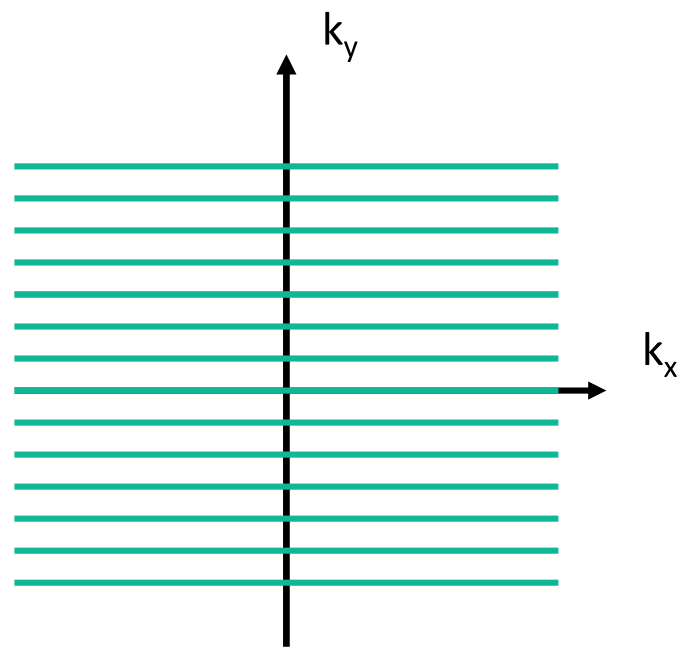


- Time penalty for simplicity of spin echo

- T1 SE clinically possible
  - 384 x 384 matrix
  - TR/TE = 500/15ms
  - 1 Average
- 3 minutes 12 seconds per slice

- Time to excite different slice during TR dead time period

- T2 SE NOT clinically possible
  - 384 x 384 matrix
  - TR/TE = 5000/100ms
  - 1 Average
- 32 minutes per slice



GRE or SE: one line of k-space per TR (usually 256, 512 lines)

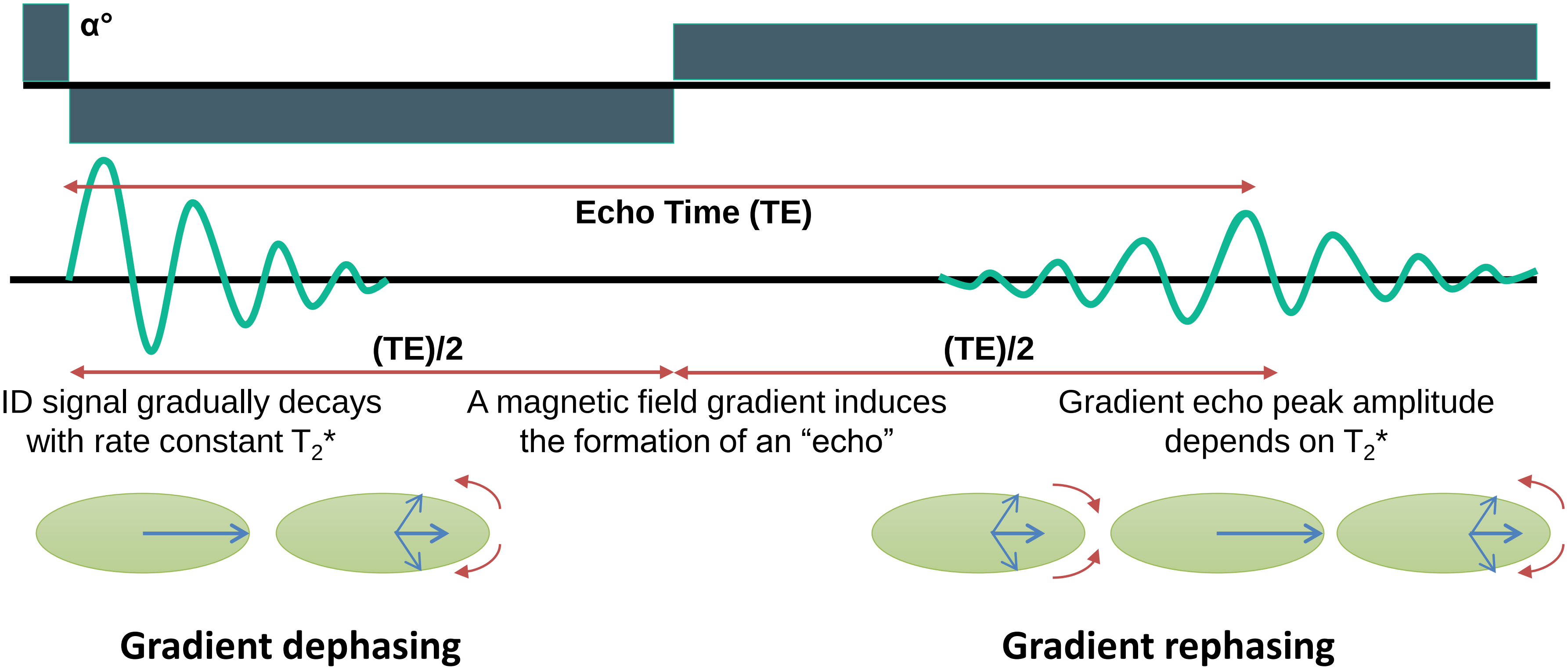
Image time = $N_{phase} \times TR \times NEX$

Gradient echo (GE/GRE)

- Gradient echo (GE/GRE) sequences utilise magnetic field gradients applied in one direction and then reversed to induce an echo
- The magnetic field gradient replaces 180° pulse used by spin echo sequences
- For a FID signal generated under a linear gradient (frequency encoding gradient), the transverse magnetisation dephases rapidly as the gradient is applied
- After a predetermined time, near instantaneous reversal of the GE polarity will rephase the protons and produce a GE that occurs when the opposite gradient polarity of equal strength has been applied for the same time as the initial gradient
- **Gradient Echo sequences can produce T_1, T_2* and P.D. weightings**

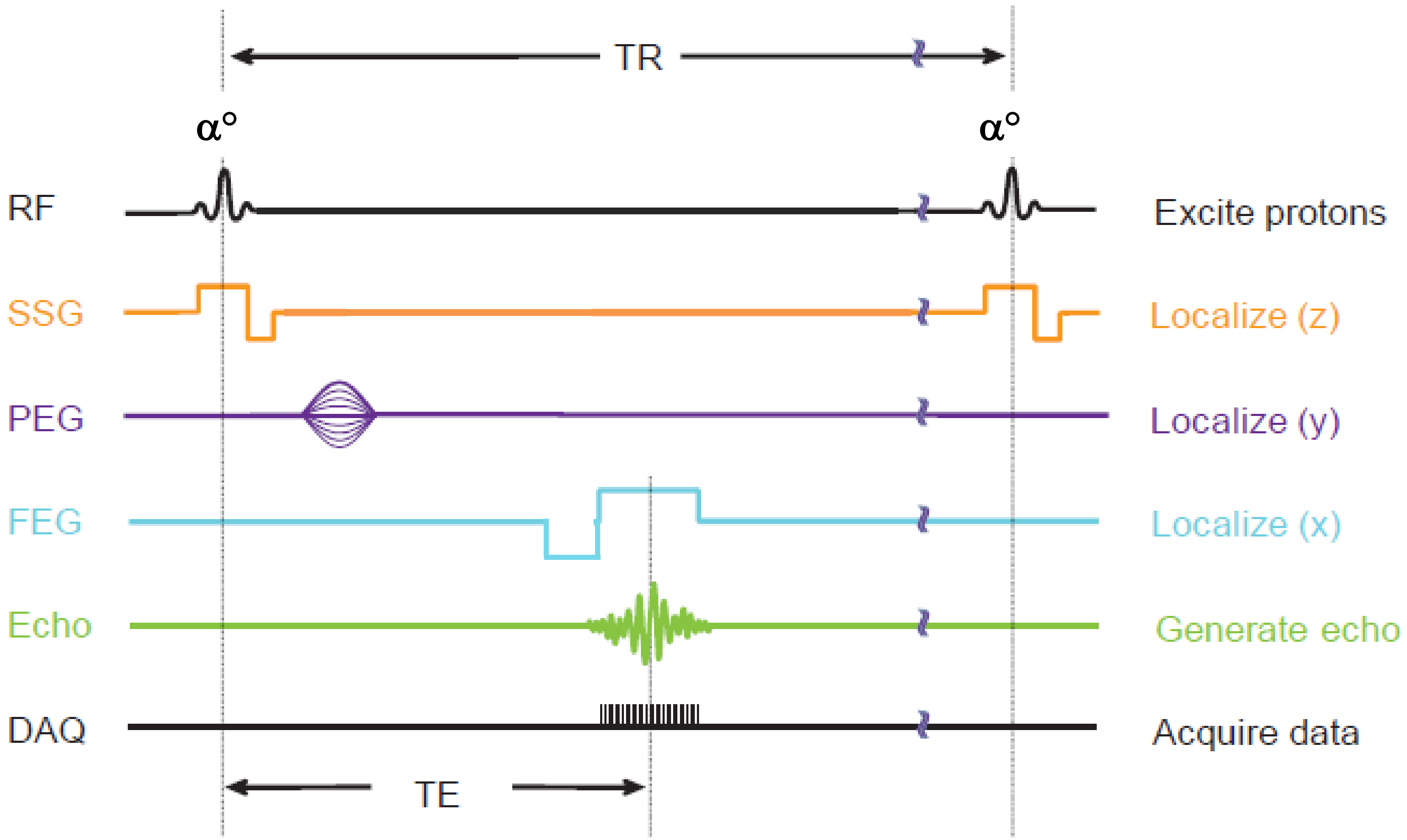
Gradient echo, spin echo

Gradient Echo (GE)



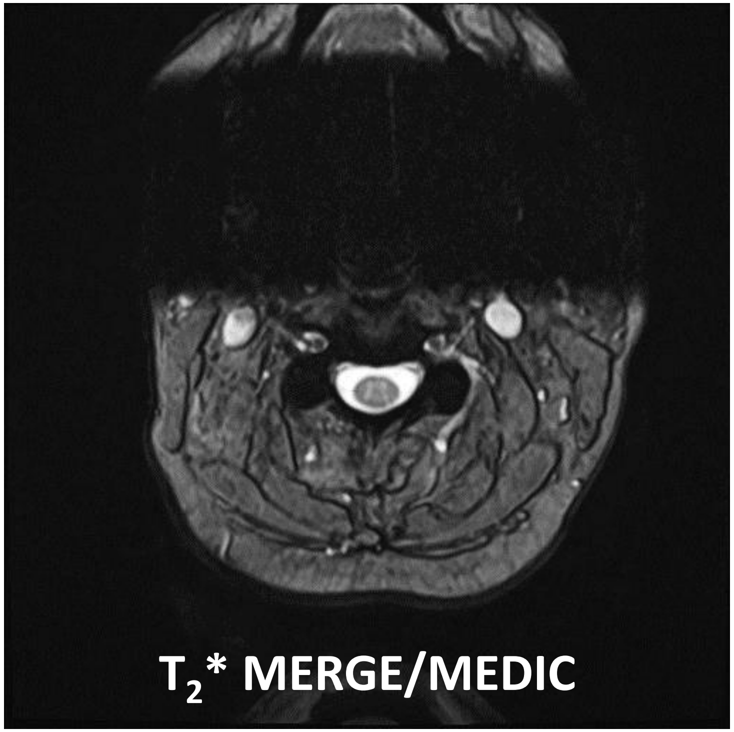
- Frequency encoding gradient is initially applied negatively to <u>speed up the dephasing of the FID</u>. Then its polarity is reversed producing rephasing of the gradient echo

Gradient Echo Sequence



Gradient echo, spin echo

- GE sequences are generally:
  - Lower SNR
  - Faster
  - More susceptible to metallic artefacts
  - **Generally used to produce T_1 and T_2^* weightings**



Multiple Echo Recombined Gradient Echo
Multi-Echo Data Image Combination

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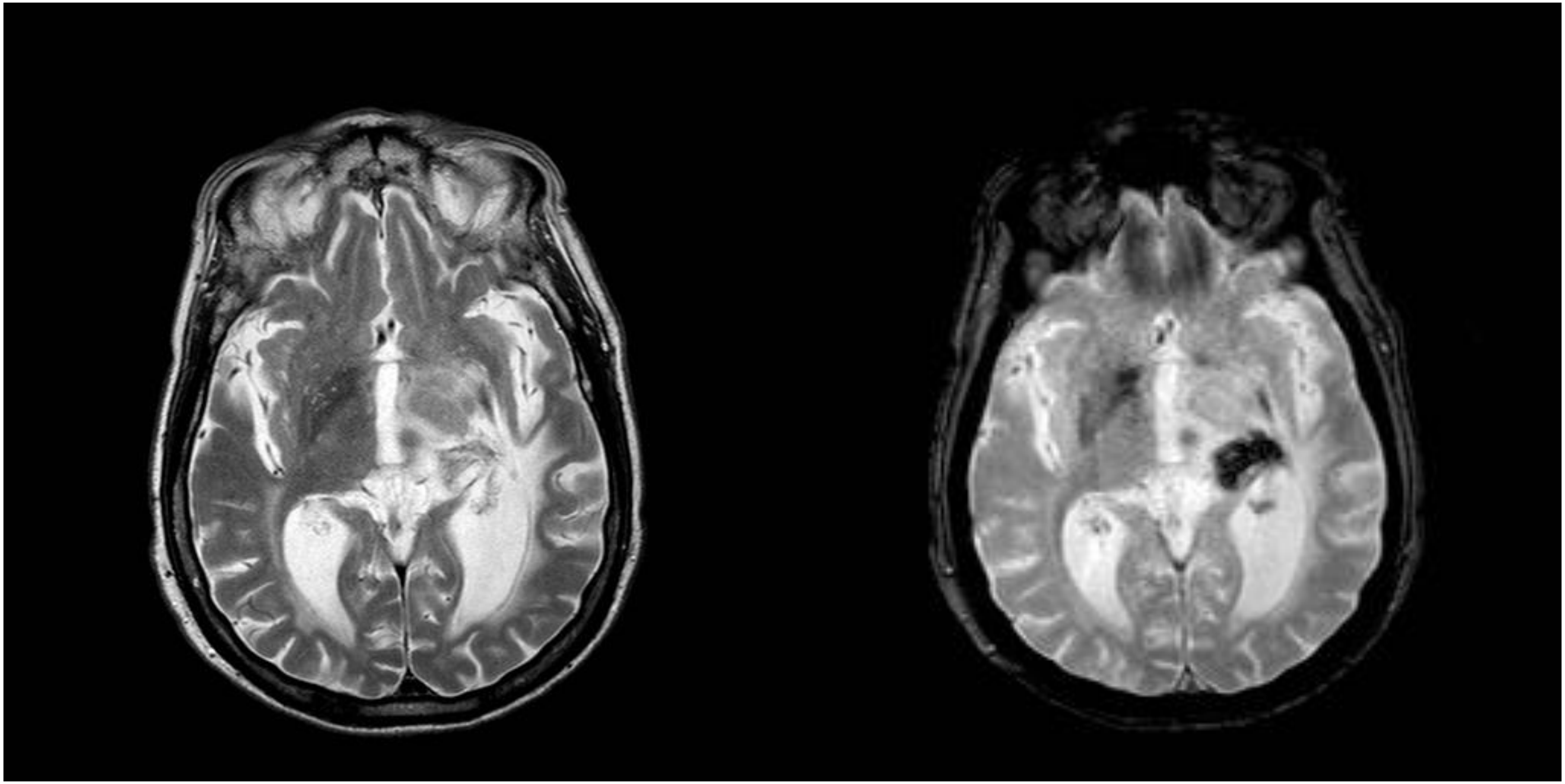
T_2/T_2^*

- In the absence of a 180° rephasing pulse, field inhomogeneities are maintained and images are T_2^* (not T_2) weighted
- GE sequences are thus more sensitive to magnetic susceptibility artefacts than spin echo sequences

T_2* Weighted Imaging



Spin Echo T_2 Gradient Echo T_2*

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Gradient Echo Image Contrast

- Flip angle (α):
  - Small α → reduced T_1 weighting
  - Large α → increased T_1 weighting

  *** Small flip angles minimise T_1-weighting because the longitudinal magnetisation (M_z) of tissues are less well differentiated*

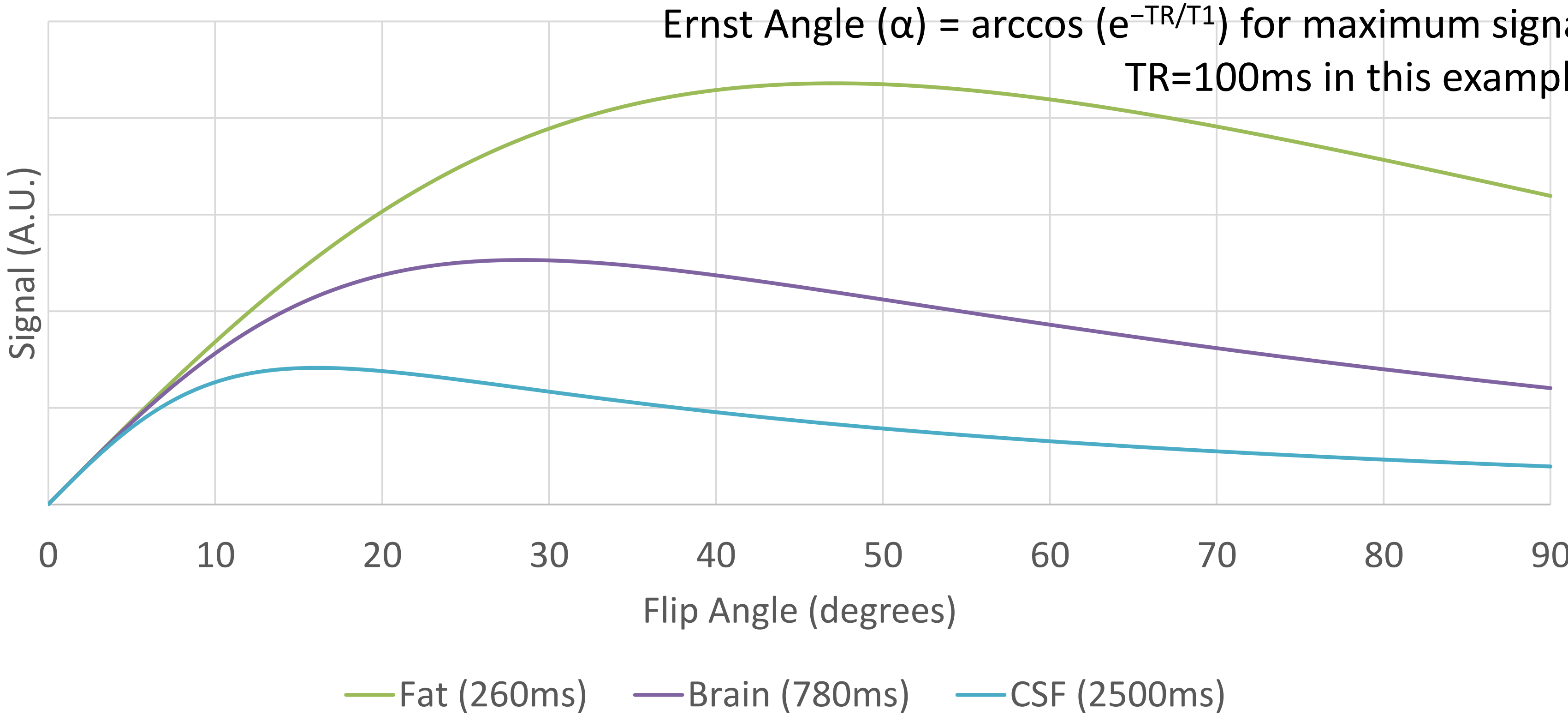
- TE:
  - Short TE → reduced T_2* weighting
  - Long TE → increased T_2* weighting.

