Lecture 2011-03-15

- Multislice acquisition (MS, 3D)
- GRE: Simple Steady-State model
- RF pulse train (multiple echoes)
  - Eight-Ball Echo
  - Stimulated Echo
  - Multiples echoes
- GRE FID and ECHO components
- Mathematical Model of GRE
- GRE contrast properties and techniques

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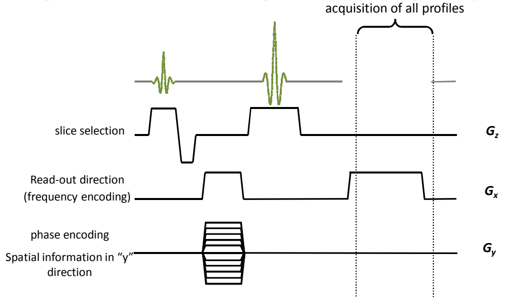
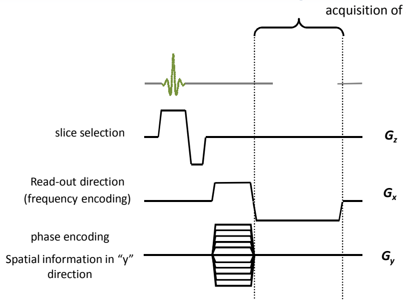
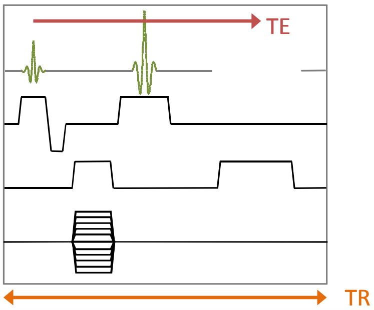
Spin Echo – k-space sampling



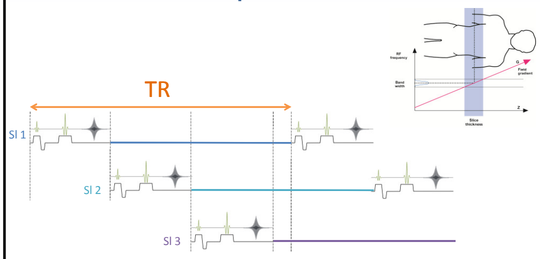
Gradient Echo – k-space sampling



TE and TR



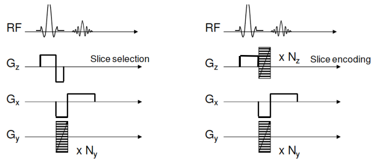
Multislice acquisition



Slice order: "Interleaved"

3D acquisition

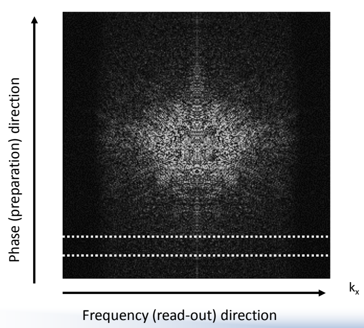
Same principle of phase encoding is applied to the slice direction (refocusing lobe of the slice selection)



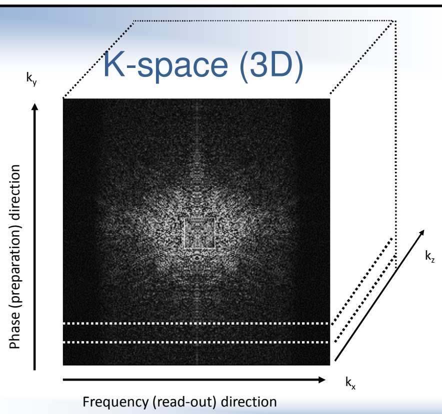
$$\rho(x,y,z) = \frac{1}{2\pi}\int_{k_x}\int_{k_y}\int_{k_z} M_T(k_x,k_y)\exp\big(j(k_x x + k_y y + k_z z)\big)dk_x dk_y dk_z$$

$$\delta z = \frac{2\pi}{\gamma G_{z\_\max} T_z}$$

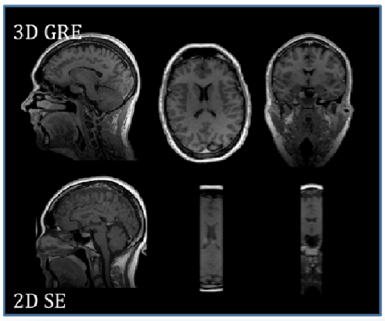
K-space (2D)



K-space (3D)



2D versus 3D acquisition



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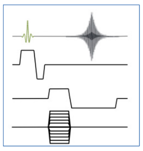
GRE properties

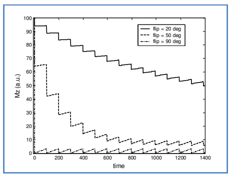
- Requires less time than SE to form an Echo (i.e. TE shorter for 1 k-space profile acquisition)
- RF pulse angle α ≤ 90°
- *SI = f(T1, T2, T2*)*



GRE: Simple steady-state model

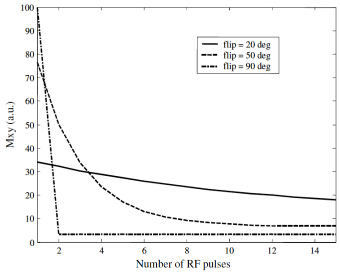
TR short, T2* << TR, pulse angle α

Repeated RF pulses → dynamic equilibrium called "Steady State"



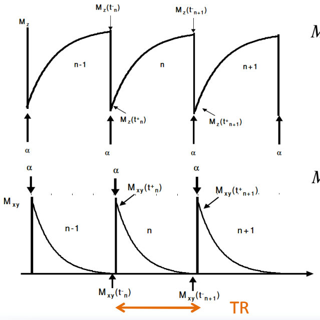
Steady-state reached at the 2nd pulse if α = 90deg.

GRE steady-state



Note that the highest signal is obtained for α = 20°

GRE: Simple *steady-state* model



$$M_Z\left(t_n^-\right)=M_Z\left(t_{n+1}^-\right)$$

$$M\left(t_{n+1}^+\right)=R_\alpha M\left(t_n^+\right)$$

Simple mathematical model

'Steady state' condition:

$$M_{y'}\left(t_{n+1}^-\right)=M_{y'}\left(t_n^-\right)$$

$$M_z\left(t_{n+1}^-\right)=M_z\left(t_n^+\right)E_1+M_0\left(1-E_1\right)$$ E_1=exp(-t/T_1) (See Eq. 2-8 in compendium)

Looking at the rotation by the α RF pulse along x' axis, we get:

$$\begin{bmatrix} M_{y'}(t_{n+1}^+) \\ M_{z'}(t_{n+1}^+) \end{bmatrix} = R_\alpha \begin{bmatrix} M_{y'}(t_{n+1}^-) \\ M_{z'}(t_{n+1}^-) \end{bmatrix} \qquad R_\alpha = \begin{bmatrix} \cos(\alpha) & \sin(\alpha) \\ -\sin(\alpha) & \cos(\alpha) \end{bmatrix}$$

We assume that $M_y\left(t_n^-\right)=0$ which is true if T2*<<TR

$$\begin{bmatrix} M_{y'}(t_{n+1}^+) \\ M_{z'}(t_{n+1}^+) \end{bmatrix} = \begin{bmatrix} \sin(\alpha) \\ \cos(\alpha) \end{bmatrix} M_{z'}(t_{n+1}^-)$$

Simple mathematical model (cont.)