- TR:
  - Short TR → reduced T_1 weighting
  - Long TR → increased T_1 weighting

Gradient Echo Image Contrast

Ernst Angle (α) = arccos ($e^{-TR/T1}$) for maximum signal

TR=100ms in this example



Flip angle:

T_1 weighting	Flip=high	TR=short	TE=short
T_2* weighting	Flip=low	TR=long	TE=long
P.D weighting	Flip=low	TR=long	TE=short

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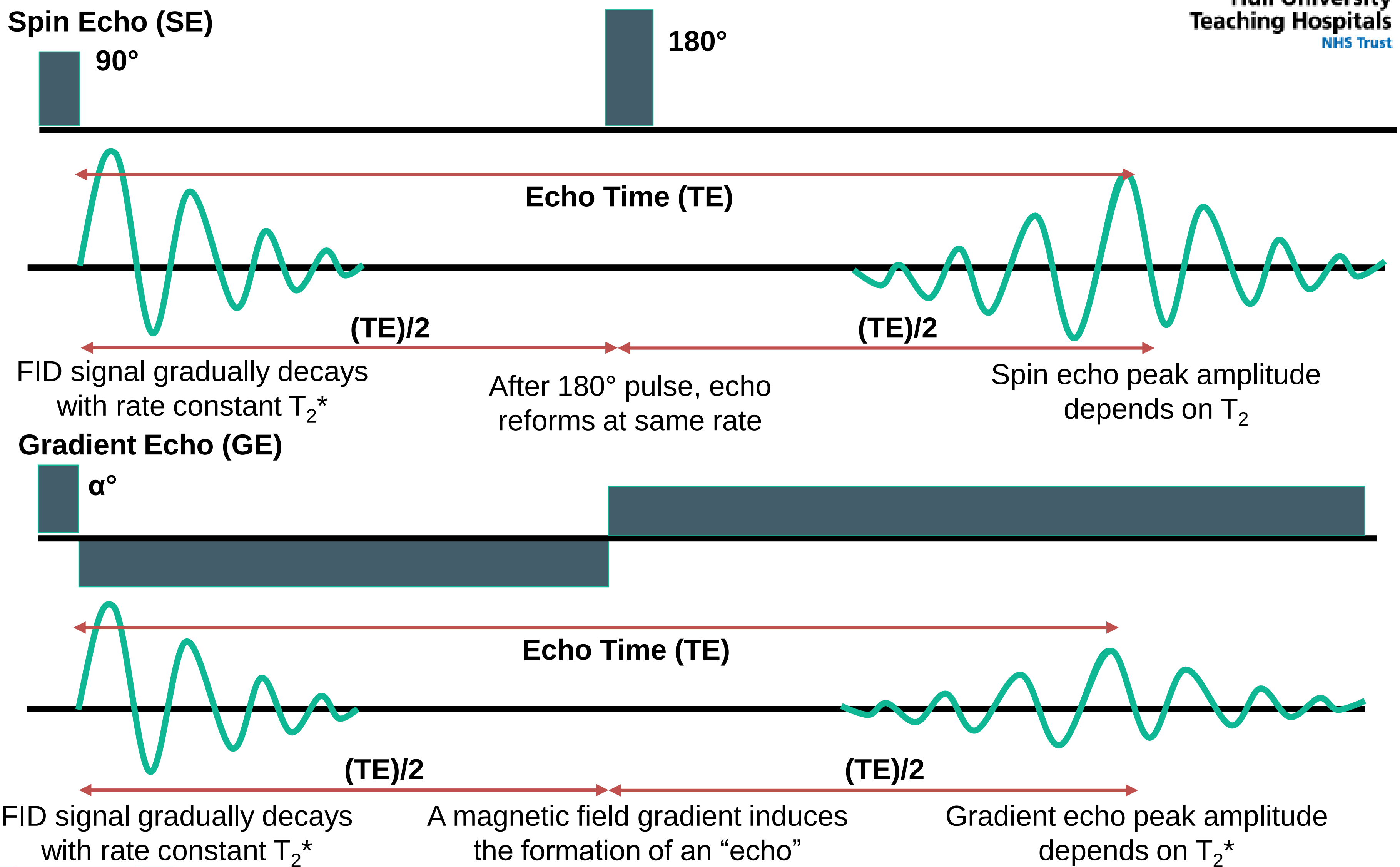
Gradient Echo vs. Spin Echo

- Flip angle is usually less than 90˚
- Absence of a 180˚ rephasing pulse
- Lower flip angle decreases amount of magnetisation tipped to transverse plane
- Faster recovery of longitudinal magnetisation
- Shorter TR/TE decreases scan time
- GE particularly useful as a rapid imaging technique. i.e. breath-hold studies, dynamic contrast examinations and angiography
- Allows new tissue contrasts (T_2*)
- Magnetic field inhomogenieties maintained!

Gradient echo, spin echo



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Multi-Echo Sequences

- Allow several images of the same slice position without increasing overall acquisition time
- Images obtained with different contrast
- After first echo is obtained, free interval until next TR
- By applying a new 180° pulse a new echo is received (but with the "same" phase encoding)
- The echo time of the 2 images differs and the second image will be more T_2 weighted than the first
- Typically used to obtain simultaneously P.D. & T_2-weighted images

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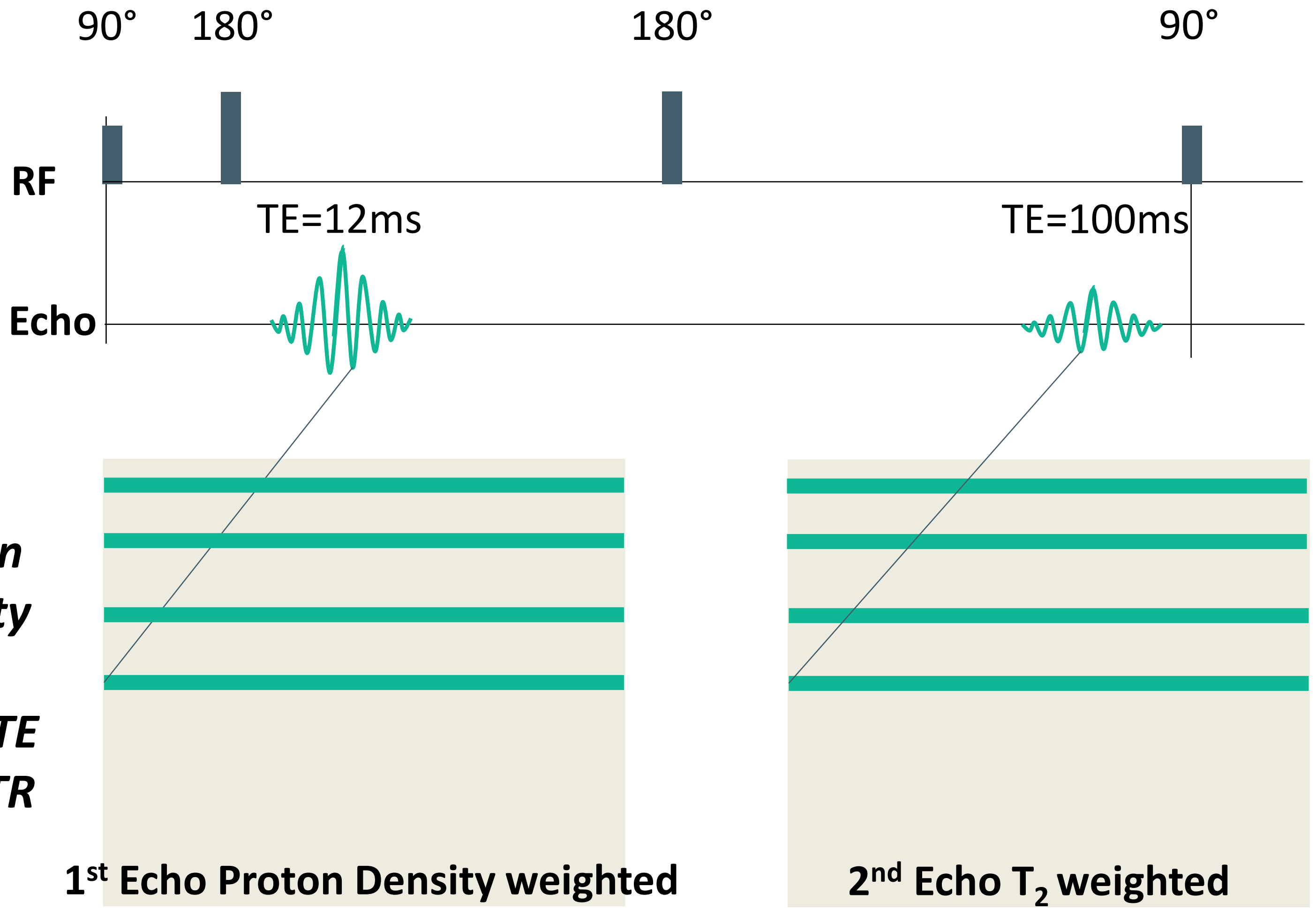
Multi-Echo Sequences



Proton Density

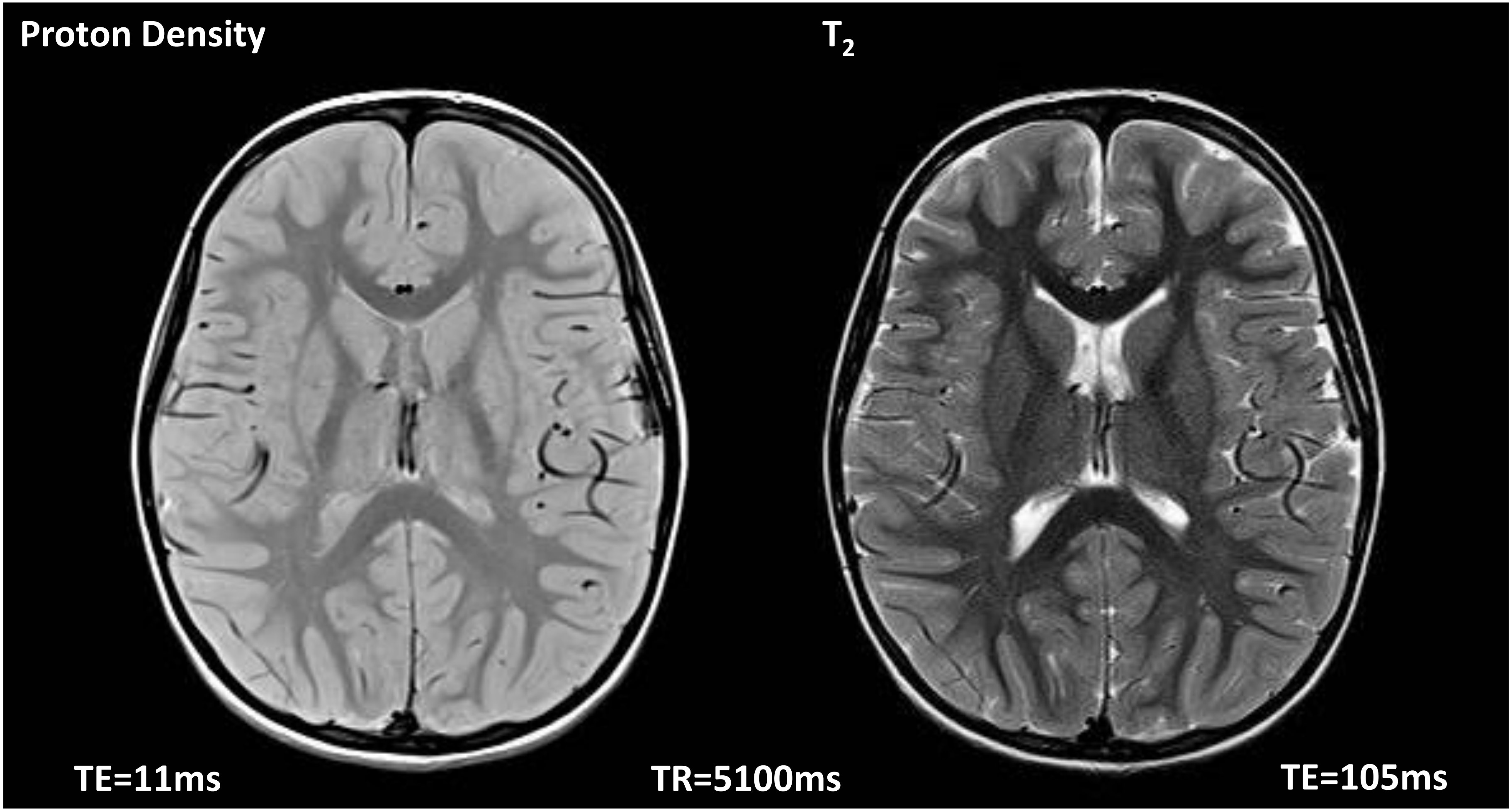
Short TE
Long TR

T_2 Weighted

Long TE
Long TR

Remarkable people.
Extraordinary place.

Multiple echo variants (TSE/FSE, EPI)



Fast Spin Echo (FSE) / Turbo Spin Echo (TSE)

- Interval time after the first echo used to retrieve echo train and fill other k-space lines.
- Done by applying new 180° pulses to obtain a spin echo "train".
- After each echo, the phase encoding is cancelled and a different phase encoding applied to the following echo
- Number of echoes received in the same repetition (TR) time is called the Turbo factor or Echo Train Length (ETL)
- Because of the reduced number of repetitions (TR), k-space is filled faster and slice acquisition time reduced.
- Time of scan = $(N_{PE} \times TR \times NEX)/ETL$

Echo Train Length (ETL)

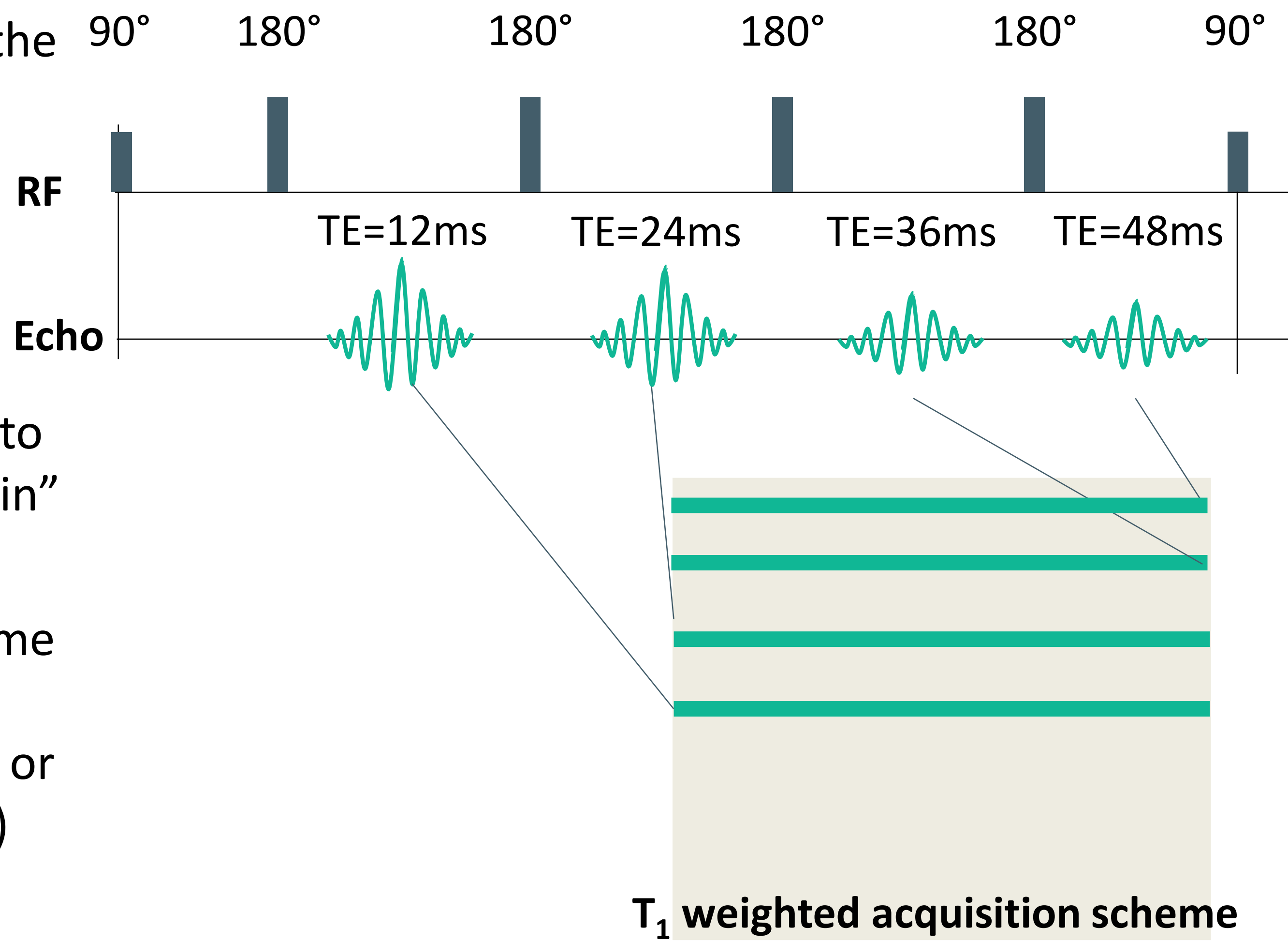
- Longer ETLs result in greater T_2-weighting since more higher TE echoes will contribute to the final image contrast
- Longer ETL are also associated with a decrease in overall signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR)
- Scan time is given by:

$$N_{PE} \times TR \times NEX / ETL$$

- For a 256x256 image with a TR of 4000ms, 1 average and an echo train length of 24, the scan time would be 43 seconds
- The effective TE (TE_{eff}) describe the TE of central echo which fills the centre of k-space

Fast Spin Echo (FSE) / Turbo Spin Echo (TSE)

- It is possible to utilise the interval time after the first echo to fill additional lines of k-space
- Achieved by applying additional 180° pulses to obtain a spin echo “train”
- Number of echoes received during the same repetition time (TR) is called the Turbo factor or Echo Train Length (ETL)

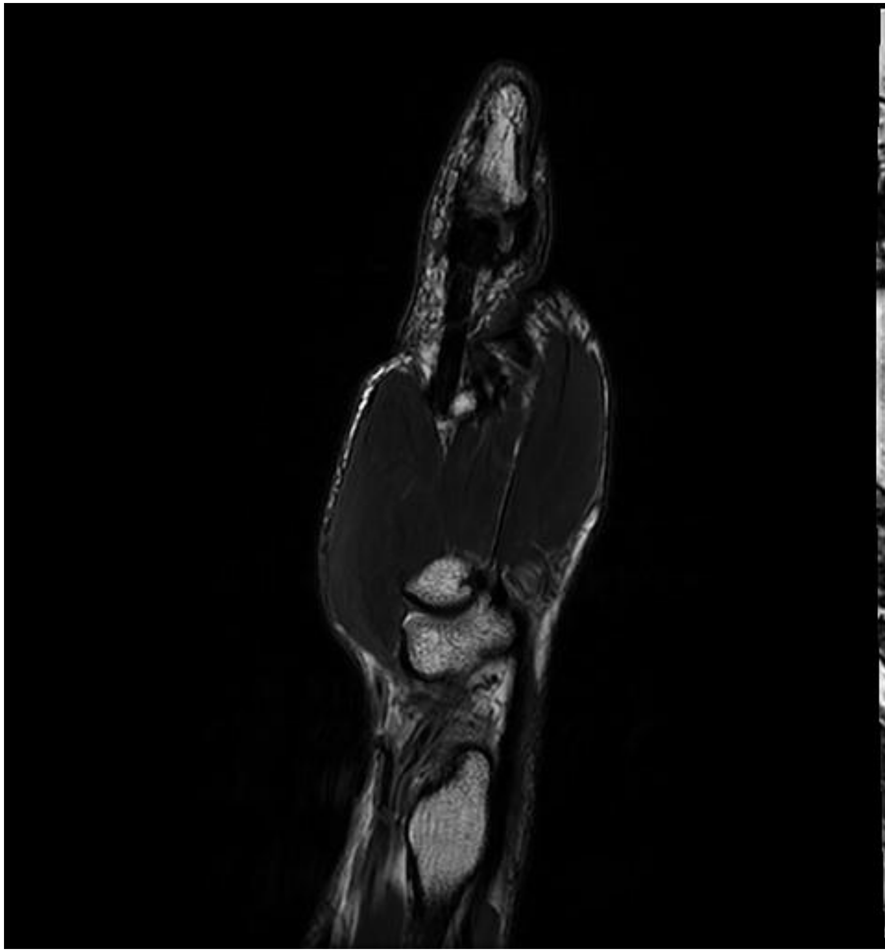


T_1 weighted acquisition scheme

Fast Spin Echo: Contrast, Resolution & Scan Time

- Contrast is modified compared to a standard SE sequence
- Longer ETLs result in more T_2-weighting because more late echoes with longer TE's contribute to the overall signal.
- Longer ETL's are also associated with a decrease in overall signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) because the later echoes are weaker.
- Time at which these echoes fill central region of k-space is called the effective TE (TE_{eff})
- FSE can be P.D., T_1 or T_2 weighted
  - In T_1 weighted sequences need to choose short TR: limits echo train length