We have now the following equations

$$\begin{vmatrix} M_y\left(t_{n+1}^+\right) \\ M_z\left(t_{n+1}^+\right) \end{vmatrix} = \begin{vmatrix} \sin\alpha \\ \cos\alpha \end{vmatrix} M_z\left(t_{n+1}^-\right) \quad \text{and} \quad M_Z\left(t_{n+1}^-\right)=M_Z\left(t_n^+\right)E_1+M_0\left(1-E_1\right)$$

At equilibrium (steady-state): $M_z\left(t_n^+\right)=M_z\left(t_{n+1}^+\right)=\cos\alpha\cdot M_z\left(t_{n+1}^-\right)$

and writing $M_z\left(t_{n+1}^-\right)=M_z$

Which then gives $M_z=\dfrac{M_0\left(1-E_1\right)}{\left(1-\cos\alpha E_1\right)}$

Applying an RF pulse of angle α $\boxed{M_y\left(t_{n+1}^+\right)=\dfrac{\sin\alpha M_0\left(1-E_1\right)}{\left(1-\cos\alpha E_1\right)}}$ Eq. 4-8 (Compendium)

Moreover, the net magnetization of GRE readout is modulated by exp(-TE/T2*)

Simple mathematical model (cont.)

Finding the maximum of this function: $\dfrac{dM_y\left(t_{n+1}^+\right)}{d\alpha}=0$

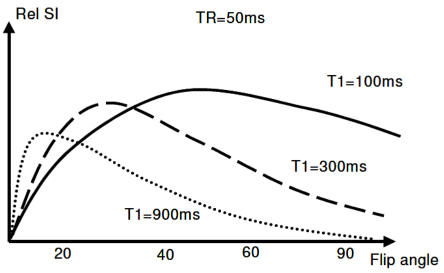
$$\frac{dM_y\left(t_{n+1}^+\right)}{d\alpha}=\frac{M_0\left(\left(1-E_1\right)\left(\cos\alpha-E_1\right)\right.}{\left(1-\cos\alpha E_1\right)^2}$$

$\boxed{\cos\alpha_e=E_1=\exp\left(TR/T1\right)}$ α_e is the Ernst angle

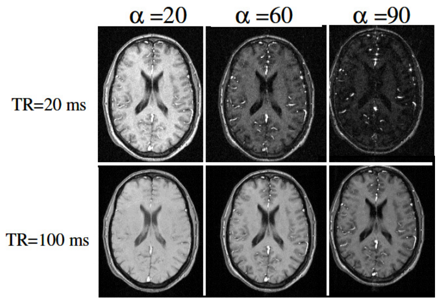
contrast weighting in a spoiled GRE sequence
- T1-weighted
- T2*-weighted (weighting depends on the TR/T1 at given α)

Short TR (TR/T1 << 1)	Large α	T1 weighting
Long TR (TR/T1 ≈1)	Low α	T2* weighting

Steady-State



Steady-State



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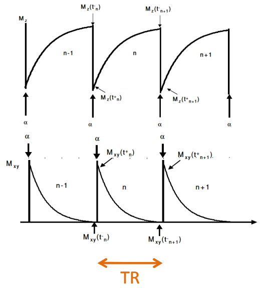
GRE: General behavior



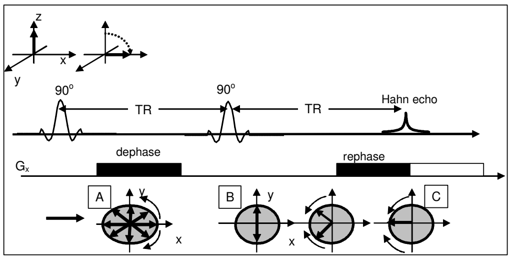
Since TR is short $M_y(t_n^-) \neq 0$

We have then:

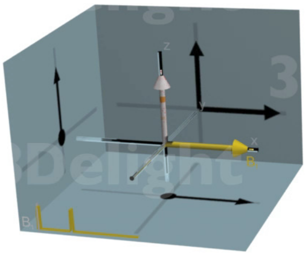
- **Longitudinal** component
- **Transverse** component