2D Fast Spin Echo



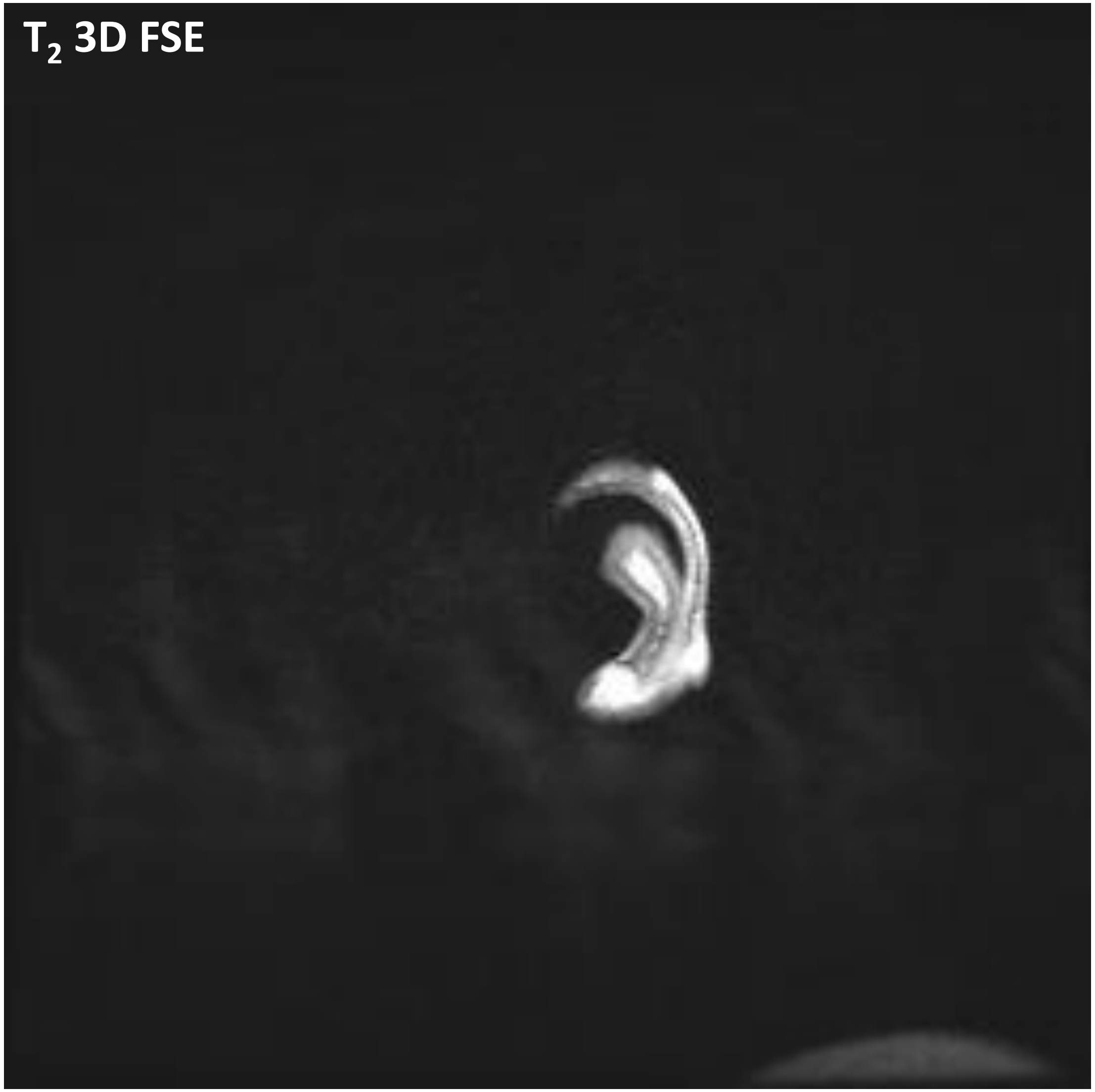
3D FSE/TSE

- SPACE/CUBE/3D BrainVIEW are 3D FSE/TSE sequences that utilise very long echo trains… up to 250 echoes long!
- Usually implement variable flip angles to limit SAR (sometimes constant)
- Ability to create T_1, T_2, P.D., FLAIR, STIR and DIR image contrasts
- Offer sub-millimetre imaging in clinical times (3-6 min)
- Possible replacement for multiple 2D acquisitions

Multiple echo variants (TSE/FSE, EPI)

T_2 3D FSE (CUBE) 0.5mm slice thickness

Multiple echo variants (TSE/FSE, EPI)



Multiple echo variants (TSE/FSE, EPI)

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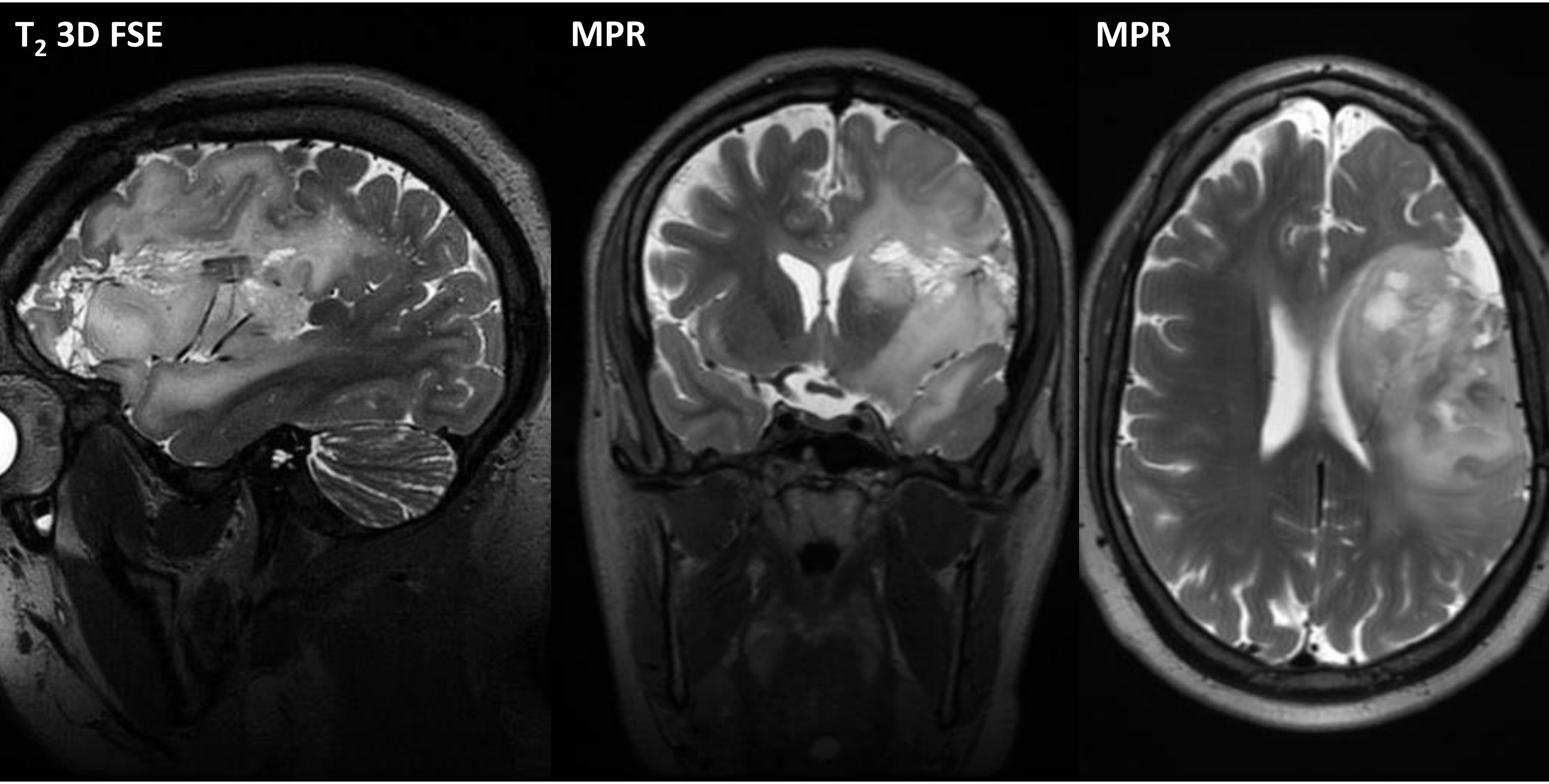


FSE

2D T_1 FSE +C

FOV = 24cm

Matrix = 384x224

Phase FOV = 0.8

TR/TE = 602/14.4

ARC = 2

SL Thick= 5/1mm

Scan Time = 1:53

3D T_1 FSE FS +C

FOV = 24cm

Matrix = 320x320

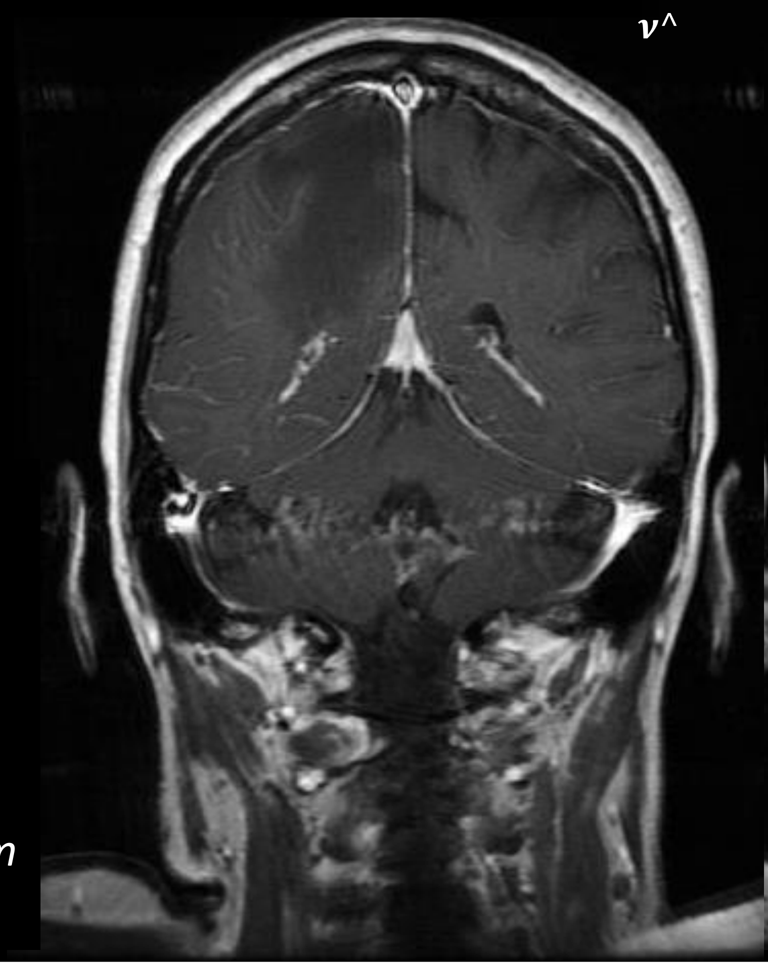
Phase FOV = 0.8

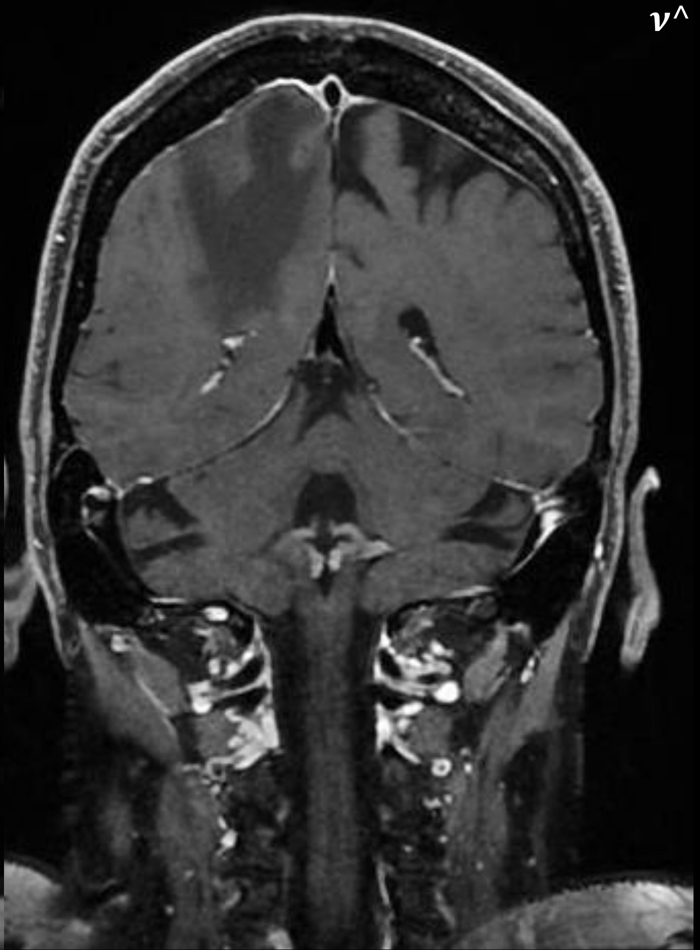
TR/TE = 602/14.4

ARC = 2 x 2

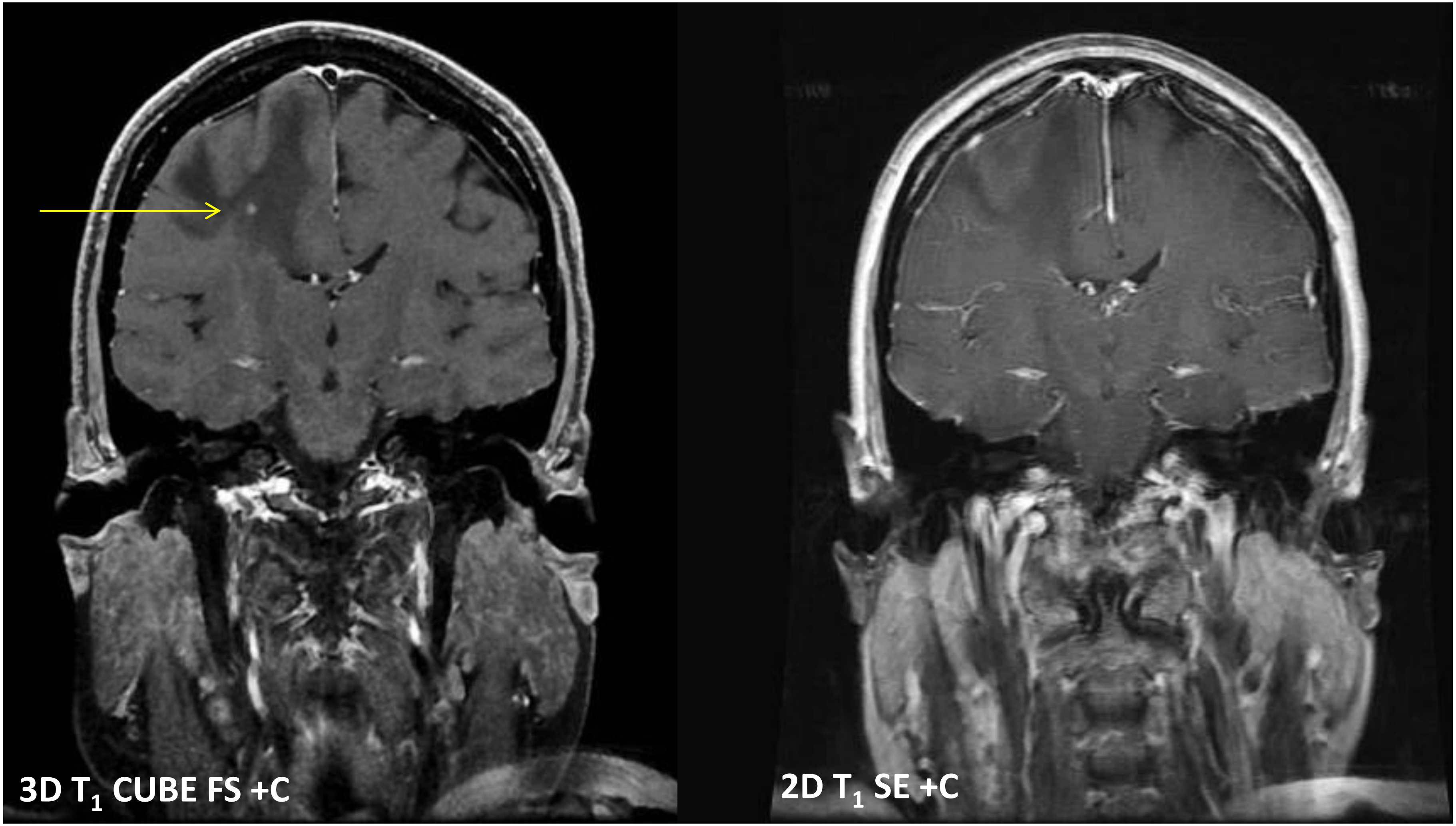
SL Thick= 0.6/0mm

Scan Time = 3:35

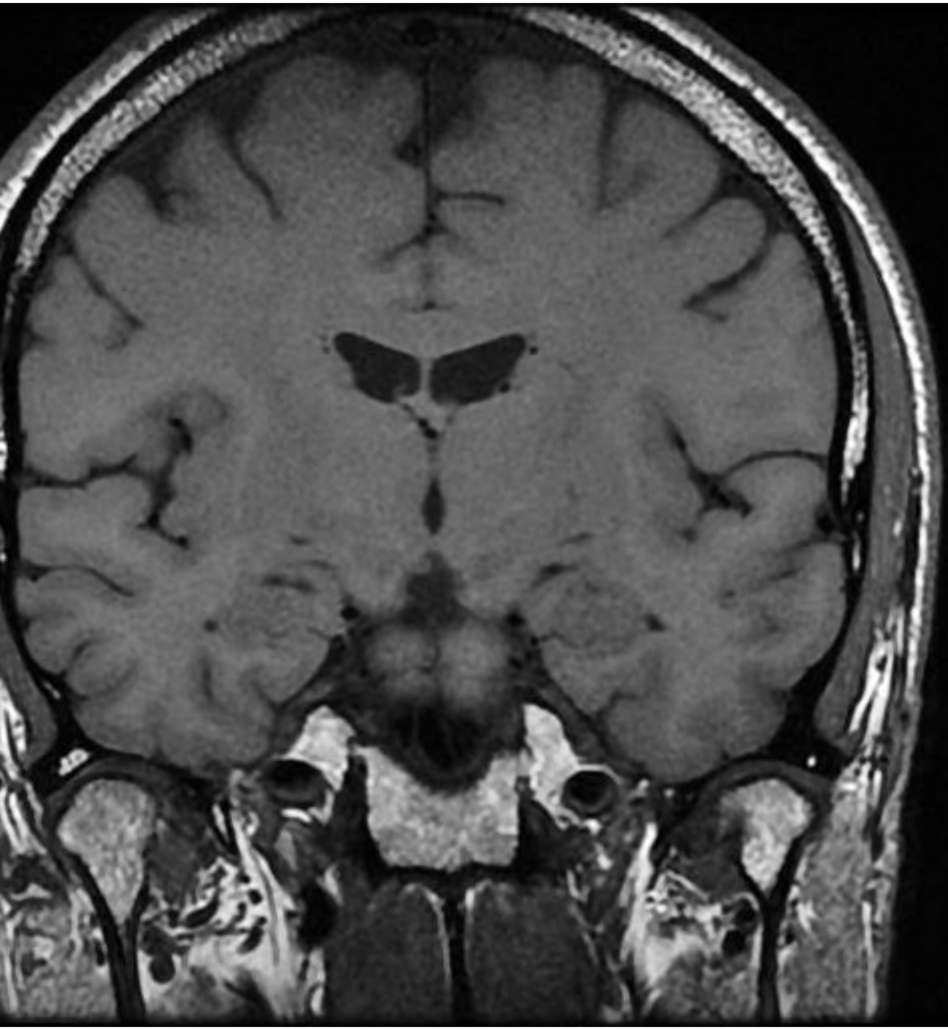




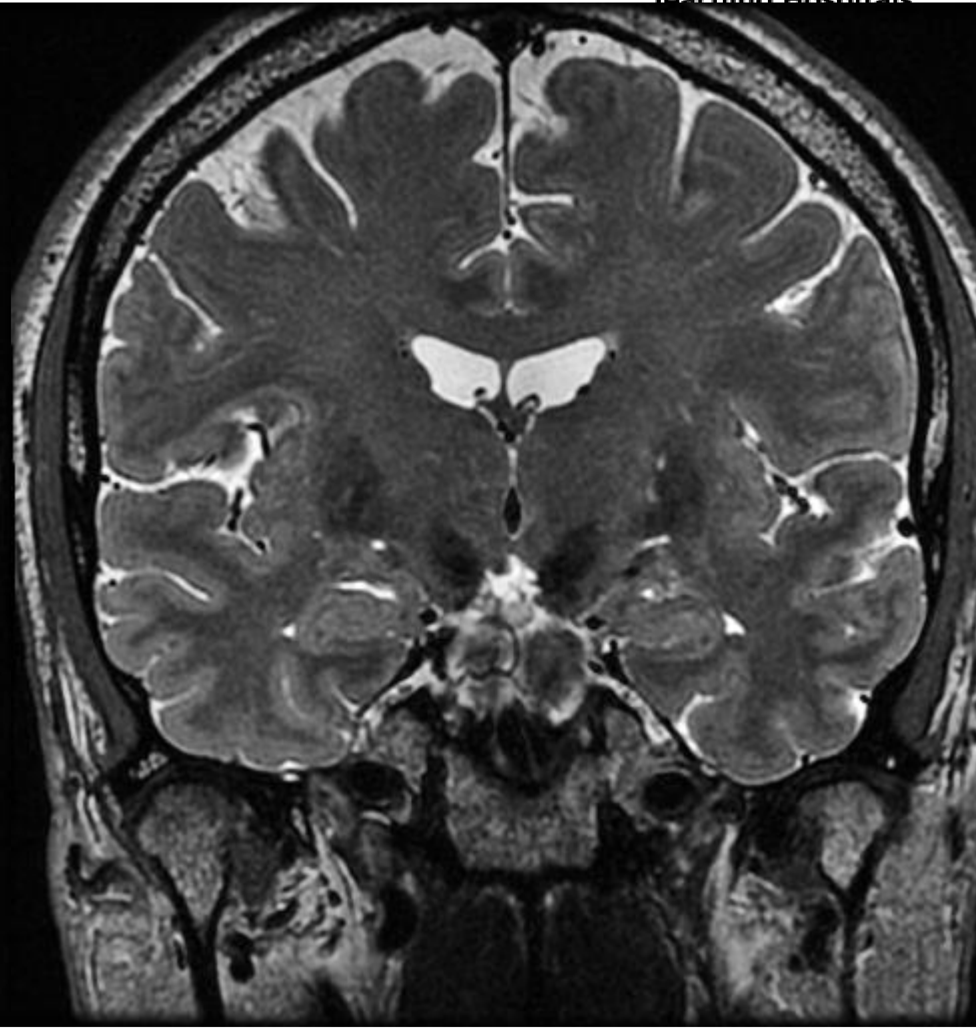
Multiple echo variants (TSE/FSE, EPI)



Multiple echo variants (TSE/FSE, EPI)



T1 3D FSE (CUBE) 0.5mm slice thickness



T_2 3D FSE (CUBE) 0.5mm slice thickness

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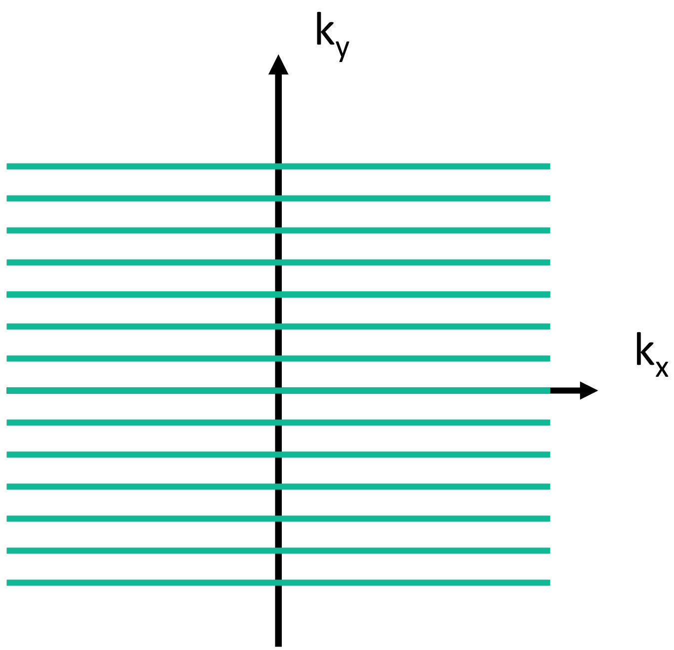
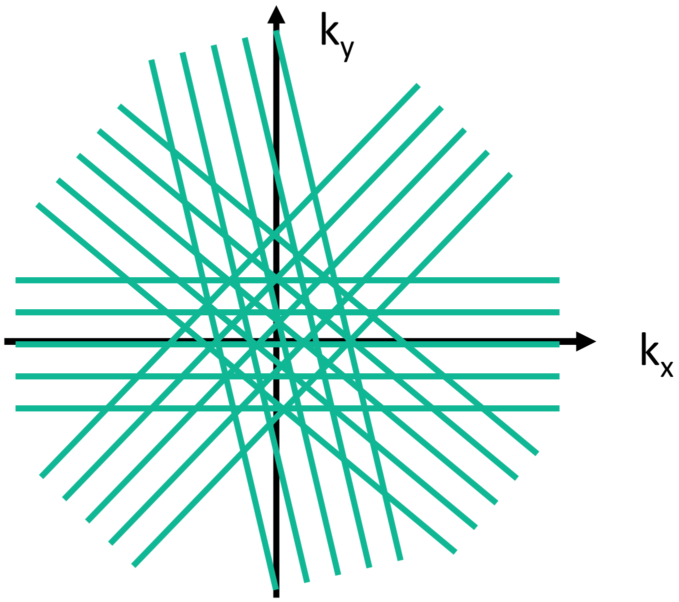
k-space trajectories

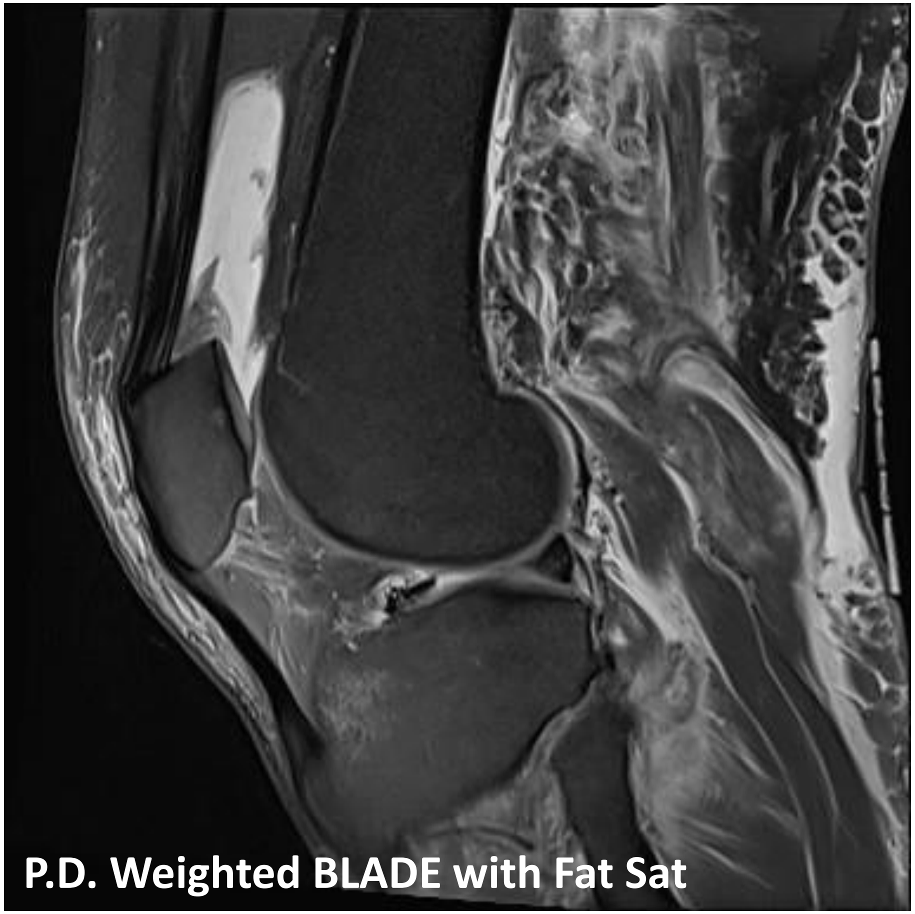


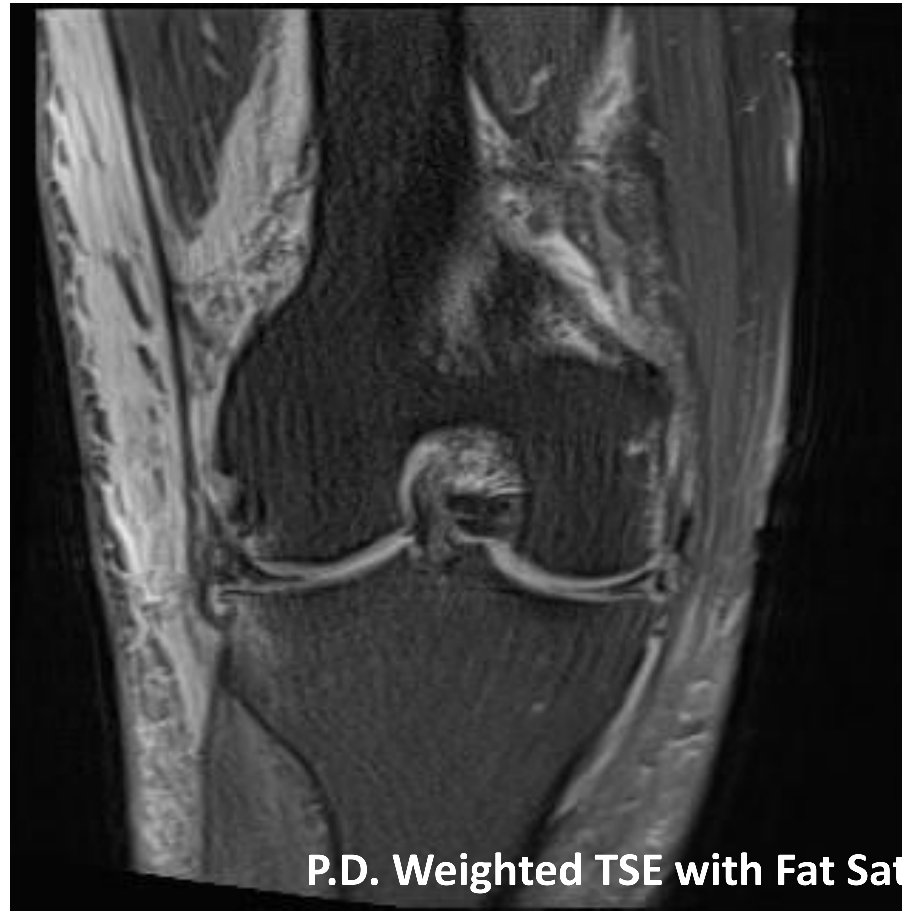


GRE or SE: one line of k-space per TR
(usually 256, 512 lines)
Image time = $N_{phase} \times TR$

Radial:
Centre oversampled
Motion compensation

2D TSE/FSE BLADE/PROPELLER

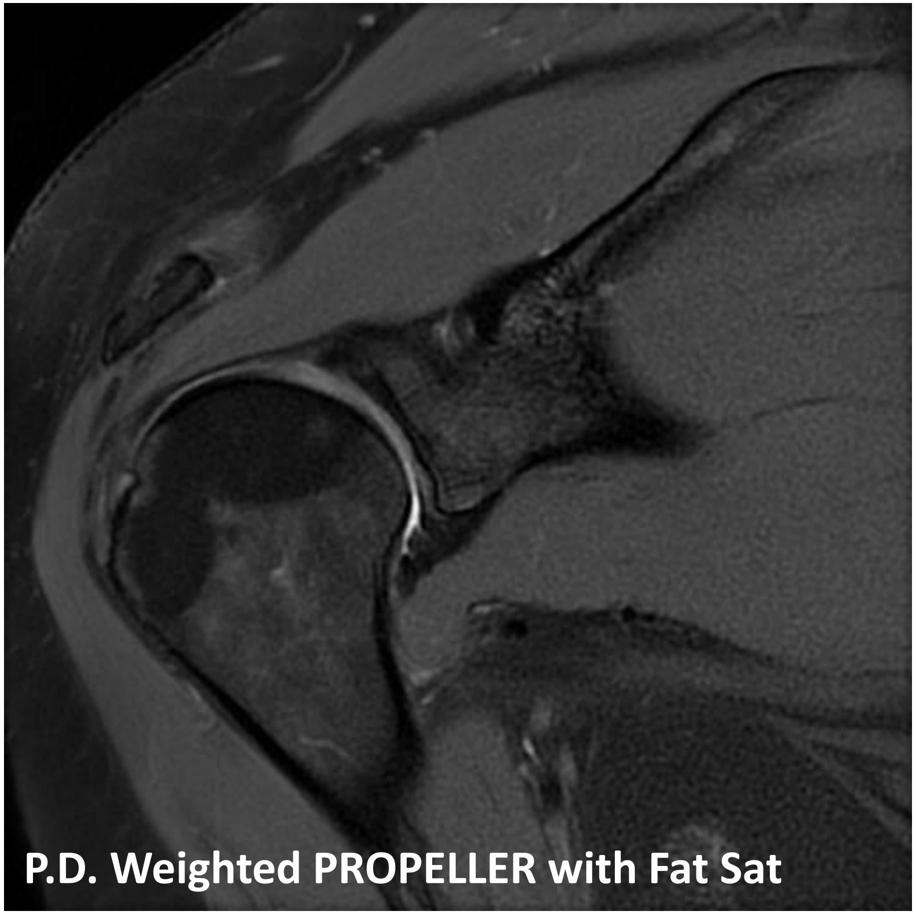

P.D. Weighted BLADE with Fat Sat


P.D. Weighted TSE with Fat Sat

PROPELLER (Periodically Rotated Overlapping ParallEL Lines with Enhanced Reconstruction)

Multiple echo variants (TSE/FSE, EPI)

2D TSE/FSE BLADE/PROPELLER



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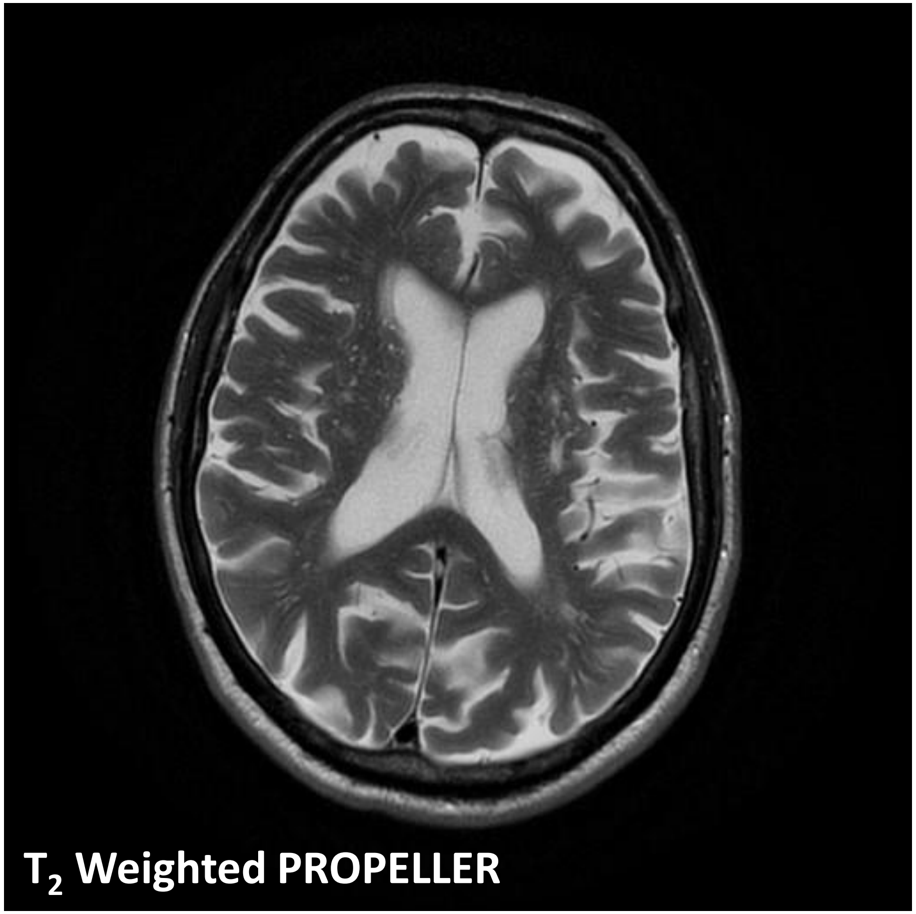
Multiple echo variants (TSE/FSE, EPI)

2D TSE/FSE BLADE/PROPELLER



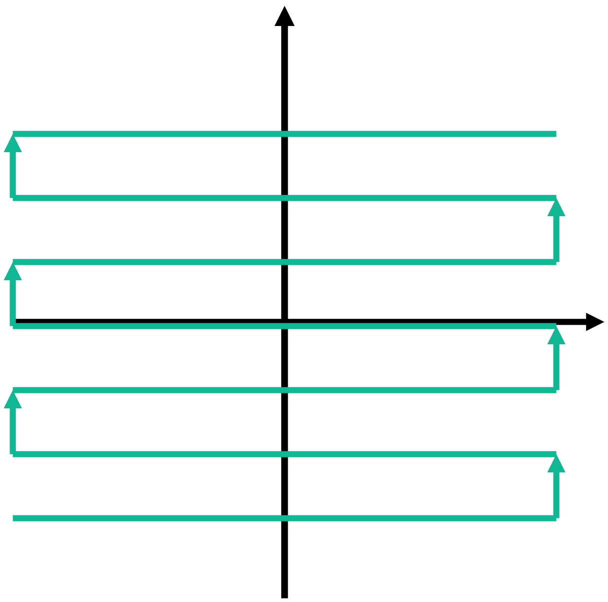
PROPELLER (Periodically Rotated Overlapping ParallEL Lines with Enhanced Reconstruction)

2D TSE/FSE BLADE/PROPELLER

PROPELLER (Periodically Rotated Overlapping ParallEL Lines with Enhanced Reconstruction)

Echo Planar Imaging (EPI)