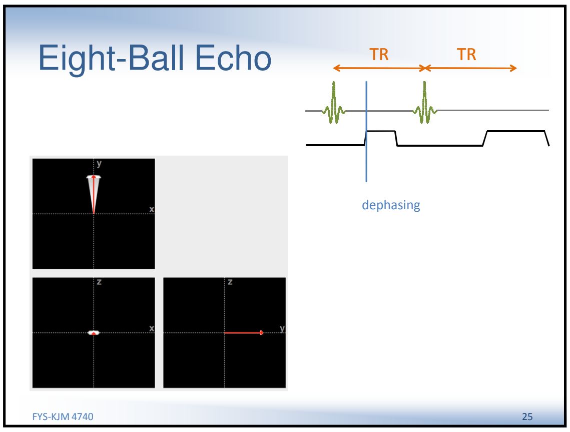
with multiple RF pulses repetition

Effect of repeated RF excitations: **eight-ball echo**



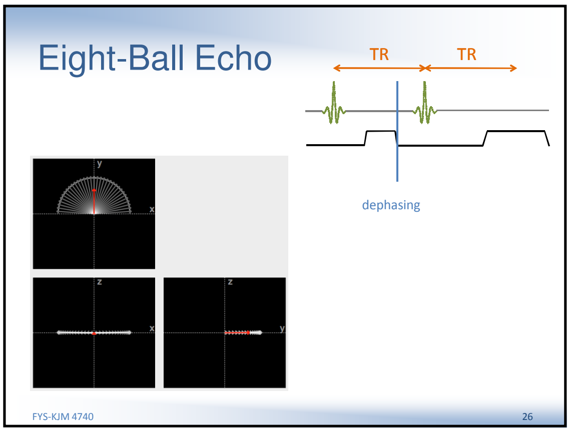
Eight-Ball Echo





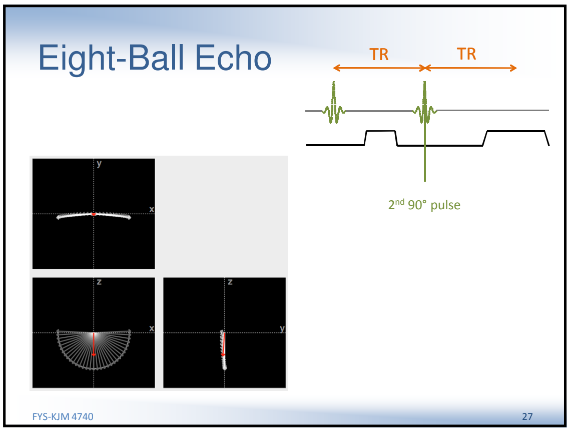
Eight-Ball Echo

dephasing



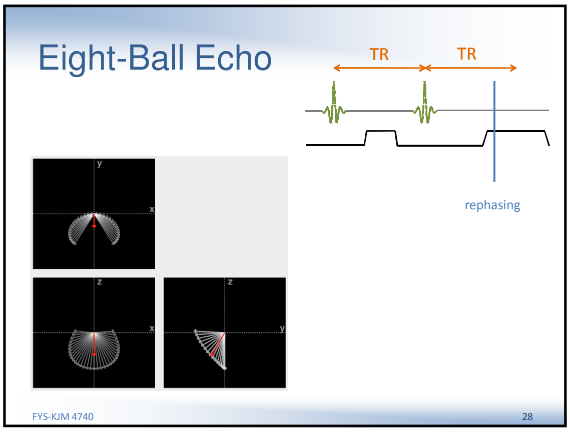
Eight-Ball Echo

dephasing



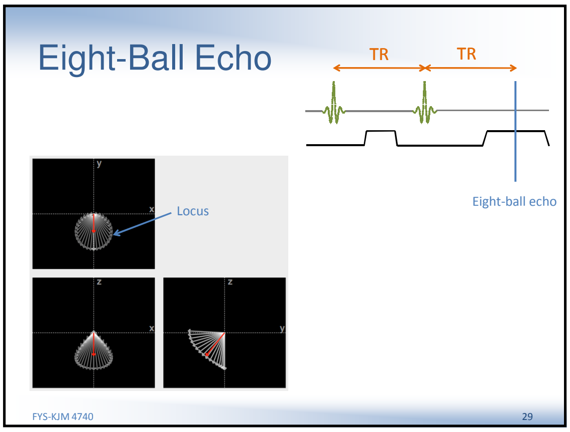
Eight-Ball Echo

2nd 90° pulse



Eight-Ball Echo

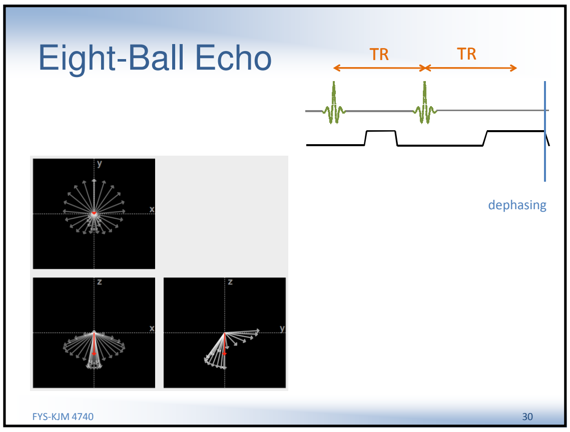
rephasing



Eight-Ball Echo

Locus

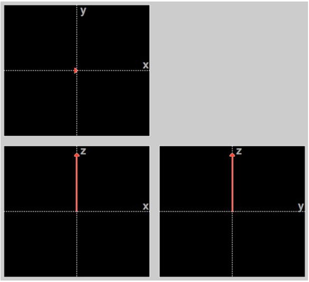
Eight-ball echo



Eight-Ball Echo

dephasing

Eight-Ball Echo

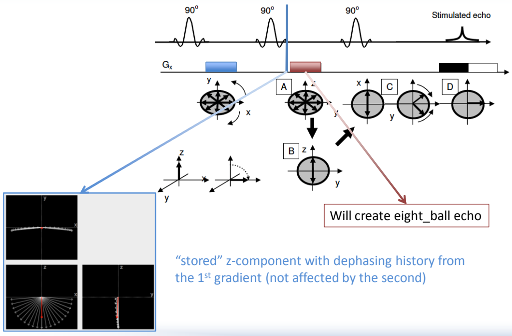


Stimulated Echo

- two 90° pulses → eight-ball echo
- The 2nd 90°pulse flipped x' component of the transverse magnetization along z-axis (this z-magnetization carries magnetization history from before 2nd RF pulse, i.e. gradient dephasing as function of position)*
- 3rd 90° pulse then flips back this longitudinal component into the transverse plane. The 3rd Gx gradient will refocus these components previously stored along z-axis

* The longitudinal component is not affected by the second gradient after RF pulse

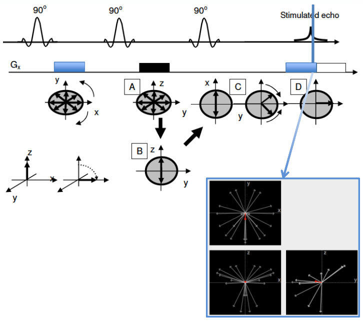
Stimulated Echo



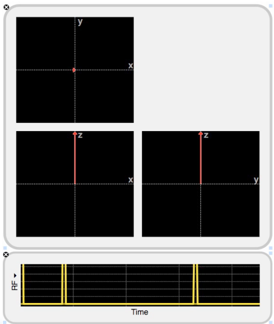
Will create eight_ball echo

"stored" z-component with dephasing history from the 1st gradient (not affected by the second)

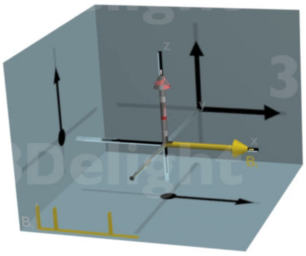
Stimulated Echo



Stimulated Echo (simulation)



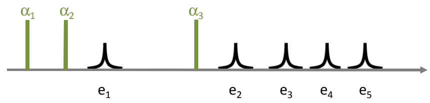
Stimulated Echo (simulation)



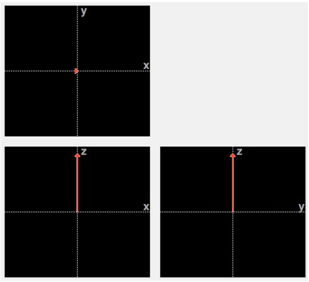
Multiple Echoes

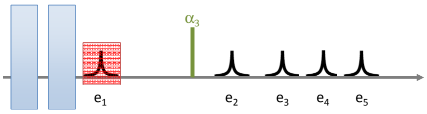
- From Steady-State simplified model / Ernst angle → $\alpha < 90°$
- → Both transverse and longitudinal components are present at any time
- → **RF pulse train generates multiple echoes**