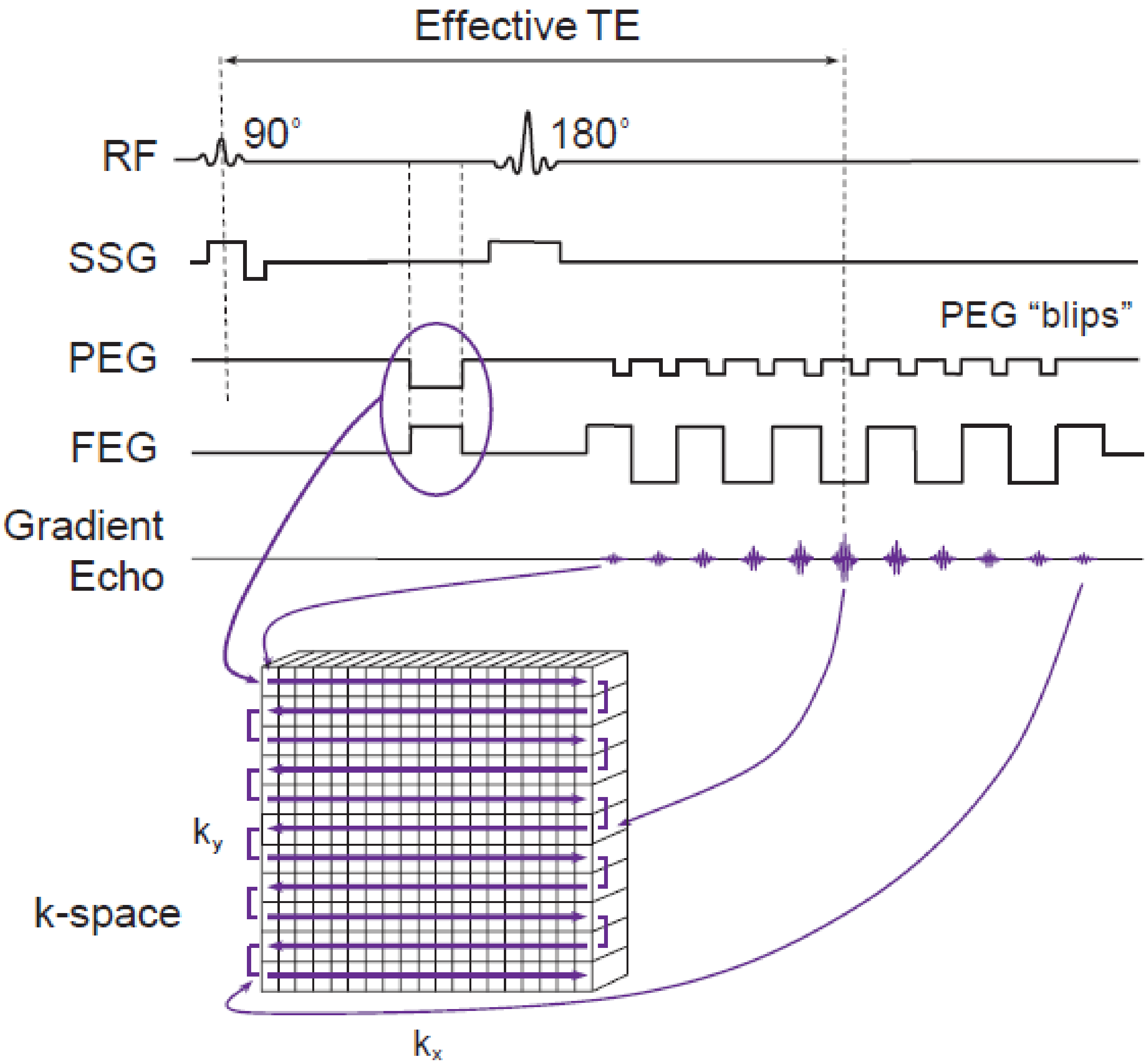
- EPI is the fastest acquisition method in MRI (100ms/ slice), but with limited spatial resolution
- Single-shot (can be run multi-shot)
    - Scan time = TR
- Inherently noisy
- Prone to distortions and ghosting
- Limited resolution (~128x128)
- Can be SE or GE based
- Widespread use in diffusion and fMRI



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

SE EPI

Blipped EPI k-space filling



EPI: Preparation & Contrast

- For GE train a readout gradient (FEG) is continuously applied, with positive & negative alternations

- With alternating gradient k-space scanned from left to right and back with each echo.

- At same time PE gradient may be permanent & constant (non-blipped) giving a zigzag trajectory or intermittent (blipped)

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EPI: Preparation & Contrast

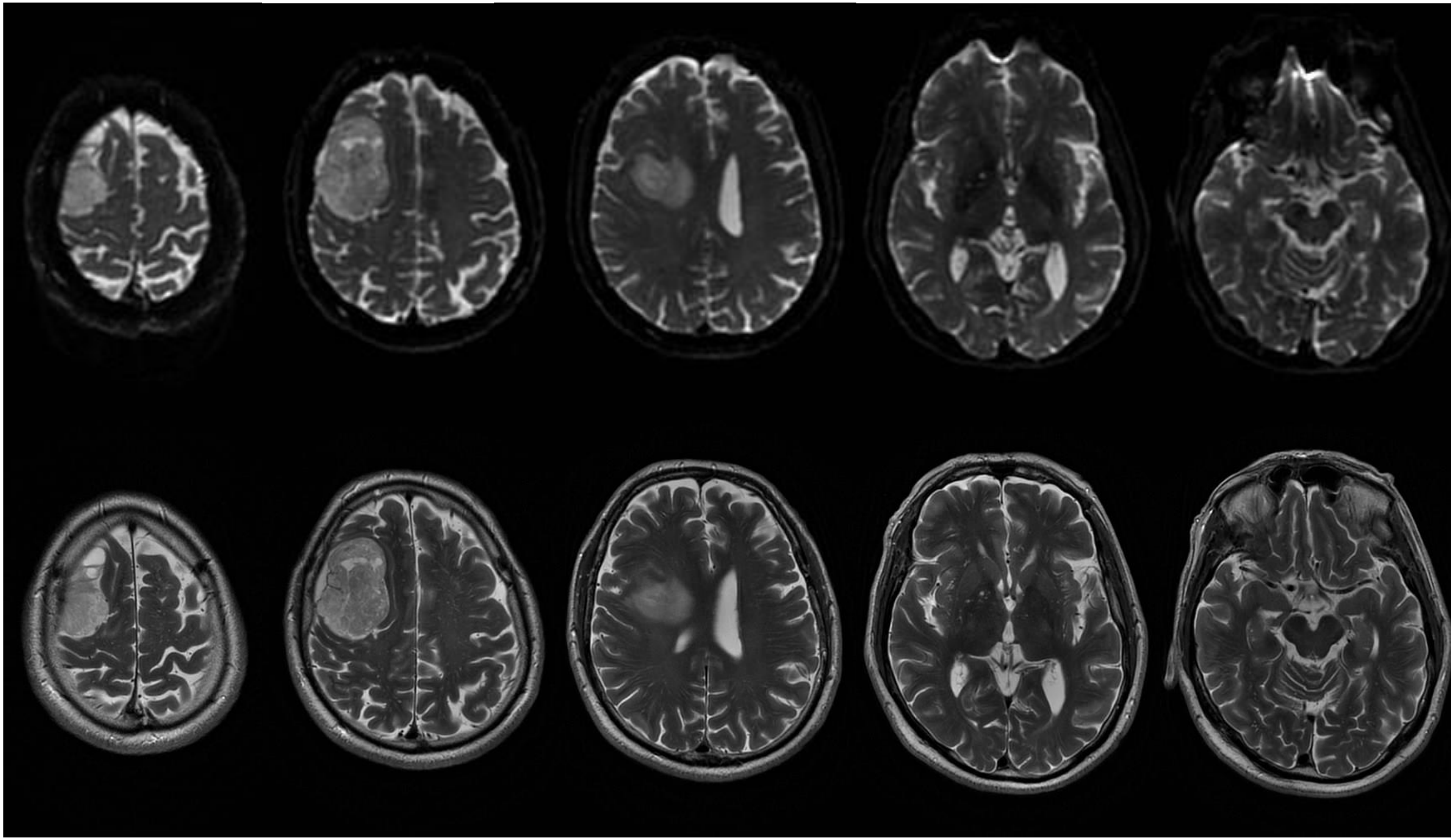
- Requires high performance gradients: need to allow rapid on-off switching of gradients.
  - Limits on how large this can be are determined by peripheral nerve stimulation

- Contrast determined by excitation pulse & possible magnetisation preparation

- Options:
  - GE-EPI: single RF pulse, with no preparation → T_2* weighting
  - SE-EPI: 90°-180° pulses → T_2 weighting
  - IR-EPI: 180° inversion pulse then RF excitation pulse → T_1 weighting
  - DW-EPI: preparatory pattern for diffusion weighting

Multiple echo variants (TSE/FSE, EPI)

EPI vs SE



Multiple echo variants (TSE/FSE, EPI)

- **Advantages**
  - rapid acquisition (effectively freezes physiological motion)
  - no problems with RF burden
  - contrast easily manipulated since EPI is just a readout module

- **Disadvantages**
  - severe hardware requirements
  - ghosting artefacts due to eddy currents induced by rapid switching of gradient coils
  - extremely sensitive to off-resonance and susceptibility effects

Single shot fast spin echo (SSFSE)

- Conventional (Cartesian) k-space filling takes in the order of seconds to minutes to fill
  - T_1 FSE – TR=500ms, 256 PE steps & ETL=3 = 43 seconds
  - T_2 FSE– TR=5000ms, 256 PE steps & ETL=24 = 53 seconds

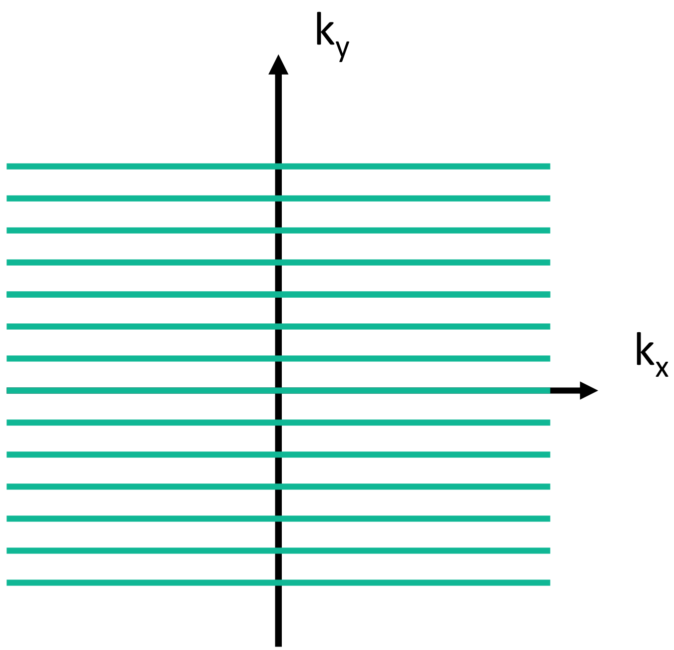
- This makes conventional k-space filling prone to motion artefacts cause by the misalignment of data in k-space prior to inverse FFT.

- Without complete filling of k-space, reconstruction artefacts occur.

The purpose of SSFSE is:

- to reduce motion artefact and imaging time
- to scan uncooperative patients in short scan times
- for breath hold abdominal and cardiac imaging
- with long TE values (300-1300 ms) to image the gallbladder and biliary tree

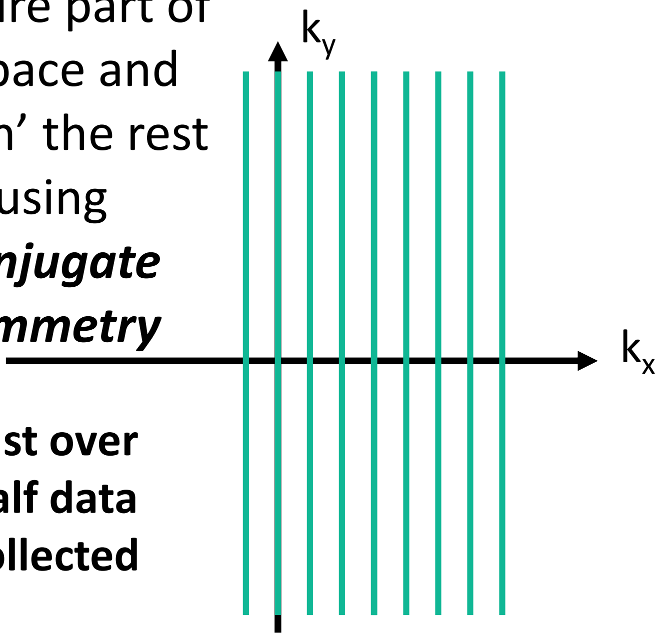
k-space trajectories



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

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

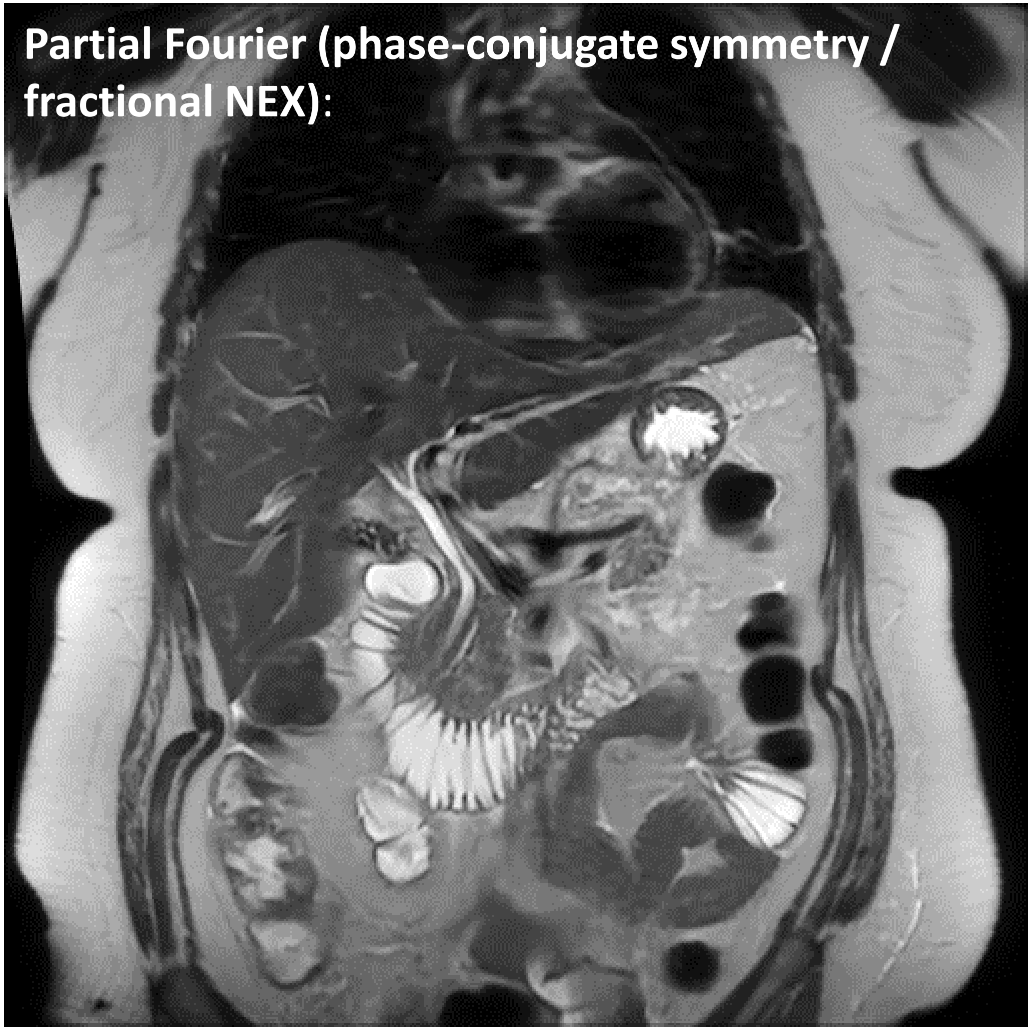
Just over half data collected



Partial Echo (Read-conjugate symmetry):
Collects half of echo reducing the shortest possible TE

Partial k-space (Single shot)

- HASTE (Half Fourier Acquisition Single Shot Turbo Spin Echo) / SS-FSE (Single-shot fast spin echo)
- Often make use of partial Fourier to reduce breath-hold time
- Short acquisition time makes sequence motion insensitive
- Image contrast is determined by the effective echo time TE_{eff}, that is, the echo time in the raw-data centre.



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Partial k-space (Single shot)

- Echo Train technique to fill entire Fourier plane with a single 90° pulse (so TR is infinite)
- Requires successive application of as many 180° pulses as there are k-space lines to fill
- Fill-in missing lines of k-space using ***conjugate symmetry***

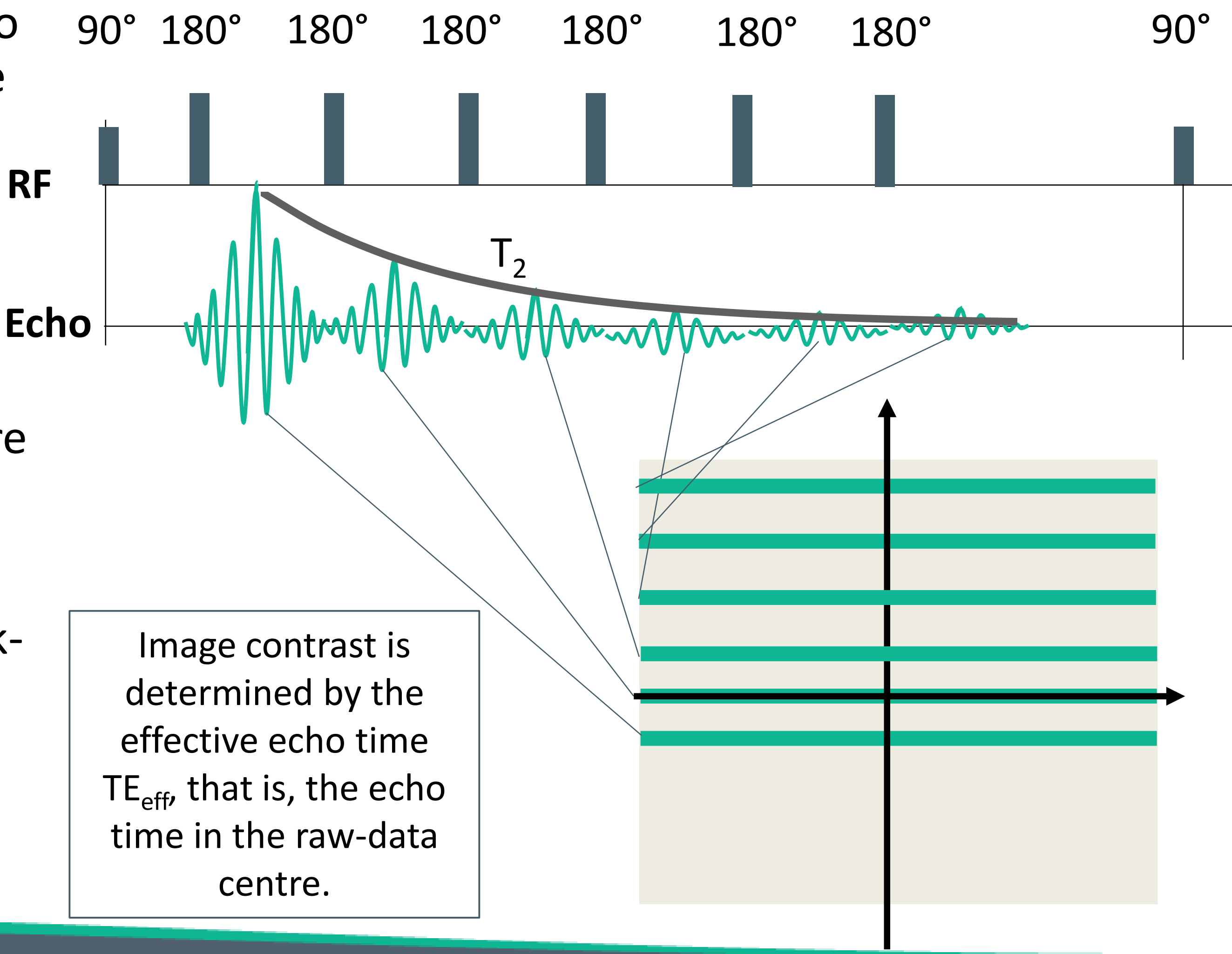

Image contrast is determined by the effective echo time TE_{eff}, that is, the echo time in the raw-data centre.