3 RF-pulses gives a total of 5 echoes

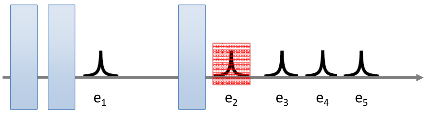


3 plans projection of 3 RF pulses effect

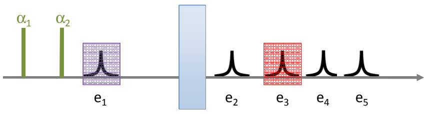




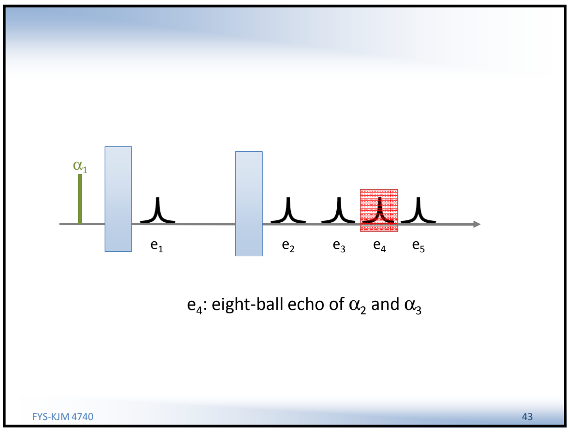
e_1: eight-ball echo of α_1 and α_2



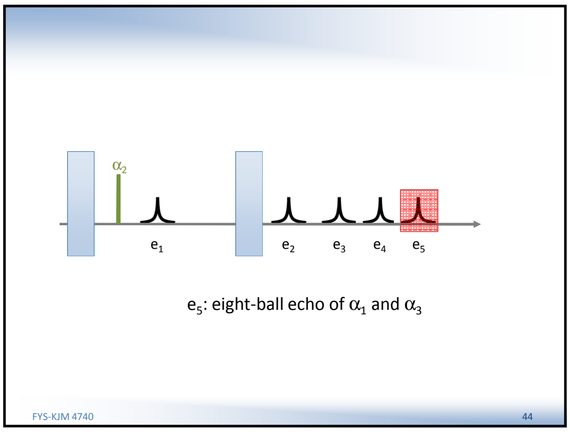
e_2: Stimulated echo of α_1,α_2 and α_3



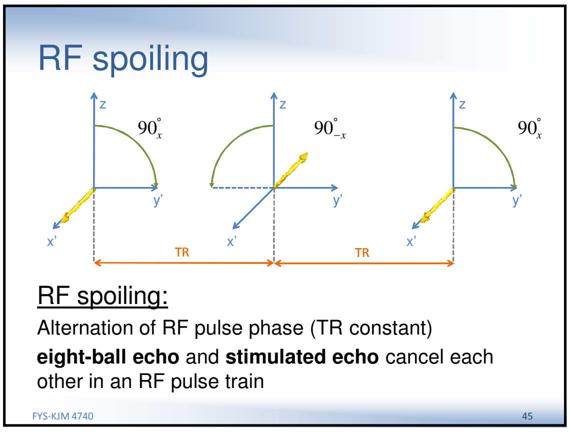
e_3: refocused e_1 by α_3



e_4: eight-ball echo of α_2 and α_3



e_5: eight-ball echo of α_1 and α_3

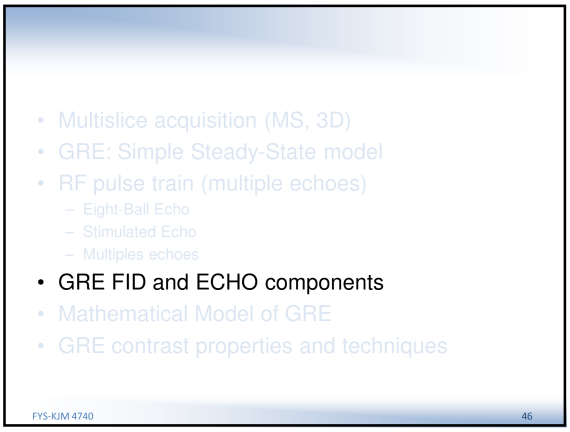


RF spoiling

RF spoiling:

Alternation of RF pulse phase (TR constant)

eight-ball echo and **stimulated echo** cancel each other in an RF pulse train



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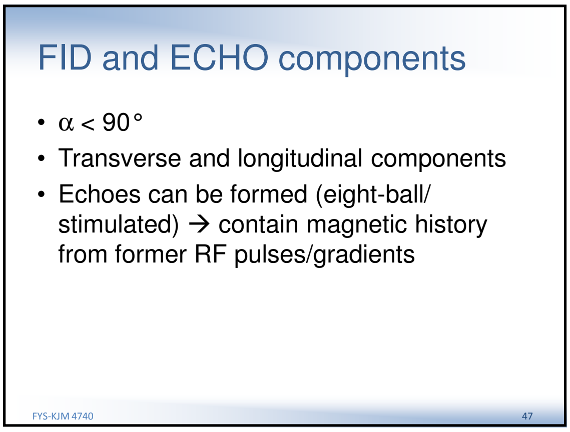
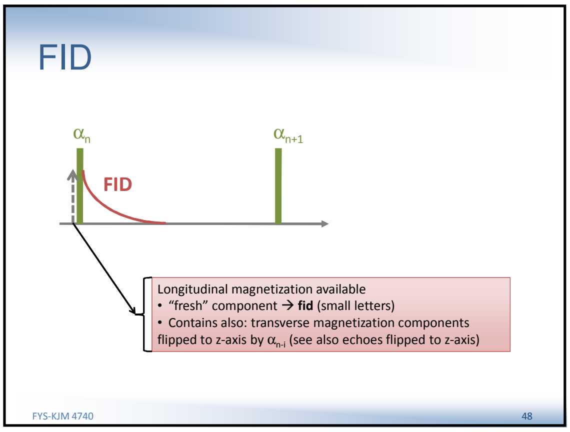


FID and ECHO components

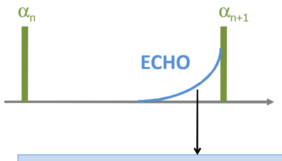
- $\alpha < 90°$
- Transverse and longitudinal components
- Echoes can be formed (eight-ball/ stimulated) → contain magnetic history from former RF pulses/gradients



FID

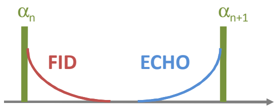
Longitudinal magnetization available
- "fresh" component → **fid** (small letters)
- Contains also: transverse magnetization components flipped to z-axis by α_{n-i} (see also echoes flipped to z-axis)

ECHO



Available transverse component preceding an RF pulse
- Refocused echoes *(position dependent history / gradients)*
- These echoes are partially rotated out of the transverse plane ($\alpha < 90°$) and a part remains in the transverse plane after the RF Pulse α_{n+1}.

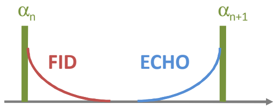
FID & ECHO



FID is mainly T1 weighted (based on available longitudinal magnetization before the RF pulse)

ECHO is mainly T2 weighted (persistence of the transverse components that form the echoes (e.g. eight-ball etc.)

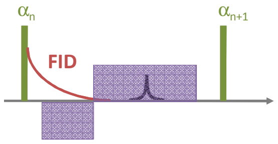
FID & ECHO



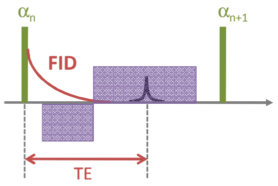
Now considering the readout gradients in this figure:

Both **FID** and **ECHO** can give a gradient echo (signal that will be encoded into k-space to form the GRE image)

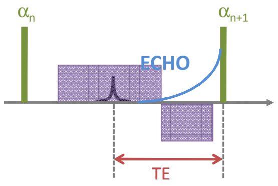
FID & ECHO



FID & ECHO



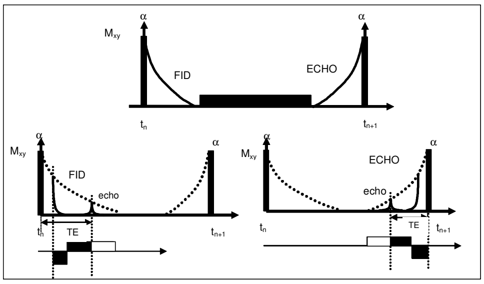
FID & ECHO



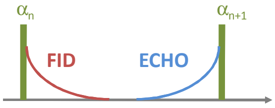
Imaging Echo (from ECHO) appears when $\int G(t)dt = 0$ between TE and TR.

Echo appears at the next a pulse but is represented normally in apparent "reversed" time

Both FID and ECHO signals are used in Imaging



FID & ECHO



FID and ECHO properties:

FID carries partially the spatial info contains in the ECHO component which is flipped to the x-y plane by the α_n pulse

It can be shown that ECHO can add parallel to the FID of anti-parallel depending on the previously acquired phase angle (i.e. position) → Periodic "band" structure in the image with different T1/T2 weighting)

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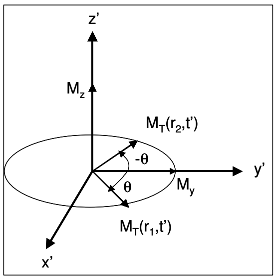
Precession: M_T is position dependent (in-plane gradient)



$$\theta(\mathbf{r}) = \gamma \int \mathbf{r} \cdot \mathbf{G}(t)dt$$

Steady-state signal behavior

From Chap 2:

Excitation

$$\mathbf{R}_{\alpha,x'} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\alpha) & \sin(\alpha) \\ 0 & -\sin(\alpha) & \cos(\alpha) \end{bmatrix}$$

Precession

$$\mathbf{P}_{\theta,z'} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 \\ -\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Relaxation

$$\mathbf{M}(t^-{}_{n+1}) = \begin{bmatrix} E_2 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_1 \end{bmatrix} \mathbf{M}(t^+{}_n) + (1-E_1)\mathbf{M_0}$$

M = $[M_x,M_y,M_z]^T$, $\mathbf{M_0}=[0,0,M_0]^T$, E_2 = exp(-t/T2) and E_1=exp(-t/T1).

Steady-state signal behavior

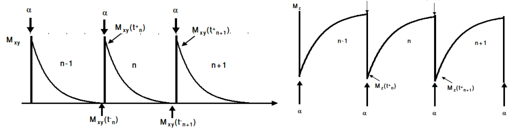
Relaxation and Precession occurs simultaneously and can be combined:

$$\mathbf{M}(t^-{}_{n+1}) = \begin{bmatrix} E_2\cos(\theta) & E_2\sin(\theta) & 0 \\ -E_2\sin(\theta) & E_2\cos(\theta) & 0 \\ 0 & 0 & E_1 \end{bmatrix} \mathbf{M}(t^+{}_n) + (1-E_1)\mathbf{M_0}$$

$$\Downarrow$$

$$\mathbf{M}(t^-{}_{n+1}) = \mathbf{Q}(E1,E2,\theta)\mathbf{M}(t^+{}_n) + (1-E_1)\mathbf{M_0}$$

Steady-state



$$\mathbf{M}(t^{-}{}_{n+1}) = \mathbf{Q}(E1, E2, \theta)\mathbf{M}(t^{+}{}_{n}) + (1 - E_1)\mathbf{M_0}$$

$$\mathbf{M}(t^{+}{}_{n+1}) = \mathbf{R}_{\boldsymbol{\alpha}} M(t^{-}{}_{n+1}) = \mathbf{M}(t^{+}{}_{n})$$

$$\Downarrow$$

$$(\mathbf{U} - \mathbf{QR}_{\alpha})\mathbf{M}(t^{+}{}_{n}) = (1 - E_1)\mathbf{R}_{\boldsymbol{\alpha}}\mathbf{M_0}$$

U = unit matrix

Steady-state

$$(\mathbf{U} - \mathbf{QR}_{\alpha})\mathbf{M}(t^{+}{}_{n}) = (1 - E_1)\mathbf{R}_{\boldsymbol{\alpha}}\mathbf{M_0}$$

$$\Downarrow$$

$$\mathbf{M}(t^{+}{}_{n}) = (\mathbf{U} - \mathbf{QR}_{\alpha})^{-1}(1 - E_1)\mathbf{R}_{\boldsymbol{\alpha}}\mathbf{M_0}$$

$$\Downarrow$$

$M_T = M_{x'} + jM_{y'}$

$$\boxed{M_T(x, y, t^{+}{}_{n}) = M_0(x, y)\frac{(1 - E_1)\sin(\alpha)(1 - E_2\exp(-j\theta))}{C\cos(\theta) + D} = M_0(x, y)F^{+}(\alpha, \theta)}$$

$$C = E_2(E_1 - 1)(1 + \cos(\alpha)) \quad D = (1 - E_1\cos(\alpha)) - (E_1 - \cos(\alpha))E_2{}^2$$

Steady-state

Transverse magn. immediately after n^th RF pulse:

$$M_T(x, y, t^{+}{}_{n}) = M_0(x, y)\frac{(1 - E_1)\sin(\alpha)(1 - E_2\exp(-j\theta))}{C\cos(\theta) + D} = M_0(x, y)F^{+}(\alpha, \theta)$$

$$\Downarrow$$

E_2=0

$$M_T(x, y, t^{+}{}_{n}) = M_0(x, y)\frac{\sin(\alpha)(1 - E_1)}{1 - \cos(\alpha)E_1}$$

The equation reduces to the 'spoiled' GRE expression when E_2=exp(-t/T2)=0 (TR >> T2 or active spoiling). In this case, the factor D in the denominator depends on T1-weighting (through E_1) only.

Steady-state

$$M_T(x, y, t^{+}{}_{n}) = M_0(x, y)\frac{(1 - E_1)\sin(\alpha)\boxed{1 - E_2\exp(-j\theta))}}{C\cos(\theta) + D} = M_0(x, y)F^{+}(\alpha, \theta)$$

The term 1-E_2exp(-jθ) in the numerator implies a varying degree of T2-weighting, dependent on θ, and hence position. This means that, if E_2 >0 the image will contain 'bands' of varying degree of T1- and T2-weighting depending on the value of exp(-jθ(**r**)) at a given position .

Steady-state: magnetization evolution between RF-excitations

Transverse magn. during n^th TR-interval:

$$M_T(x, y, t) = M_T(x, y, t^{+}{}_{n})\boxed{\exp(-t/T2)}\boxed{\exp(j\varphi(r, t))}$$

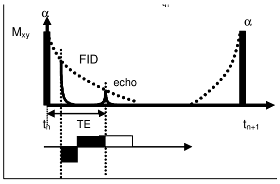
relaxation

Gradient effects

$$\varphi(r, t) = \gamma\int_{t_n}^{t} G(r, t)dt$$

The FID signal

$$M_T(x, y, t^{+}{}_{n}) = M_0(x, y)\frac{(1 - E_1)\sin(\alpha)(1 - E_2\exp(-j\theta))}{C\cos(\theta) + D} = M_0(x, y)F^{+}(\alpha, \theta)$$



$$S(t') = \exp(-t/T2^*)\int_x\int_y M_0(x, y)F^{+}(\alpha, \theta)\exp(j\gamma(G_x t' x + G_{y,n}T_y y))dxdy$$

Steady-state: from magnetization to FID signal

Transverse magn. during n^th TR-interval:

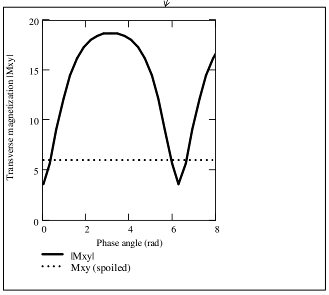
$$M_T(x,y,t) = M_T(x,y,t^+{}_n)\exp(-t/T2)\exp(j\varphi(r,t))$$

$\Phi(r,t)=G_x tx + G_{y,n}T_y y$ (see chapt 2)

FID signal:

$$S(t') = \exp(-t/T2^*)\int_x\int_y M_0(x,y)F^+(\alpha,\theta)\exp(j\gamma(G_x t' x + G_{y,n}T_y y))dxdy$$

$$S(t') = \exp(-t/T2^*)\int_x\int_y M_0(x,y)F^+(\alpha,\theta)\exp(j\gamma(G_x t' x + G_{y,n}T_y y))dxdy$$



The ECHO signal

M_T just before the n+1^th RF-pulse

$$M_T(x,y,t^-{}_{n+1}) = M_T(x,y,t^+{}_n)\exp(-TR/T2)\exp(j\theta(x,y))$$

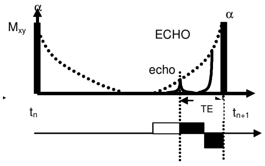
$E_2=\exp(-TR/T2)$

$$M_T(x,y,t^-{}_{n+1}) = M_0(x,y)\frac{\sin(\alpha)(1-E_1)(\exp(j\theta)-E_2)E_2}{C\cos(\theta)+D}$$

$$S(t') = \exp(TE/T2)\int_x\int_y M_0(x,y)F^+(\alpha,\theta)\exp(j\gamma(G_x t' x + G_{y,n}T_y y))dxdy$$

The ECHO signal

$$M_T(x,y,t^-{}_{n+1}) = M_0(x,y)\frac{\sin(\alpha)(1-E_1)(\exp(j\theta)-E_2)E_2}{C\cos(\theta)+D}$$



$$S(t') = \exp(TE/T2)\int_x\int_y M_0(x,y)F^+(\alpha,\theta)\exp(j\gamma(G_x t' x + G_{y,n}T_y y))dxdy$$

FID vs ECHO

FID:

$$M_T(x,y,t^+{}_n) = M_0(x,y)\frac{(1-E_1)\sin(\alpha)(1-E_2\exp(-j\theta))}{C\cos(\theta)+D}$$

ECHO:

$$M_T(x,y,t^-{}_{n+1}) = M_0(x,y)\frac{\sin(\alpha)(1-E_1)(\exp(j\theta)-E_2)E_2}{C\cos(\theta)+D}$$

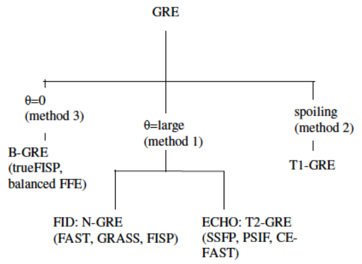
For both signals, T2-contribution to magnetization is function of position (through exp(jθ))