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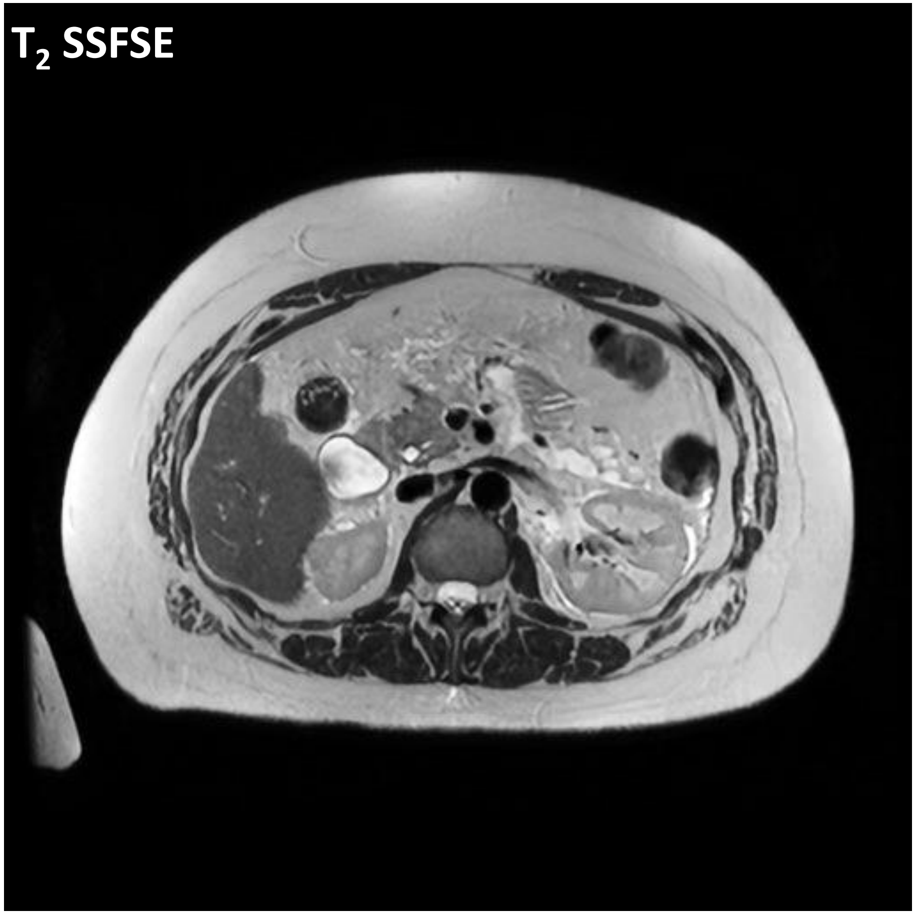
Partial k-space (Single shot)

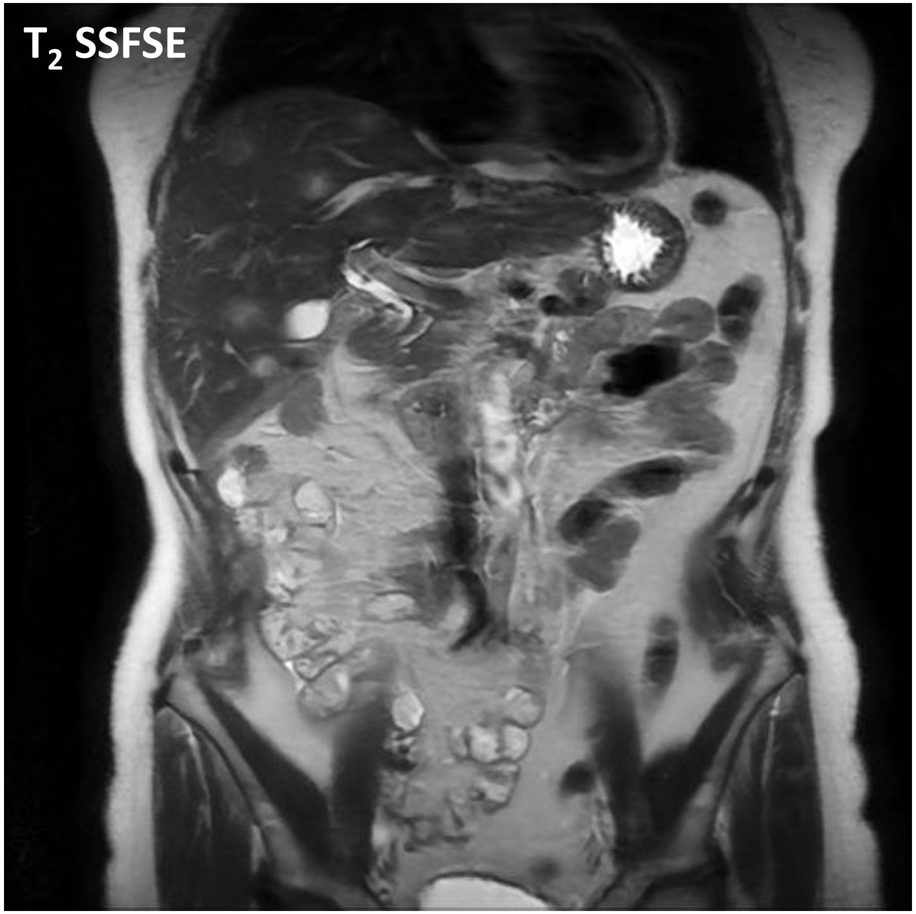
- Images are highly T_2 weighted as majority of k-space lines are filled with long TE echoes.
- Duration = TE * N_{PE}
- Well adapted to imaging non-circulating liquid structures appearing as highly T_2 weighted signal: Cholangio MRI (gallbladder, biliary system and pancreas: MRCP); Uro-MRI

k-space trajectory	Advantages	Disadvantages
Cartesian	Simple to acquire. Minimal distortion artefacts. Works with parallel imaging	Prone to ghosting in PE direction. Requires complete filling of k-space. Image contrast generated ½ way through acquisition.
Partial Fourier (phase-conjugate symmetry)	Reduced acquisition time Preservation of spatial resolution	Reduced SNR. Square root % of data acquired. E.g. ½ data has 70% SNR compared to full k-space.

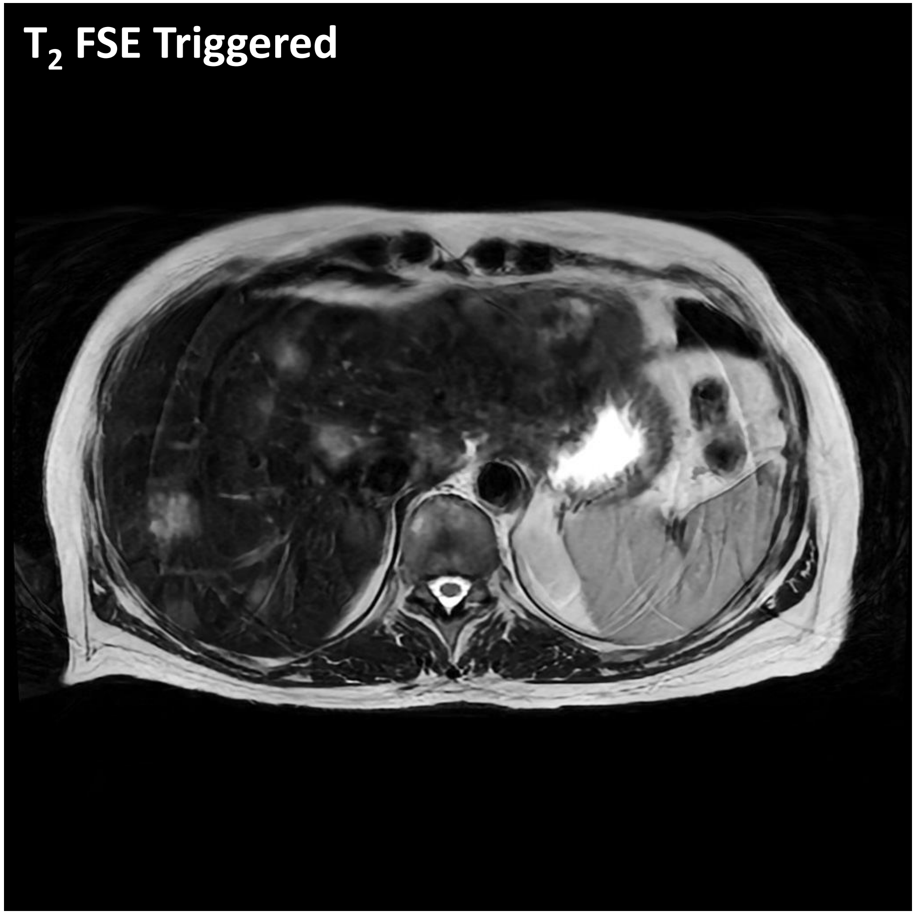
Single shot versus multi shot



Single shot versus multi shot



Single shot versus multi shot



Single shot versus multi shot

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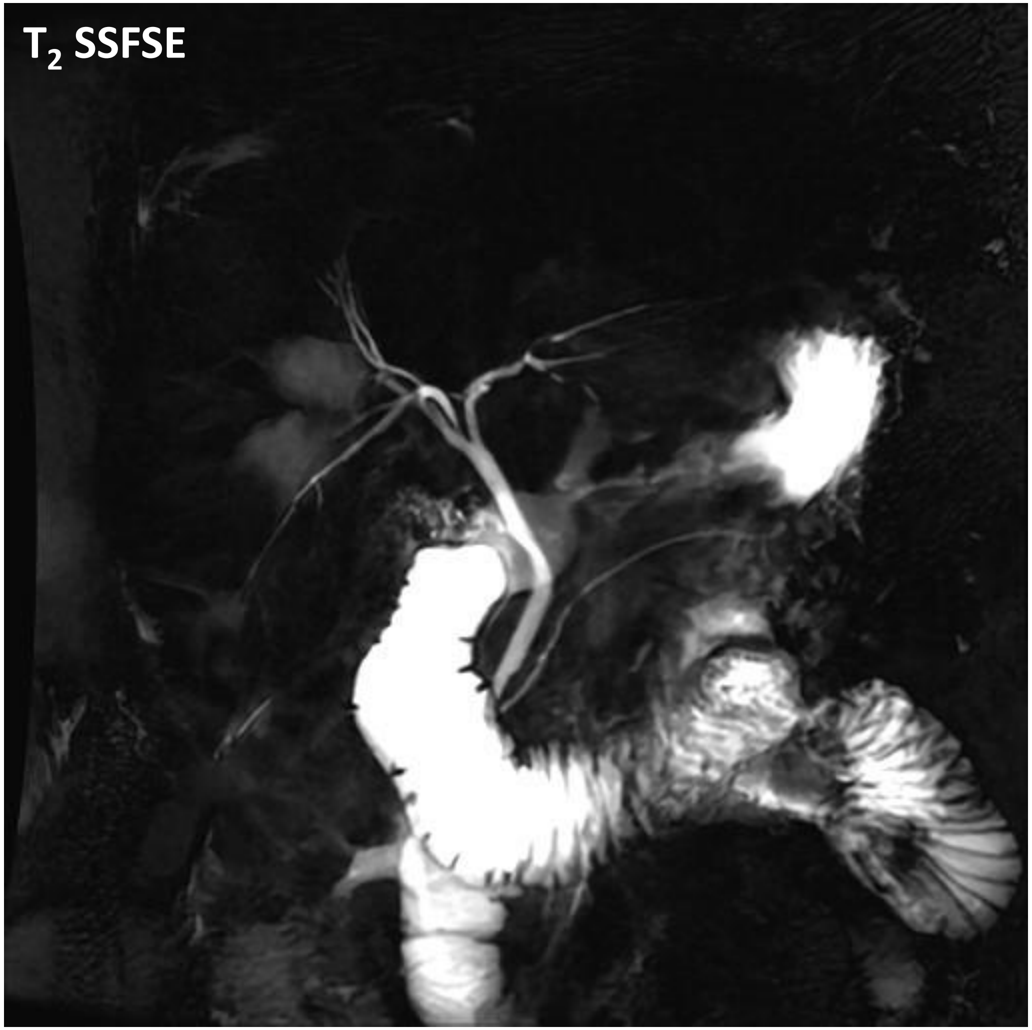
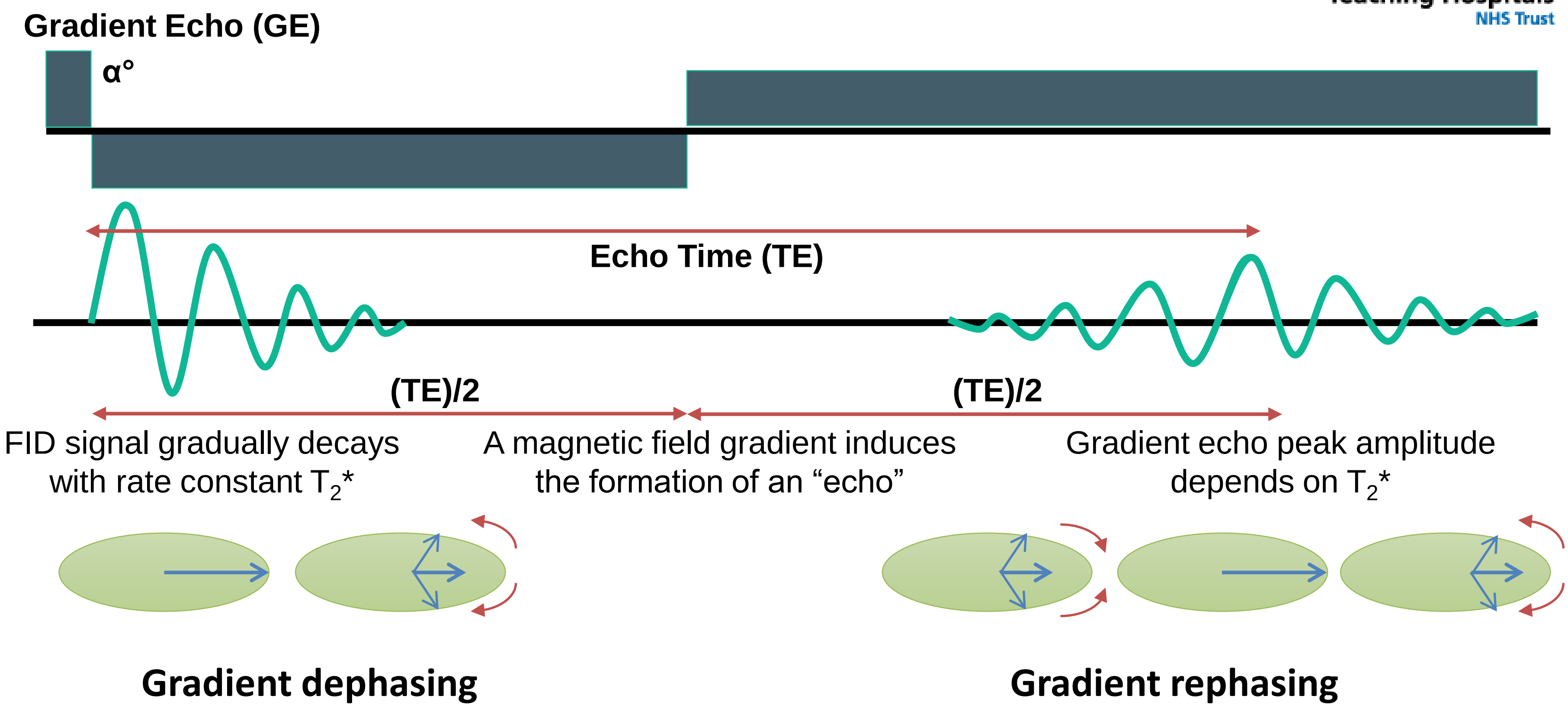


Magnetic resonance cholangiopancreatography (MRCP)

Gradient Echo (GE) Pulse Sequences



- Frequency encoding gradient is initially applied negatively to <u>speed up the dephasing of the FID</u>. Then its polarity is reversed producing rephasing of the gradient echo

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Steady State Gradient Echo

- Using a RF pulse, longitudinal magnetisation (M_z) is tilted into the transverse plane (M_{xy}). However, when TR is short, there is no time for the transverse (M_{xy}) magnetisation to decay before the pulse sequence is repeated

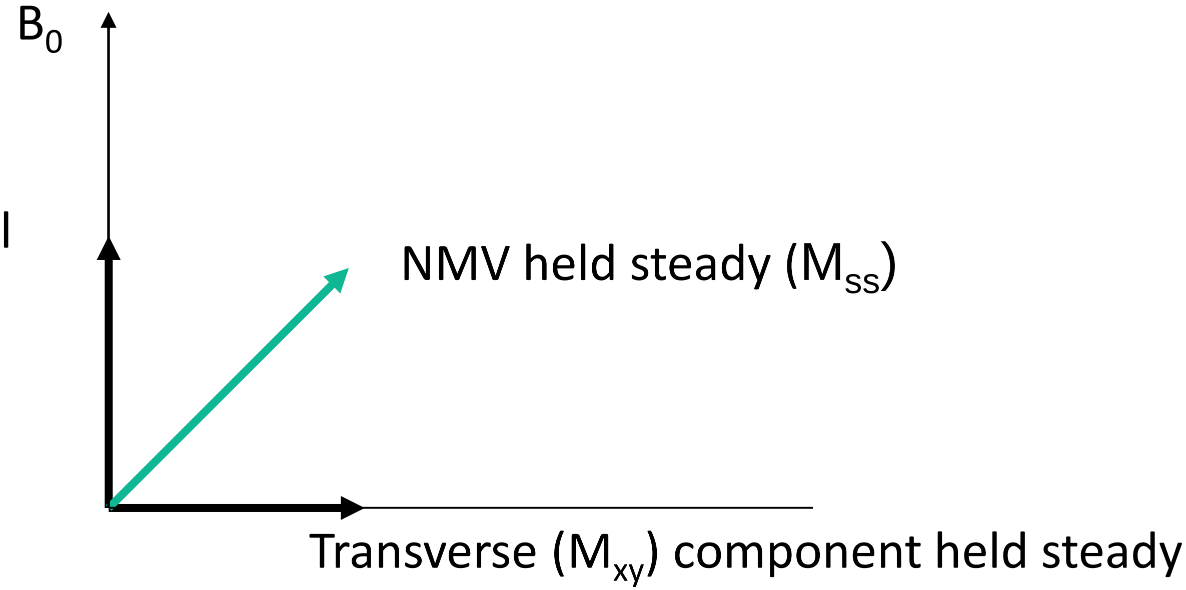
- Therefore there is coexistence of both longitudinal (M_z) and transverse (M_{xy}) magnetization

- *The net magnetisation vector (NMV) is the sum of M_z and M_{xy}*

- "Steady State" is where the TR is shorter than the T_1 and T_2 relaxation times of the tissue being imaged

- Flip angle and TR can maintain the "steady state" which holds the longitudinal and transverse components stationary during data acquisition

Steady State Gradient Echo



- When steady state is maintained, the transverse component does not have time to decay during pulse sequence
- This transverse magnetisation, produced as a result of previous excitations is called the residual transverse magnetisation (RTM)

M_{ss} = steady state magnetisation

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Steady State Gradient Echo

- The residual transverse magnetization (RTM) affects image contrast as it results in tissues with long T_2 times, appearing bright on the image
- Most gradient echo sequences use “steady state” approach since shorter scan times can be achieved (shorter TR)
- Gradient echo sequences are classified according to whether the residual transverse magnetisation is in phase (coherent) or out of phase (incoherent)

Steady State Gradient Echo

Two main classes of GE sequence depending on how residual transverse magnetisation (RTM) is managed:

- **Coherent or Rewound GE** (GRE/FISP/FFE)
  - M_{ss} conserved. Rewinder gradient applied to PE direction at end of cycle to reverse effects
  - By maintaining residual transverse magnetisation excitation pulses will produce new echoes (Hahn echoes, stimulated echoes) in addition to the GE
- **Spoiled or incoherent GE** (SPGR/FLASH/T_1FFE/RAGE)
  - M_{ss} eliminated by use of RF / gradient spoiling
- ***M_{ss} = steady state magnetisation***