Methods to eliminate phase effect

1. Make θ large (large net gradient surface) relative to the voxel size so that the bands of varying T1- and T2-weighting is averaged out over each voxel.
2. Apply RF- or gradient spoiling (E2=0); removing all transverse coherence prior to each RF-pulse.
3. Make θ = 0 by balancing all gradients at the time of the signal readout

- Multislice acquisition (MS, 3D)
- GRE: Simple Steady-State model
- RF pulse train (multiple echoes)
  - Eight-Ball Echo
  - Stimulated Echo
  - Multiples echoes
- GRE FID and ECHO components
- Mathematical Model of GRE
- GRE contrast properties and techniques

Steady-state sequences


GRE

θ=0
(method 3)

B-GRE
(trueFISP,
balanced FFE)

θ=large
(method 1)

FID: N-GRE
(FAST, GRASS, FISP)

ECHO: T2-GRE
(SSFP, PSIF, CE-FAST)

spoiling
(method 2)

T1-GRE

Steady-state sequences in practice:

T1-GRE (fid, spoiling; E2=0)

$$M_T(x,y,t^+{}_n) = M_0(x,y)\frac{\sin(\alpha)(1-E_1)}{1-\cos(\alpha)E_1}$$

N-GRE (FID, large θ)

$$\left\langle M^+{}_T(x,y)\right\rangle = M_0(x,y)\frac{(1-E_1)\sin(\alpha)}{C}\left(\frac{C+DE_2}{\sqrt{D^2-C^2}}-E_2\right)$$

T2-GRE (ECHO, large θ)

$$\left\langle M^-{}_T(x,y)\right\rangle = M_0(x,y)\frac{(1-E_1)E_2\sin(\alpha)}{C}\left(1-\frac{D+CE_2}{\sqrt{D^2-C^2}}\right)$$

Steady-state sequences in practice:

B-GRE (balanced FFE, θ=0)

$$M_T = M_0\frac{\sin(\alpha)(1-E_1)\sqrt{E_2}}{1-(E_1-E_2)\cos(\alpha)-E_1E_2}$$

TR << T1,T2 and $\alpha > \alpha_e$:

$$M_T = M_0\frac{\sin(\alpha)}{1+\cos(\alpha)+(1-\cos(\alpha))(T1/T2)} \approx \frac{\sin(\alpha)}{1-\cos(\alpha)}\frac{T2}{T1}$$

Reminder: what happens with θ= 0

FID:

$$M_T(x,y,t^+{}_n) = M_0(x,y)\frac{(1-E_1)\sin(\alpha)(1-E_2\exp(-j\theta))}{C\cos(\theta)+D}$$

ECHO:

$$M_T(x,y,t^-{}_{n+1}) = M_0(x,y)\frac{\sin(\alpha)(1-E_1)(\exp(j\theta)-E_2)E_2}{C\cos(\theta)+D}$$

For both signals, T2-contribution to magnetization is function of position (through exp(jθ))

Steady-state sequences in practice:

B-GRE (balanced FFE, θ=0)

$$M_T = M_0\frac{\sin(\alpha)}{1+\cos(\alpha)+(1-\cos(\alpha))(T1/T2)} \approx \frac{\sin(\alpha)}{1-\cos(\alpha)}\frac{T2}{T1}$$

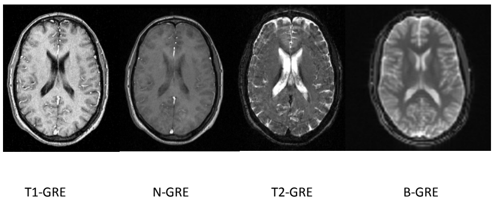
At optimal flip angle:

$$\cos(\alpha_e) = \frac{T1-T2}{T1+T2}$$

$$M_{T,peak} = M_0\frac{1}{2}\sqrt{T2/T1}$$

Very high signal-noise!

Steady-state sequences in practice:



Signal in Gradient Echo

There are several ways to control the contrast in Gradient Echo techniques.

- “normal” FFE Gradient Spoiling (destroy SE’s)
- T1 enhanced FFE* RF Spoiling (destroy SE’s)
- T2 enhanced FFE Gradient Spoiling (destroy FID)
- Balanced FFE (SSFP) NO SPOILING
  - Very Short TR
  - TE = ½ TR
  - High Flip Angle
  - Intrinsic Flow Compensation
  - No spoiling...

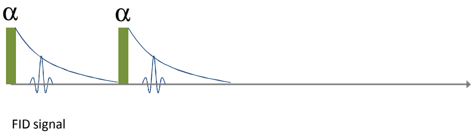
* RF spoiling does not lengthen the TR. Therefore it is very useful in sequences with very short TR such as 3D T1w FFE.

Gradient Echo

Any RF excitation results in a FID echo

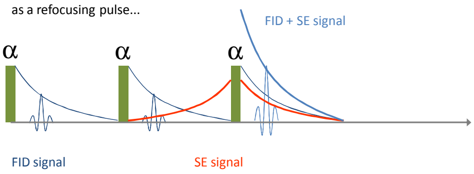
Gradient Echo

Any RF excitation results in a FID echo



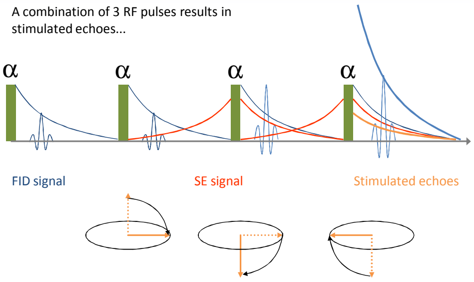
Gradient Echo

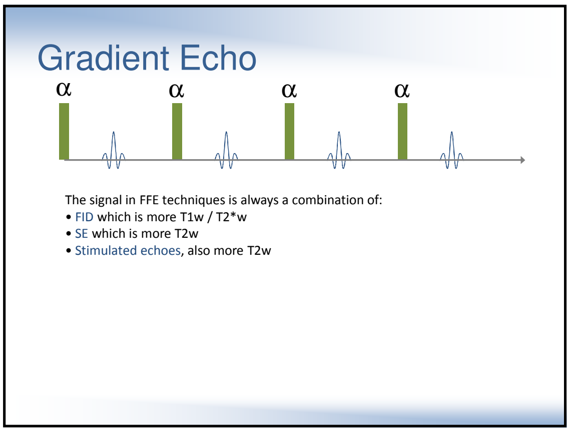
Each RF pulse also acts
as a refocusing pulse...



Gradient Echo

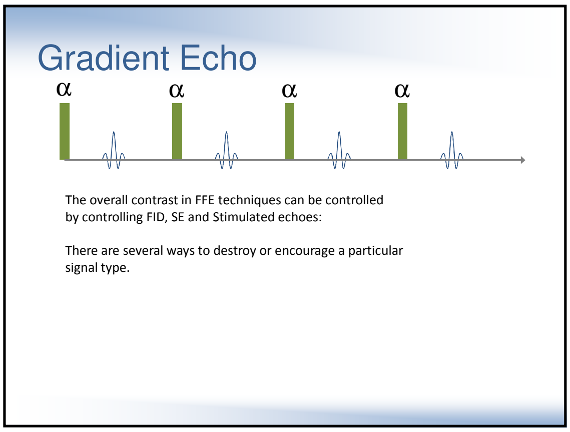
A combination of 3 RF pulses results in
stimulated echoes...





Gradient Echo

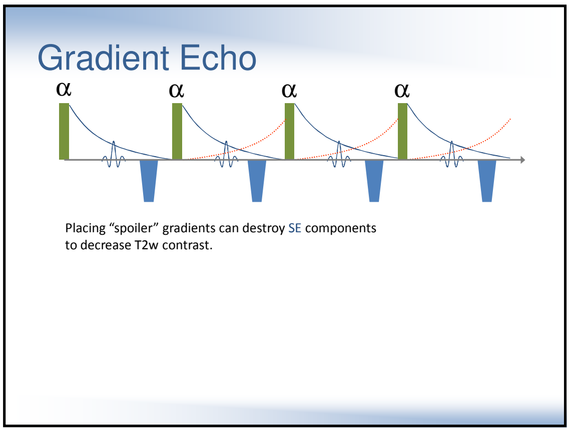
The signal in FFE techniques is always a combination of:
- FID which is more T1w / T2*w
- SE which is more T2w
- Stimulated echoes, also more T2w



Gradient Echo

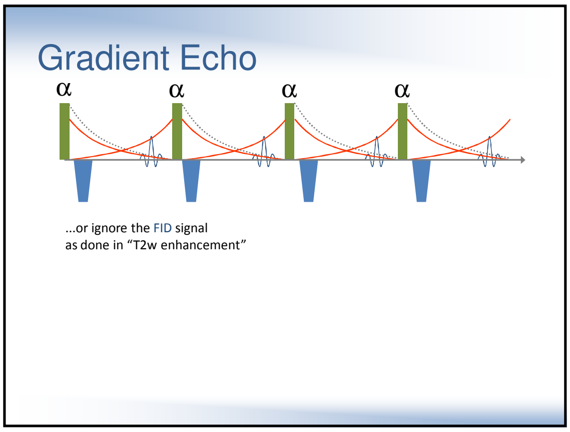
The overall contrast in FFE techniques can be controlled by controlling FID, SE and Stimulated echoes:

There are several ways to destroy or encourage a particular signal type.



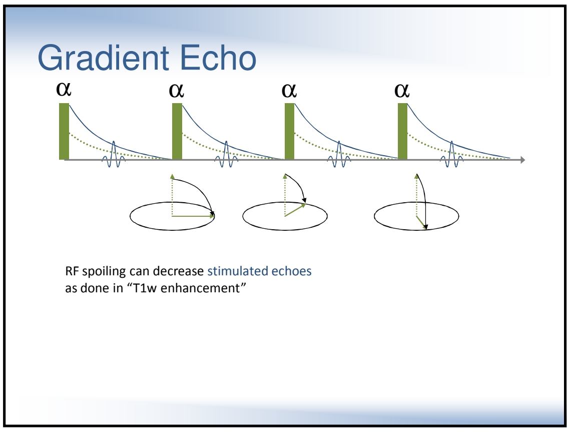
Gradient Echo

Placing "spoiler" gradients can destroy SE components to decrease T2w contrast.



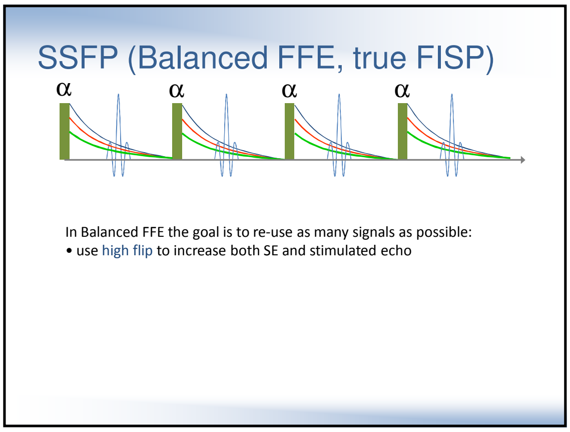
Gradient Echo

...or ignore the FID signal as done in "T2w enhancement"



Gradient Echo

RF spoiling can decrease stimulated echoes as done in "T1w enhancement"

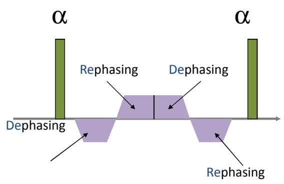


SSFP (Balanced FFE, true FISP)

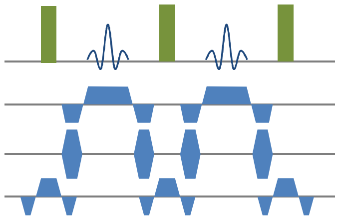
In Balanced FFE the goal is to re-use as many signals as possible:
- use high flip to increase both SE and stimulated echo

SSFP (Balanced FFE, true FISP)

- In balanced FFE we MUST de-encode the signal, before the next excitation to avoid artifacts.
- … And now we can use this signal that is left after the echo…

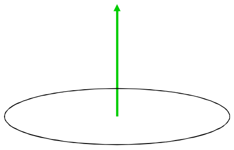


SSFP (Balanced FFE, true FISP)