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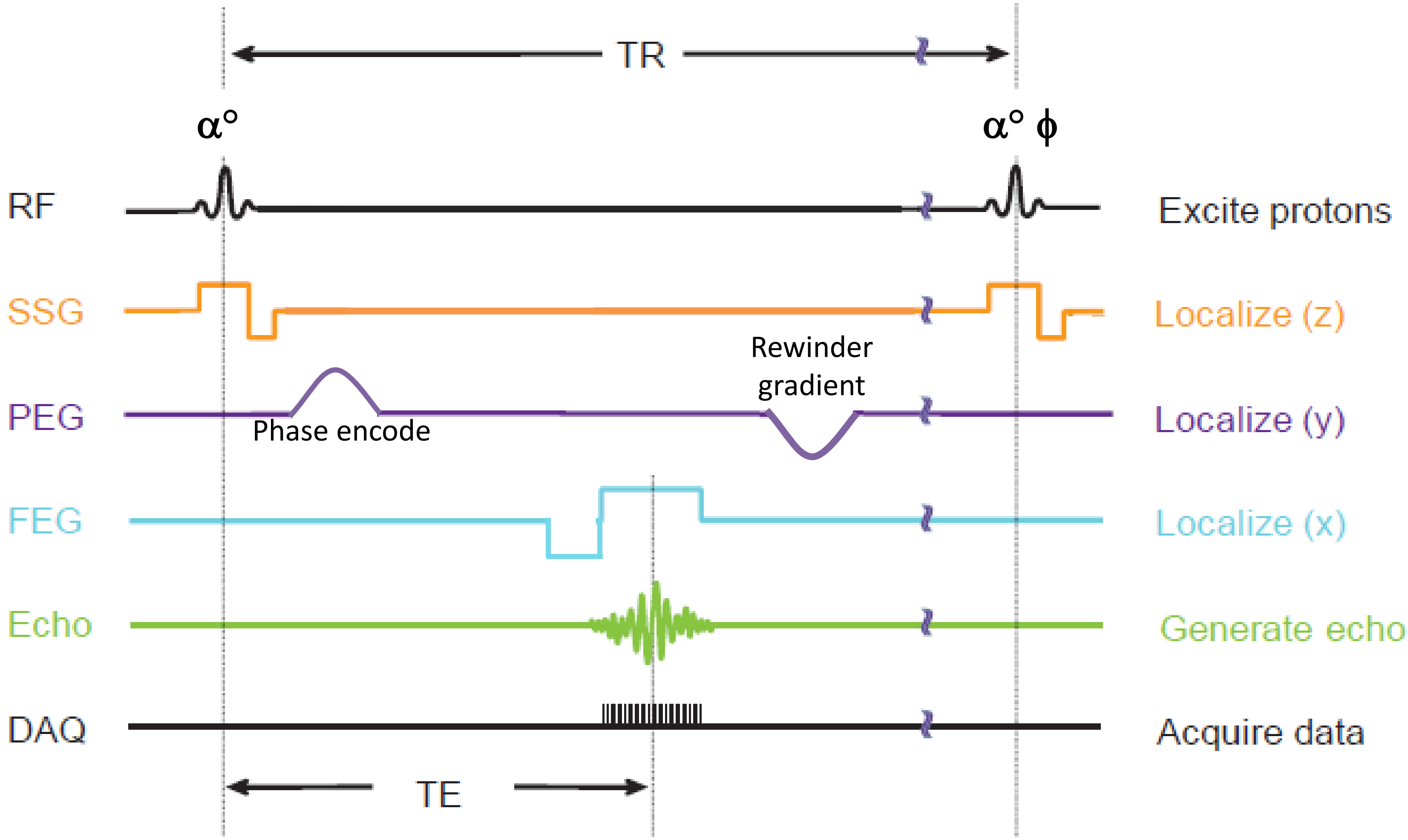
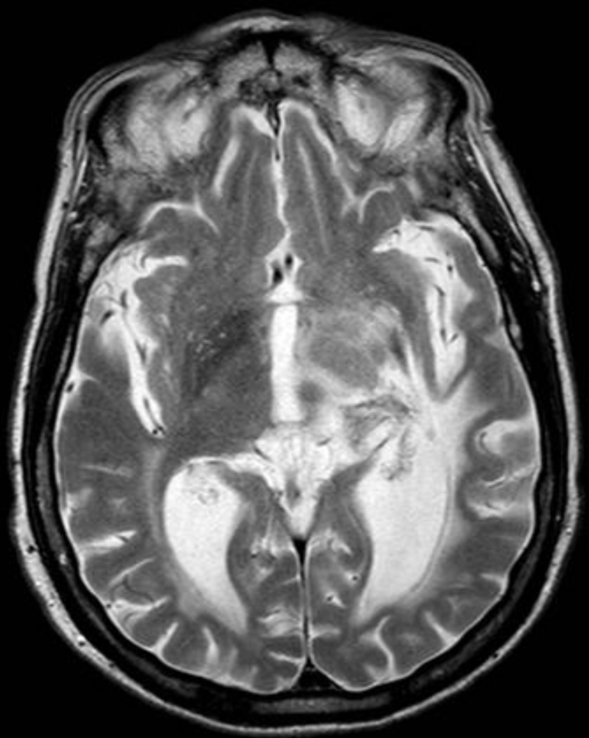
Coherent Gradient Echo (GRASS, FISP, FAST, FFE)

- This type of pulse sequence uses a variable flip angle excitation pulse followed by gradient rephasing, to produce a gradient echo
- Steady state is maintained by selecting TR shorter than T_1 and T_2
- There is therefore RTM left over when the next excitation pulse is applied
- The RTM is kept coherent by a process known as rewinding
- Rewinding is achieved by reversing the slope of the phase encoding gradient after readout
- This results in RTM rephasing, so that it is in phase at the beginning of the next repetition. This allows the RTM to build up so that tissues with a long T_2 time produce a high signal

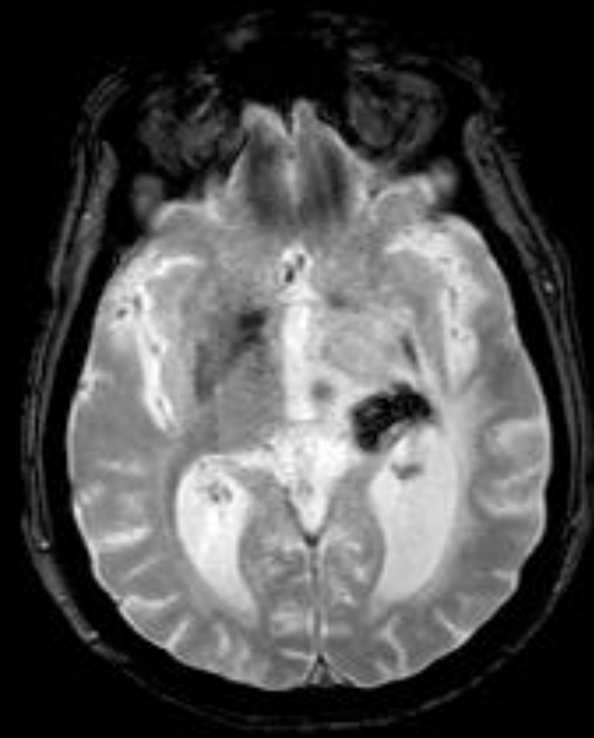
Coherent Gradient Echo Sequence



T_2* Weighted Imaging

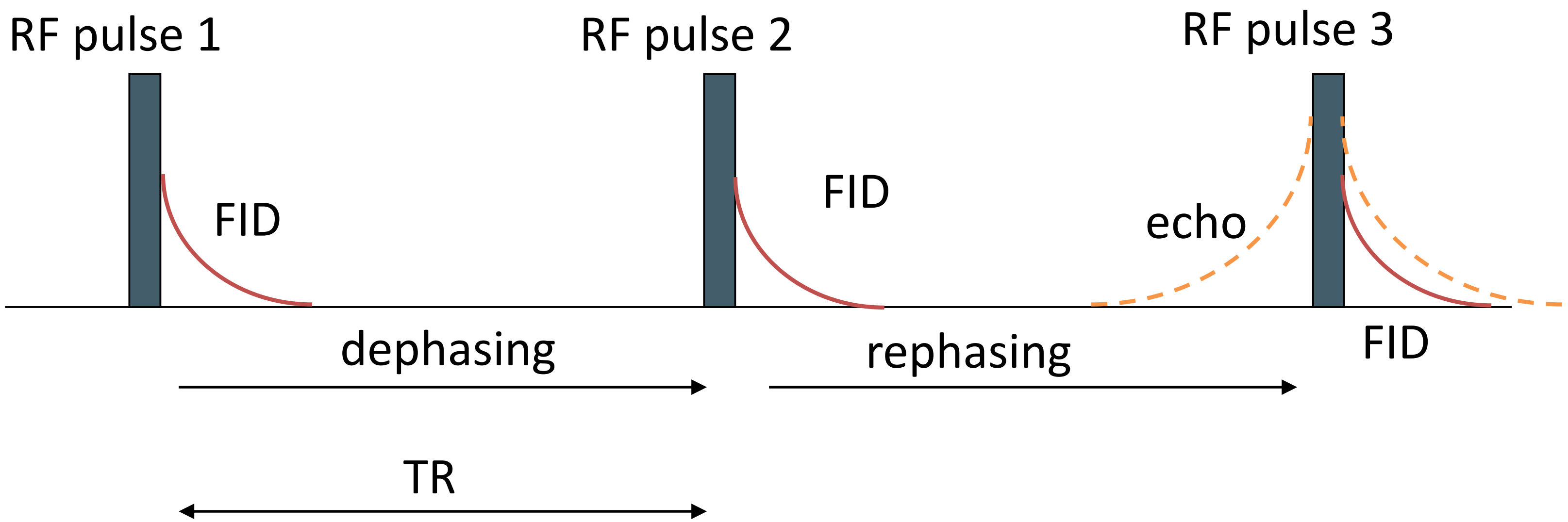


Spin Echo T_2



Gradient Echo T_2*

Hahn / Stimulated echoes

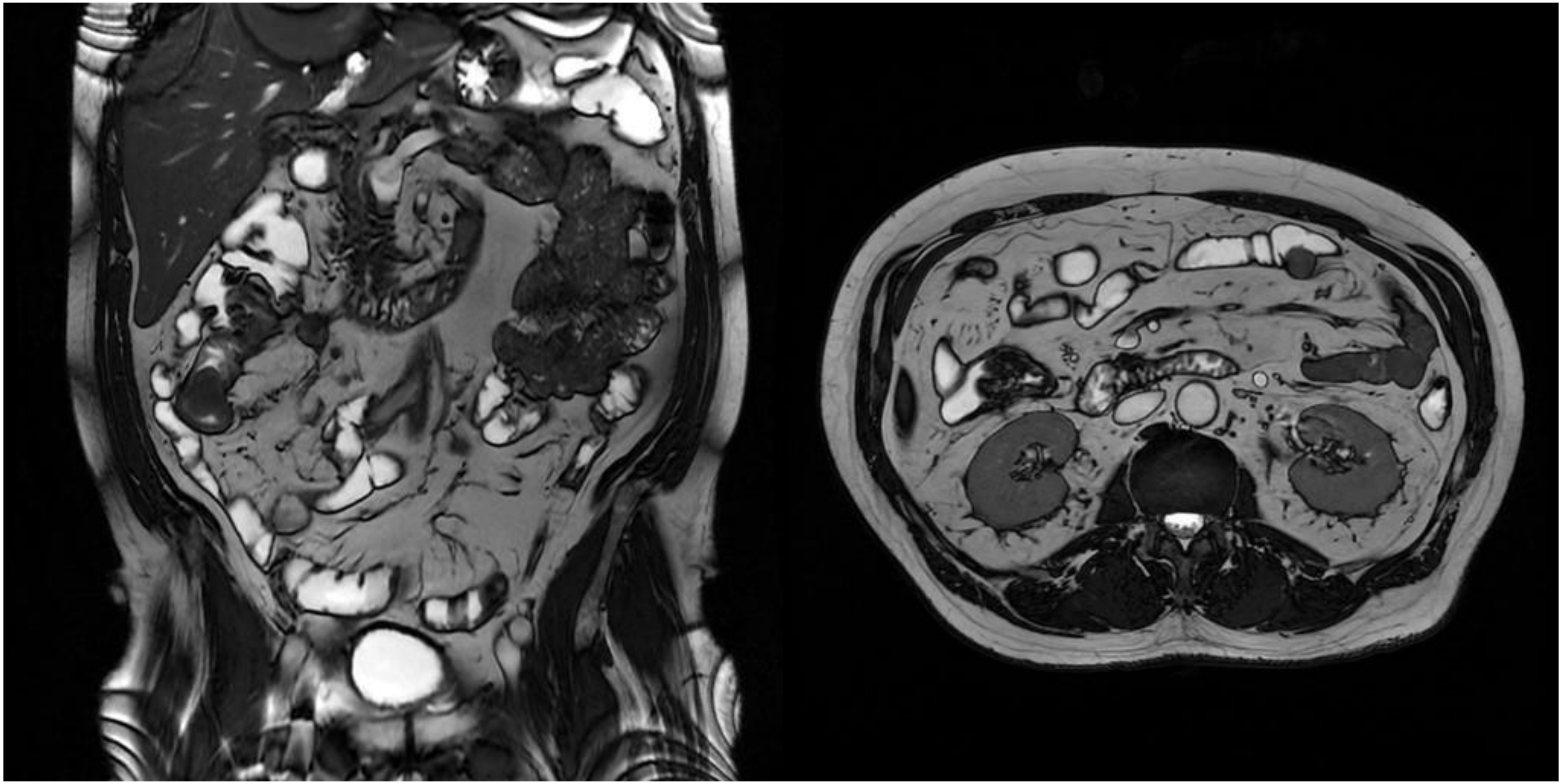


- A FID and an echo occur at each RF pulse
- The echoes produced are sometimes called Hahn or stimulated echoes
- The first RF pulse excites the nuclei regardless of its net amplitude
- The second RF pulse rephases the FID resulting from the first

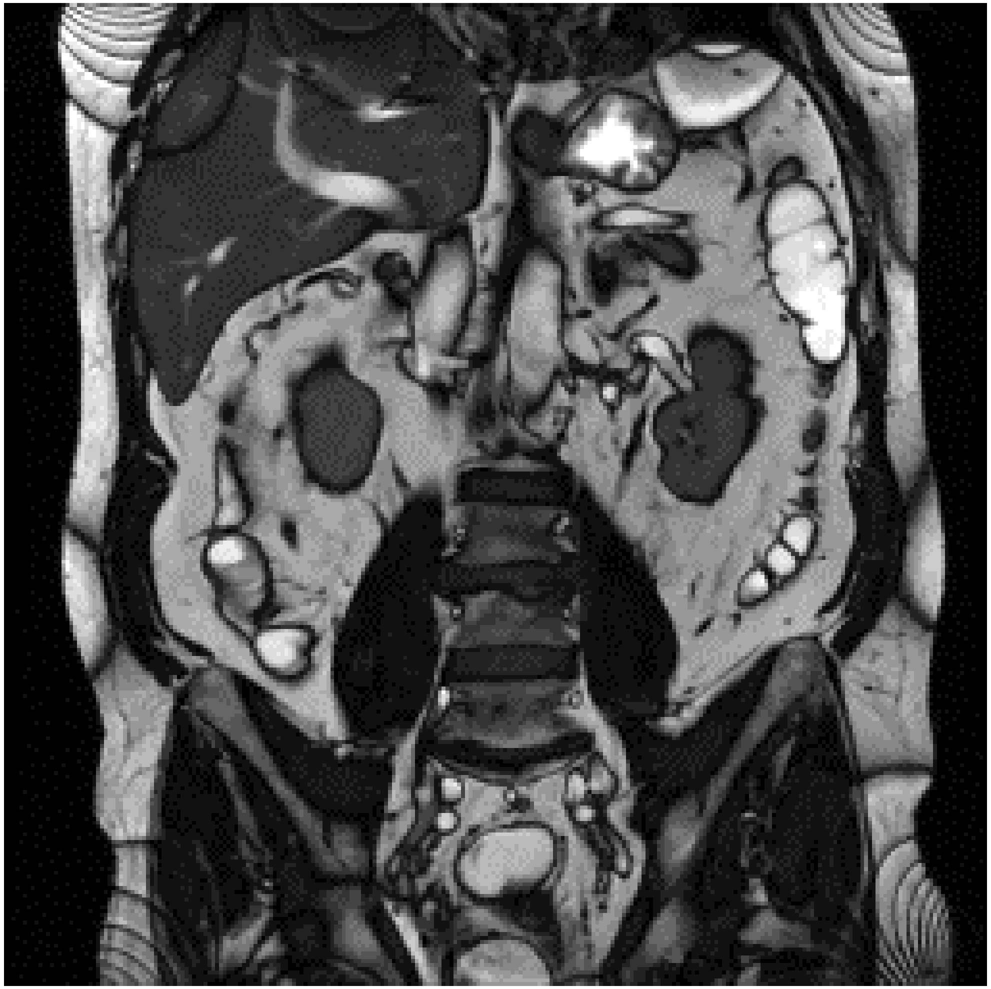
Gradient Echoes: Steady State Free Precession (SSFP/PSIF)

- Hahn echo origin
- Images give a T_2 weighted appearance but with advantage of faster acquisition than spin echo
- Sensitive to motion (still quicker than spin echo)
- Less sensitive to flow
- Relatively low SNR
- Used a lot before 3D T_2 FSE became available
- Mixed T_2/T_1 image contrast

2D-SSFP



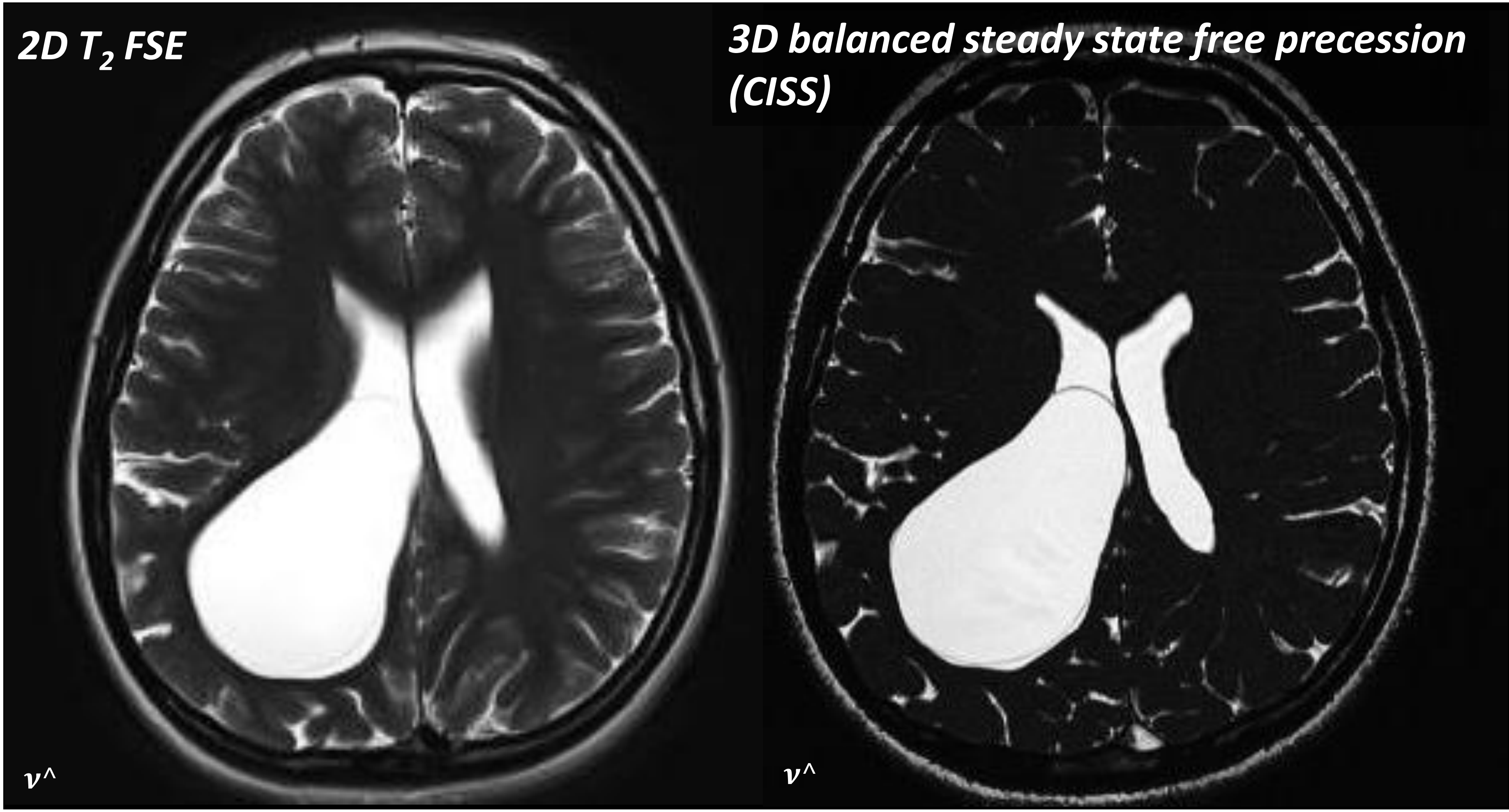
2D CINE-SSFP



2D Gated CINE-SSFP

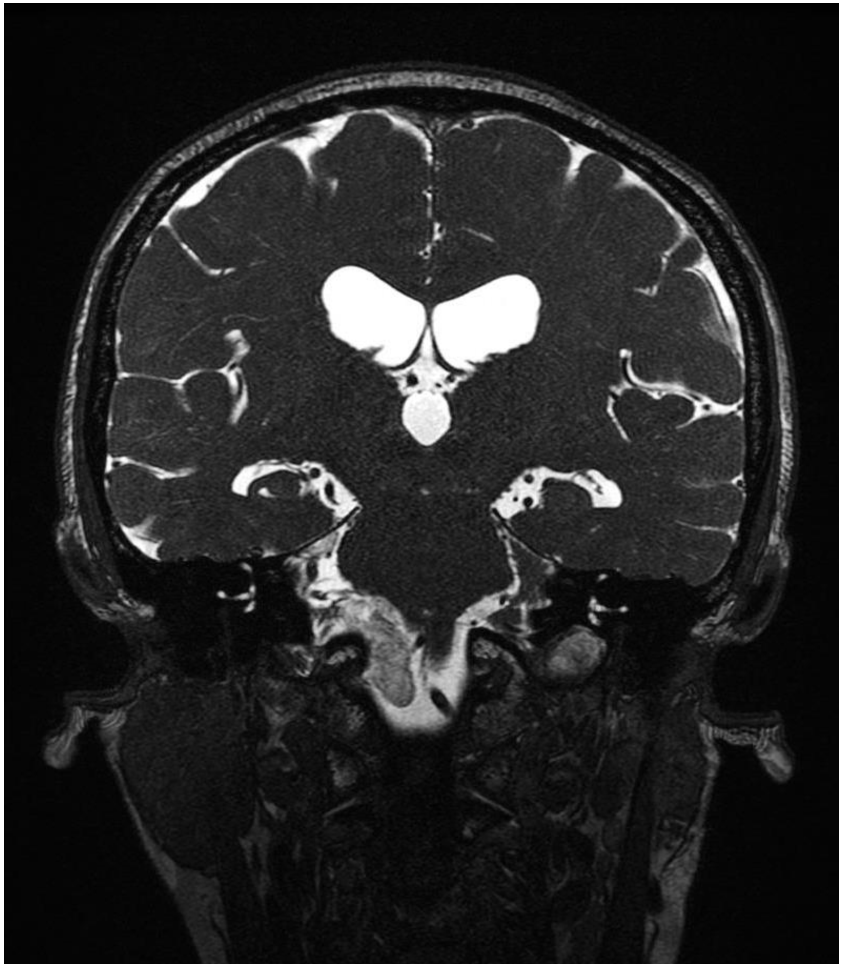
Gradient Echo (GE) Pulse Sequences

TSE vs SSFP



3D SSFP

3D SSFP



Gradient Echo (GE) Pulse Sequences

Spin Echo (SE)

Typical Parameters	T_1	T_2/T_1	T_2	T_2*	P.D.
Flip angle (degrees)	90	N/A	90	N/A	5–30
TR (ms)	400–600	N/A	2000–4000	N/A	2000–4000
TE (ms)	5–30	N/A	60–150	N/A	5–30

Gradient Echo (GRE)

Typical Parameters	T_1	T_2/T_1	T_2	T_2*	P.D.
Flip angle (degrees)	45–90	30–50	5–15	5–15	5–30
TR (ms)	200–400	10–50	200–400	100–300	100–300
TE (ms)	3–15	3–15	30–50	10–20	5–15

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Spoiled Gradient Echo (SPGR/FLASH/T1FFE/RAGE)

- Incoherent gradient echo (gradient spoiled) is a type of sequence that uses continuous shifting of the RF pulse to spoil (destroy) the remaining transverse (M_{xy}) magnetisation

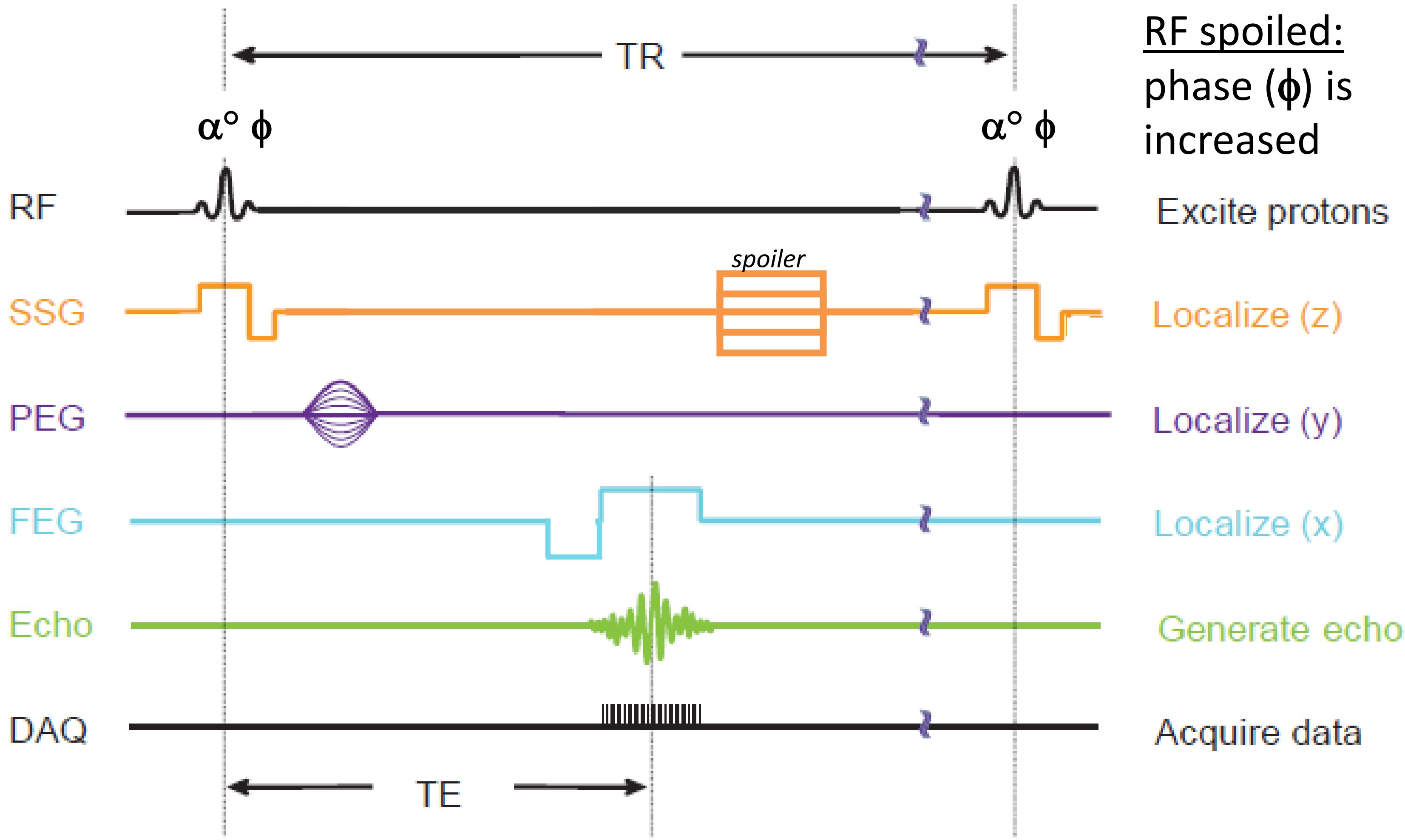
- The transverse (M_{xy}) magnetisation is spoiled by a magnetic field gradient resulting in **more T_1 weighting**

- Gradient spoiling occurs after each echo using strong gradients in the slice-select direction after the frequency encoding and before the next RF pulse

- Because spins in different locations in the magnet thereby experience a variety of magnetic field strengths, they will precess at differing frequencies; as a consequence they will quickly become dephased

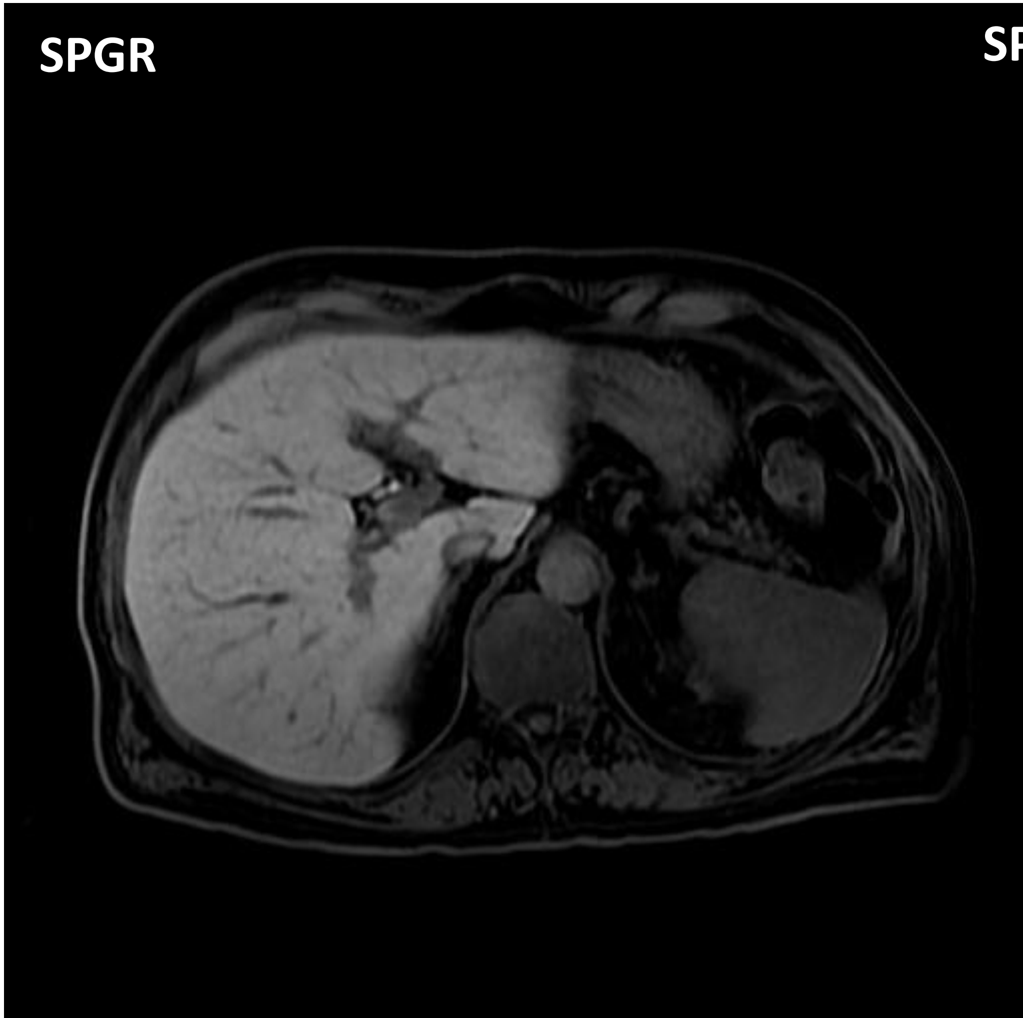
- Generally scan times are quicker and subsequently allow for 3D and/or breath-hold implementations

Spoiled Gradient Echo Sequence

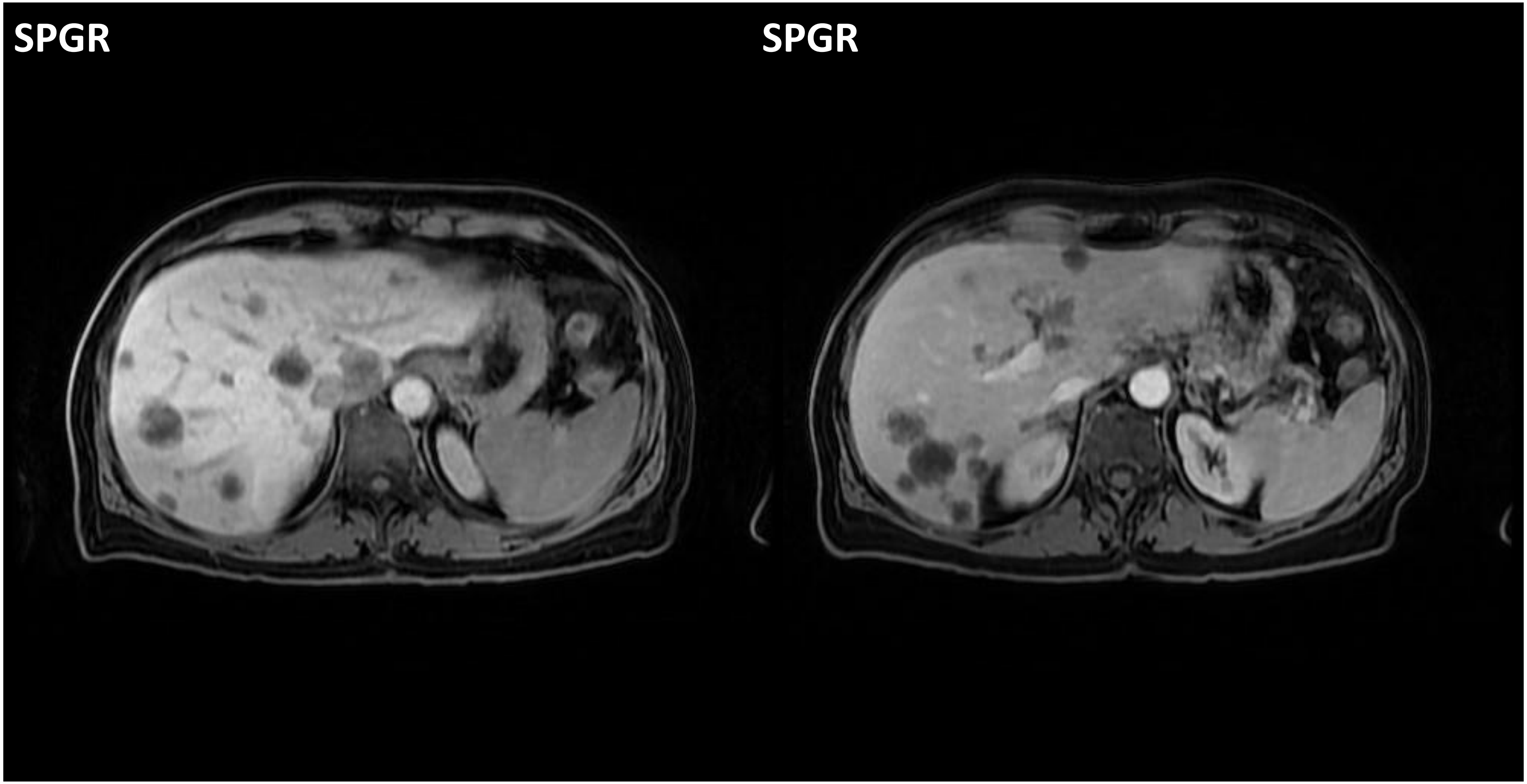


<u>RF spoiled:</u>
phase (ϕ) is increased

Gradient Echo (GE) Pulse Sequences



Gradient Echo (GE) Pulse Sequences



Gradient Echo (GE) Pulse Sequences

BASG	Balanced SARGE (Steady-state Acquisition Rewound Gradient Echo)
BRAVO	Brain Volume imaging
CISS	Constructive Interference in the Steady Steady State
COSMIC	Coherent Oscillatory State Acquisition for Manipulation of Imaging Contrast
DESS	Double Echo Steady State
FAME	Fast Acquisition with Multiphase Elliptical fast gradient echo
FE	Field Echo
FFE	Fast Field Echo
FIESTA	Fast Imaging Employing Steady State Acquisition
FIESTA-C	Fast Imaging Employing Steady State Acquisition - Constructive Interference
FISP	Fast Imaging with Steady Precession
FLASH	Fast Low Angle Shot
GE, GRE	Gradient Echo/ Gradient Recalled Echo
GEIR	Gradient Echo Inversion Recovery
GRASE	Gradient And Spin Echo
GRASS	Gradient Recalled Acquisition in the Steady State
LAVA	Liver Acquisition with Volume Acceleration
MEDIC	Multi-Echo Data Image Combination
MENSA	Multi-Echo iN Steady-state Acquisition
MERGE	Multiple Echo Recombined Gradient Echo
M-FFE	Multiple Fast Field Echo
MP-RAGE	Magnetization Prepared Rapid Gradient Echo
PBSG	Phase Balanced SARGE
PSIF	Time-reversed FISP
RGE	Rapid Gradient Echo
RSSG	RF-Spoiled SARGE
SARGE (SG)	Steady-state Acquisition Rewound Gradient Echo
SSFP	Turbo Gradient Spin Echo
TGSE	Steady State Free Precession
THRIVE	T1-weighted High Resolution Isotropic Volume Examination
TIGRE	T1-weighted Gradient Echo
TRSG	Time-Reversed SARGE
VIBE	Volumetric Interpolated Breath-hold Examination

7.3 Basic MRI sequences & common variants

- Spoiled gradient echo, spin echo
  - *SE is simple 90°–180° pulse sequence. Gradient echo has a flip angle α and magnetic field gradients to generate echo. GE sequences are quicker than SE.*

- Multiple echo variants (TSE/FSE, EPI)
  - *FSE/TSE uses dead time in TR to acquire additional lines of k-space using additional 180° pulses. 90°–180°–180°–180°. EPI fills all of k-space in a single go.*

- Single shot versus multi shot
  - *Single shot - fill all of required k-space in a single acquisition. T_2 weighted.*

- Pulse sequence diagrams *(interspersed throughout lecture)*

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7.3 Basic MRI sequences & common variants

- Basics of steady-state sequences
    - *Two main types of GE sequence: Coherent or Rewound GE (GRE/FISP/FFE) and spoiled or incoherent GE (SPGR/FLASH/T1FFE/RAGE). Depend on how residual transverse magnetisation (RTM) is managed. Spoiled gradient echo used for rapid T_1 weighted imaging. Rewound GE used for T_2**

Questions

In gradient echo sequences use in magnetic resonance imaging (MRI)

A. a gradient replaces the 90 degree rephasing pulse used in spin echo imaging

B. Higher flip angles (30-50°) provide more T_1 weighting

C. TR is characteristically shorter than spin echo sequences

D. Resultant images are affected by T_2* information

Questions

In magnetic resonance imaging the following are true:

A. Within a single TR, following collection of PD-weighted data the echo can be re-sampled after another TE to provide T_2-weighted data

B. Fast (turbo) spin-echo (FSE) techniques use several refocusing 180° RF pulses to rephase and produce extra echoes at different phase gradients for each excitation