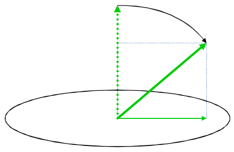


All signals are de-encoded by rephasing gradients in three directions

Contrast in SSFP

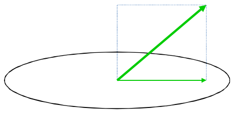


Contrast in SSFP

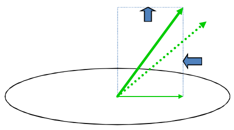


It all starts with half the flip angle…

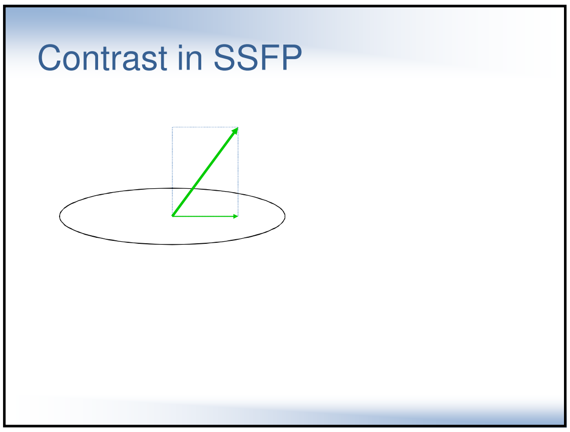
Contrast in SSFP



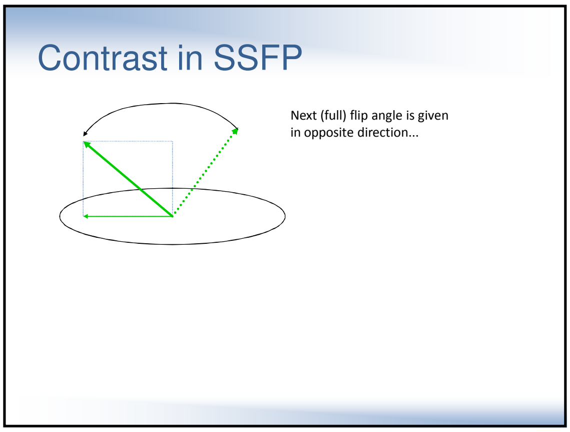
Contrast in SSFP



T1 and T2 relaxation

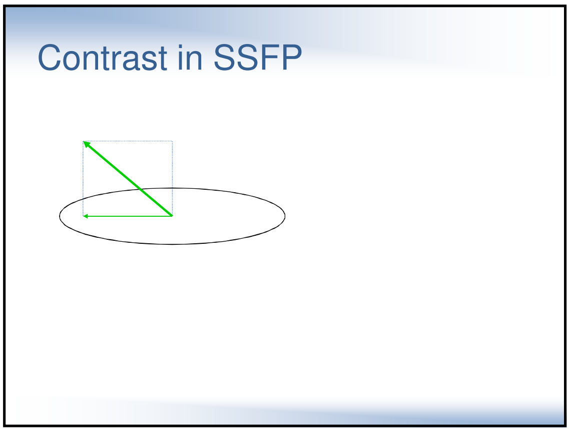


Contrast in SSFP

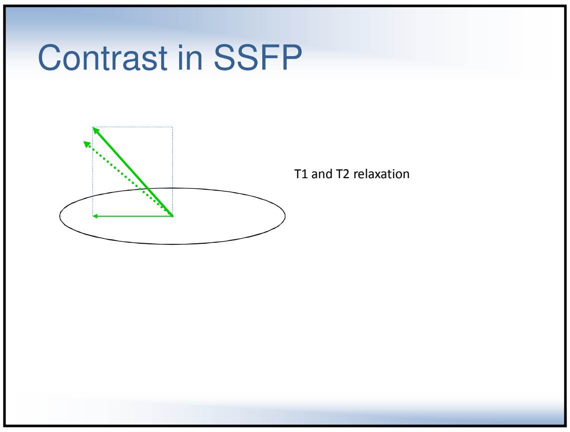


Contrast in SSFP

Next (full) flip angle is given
in opposite direction…

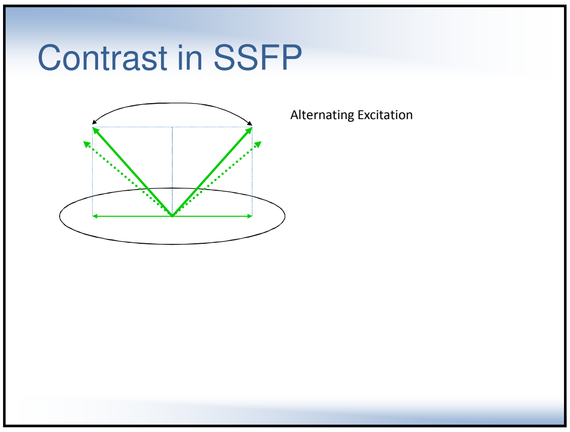


Contrast in SSFP



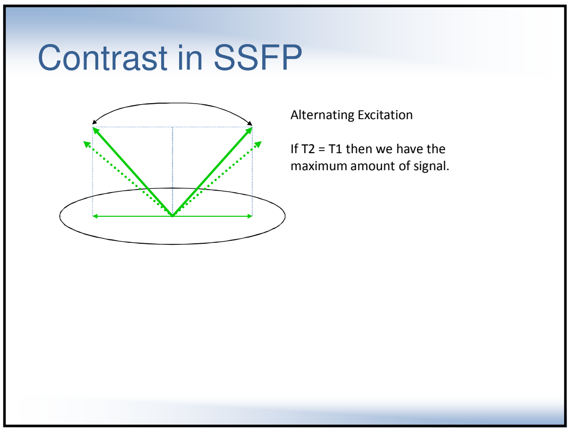
Contrast in SSFP

T1 and T2 relaxation



Contrast in SSFP

Alternating Excitation

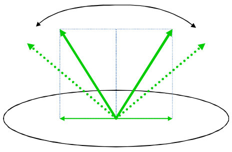


Contrast in SSFP

Alternating Excitation

If T2 = T1 then we have the
maximum amount of signal.

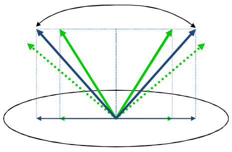
Contrast in SSFP



Alternating Excitation

If T2 < T1 then we have the less signal.

Contrast in SSFP



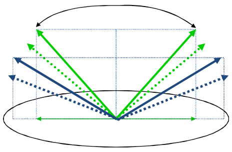
Alternating Excitation

If T2 < T1 then we have the less signal.

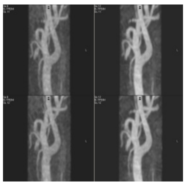
In balanced FFE tissue with high T2/T1 (yellow) gives the brightest signal. (Blood, Fat*, Fluid)

Optimize sequence

- Flip angle 90^o to 110^o



Alternating Excitation

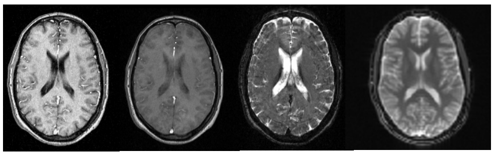


Flip 60^0 Flip 100^0

SSFP requirements

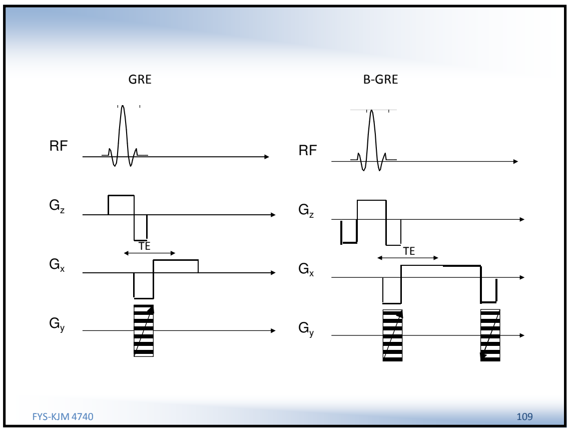
- Low flip angle to not destroy slice profile
- Short TR: +/- 3ms
- very high B0 homogeneity
- STRONG and FAST GRADIENTS
- smallest Water Fat Shift

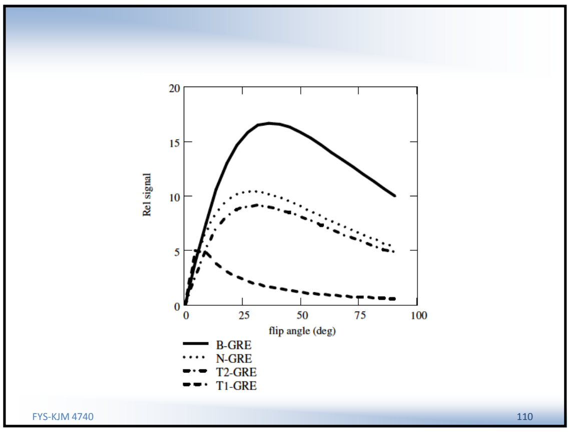
Steady-state sequences in practice:

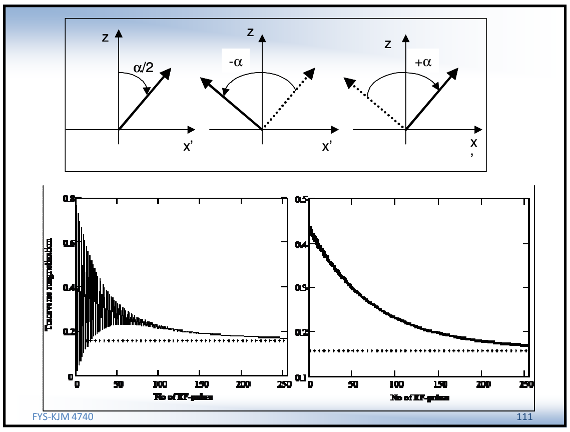


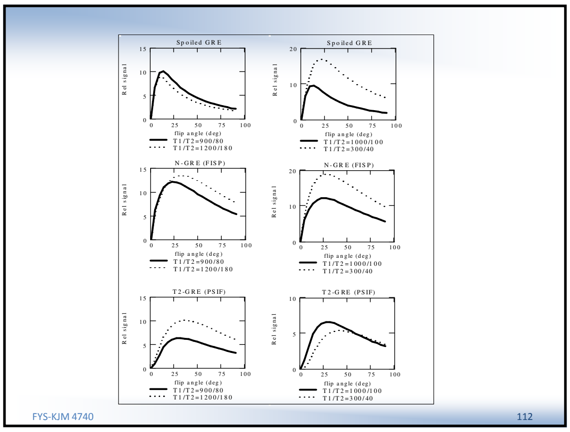
T1-GRE N-GRE T2-GRE B-GRE

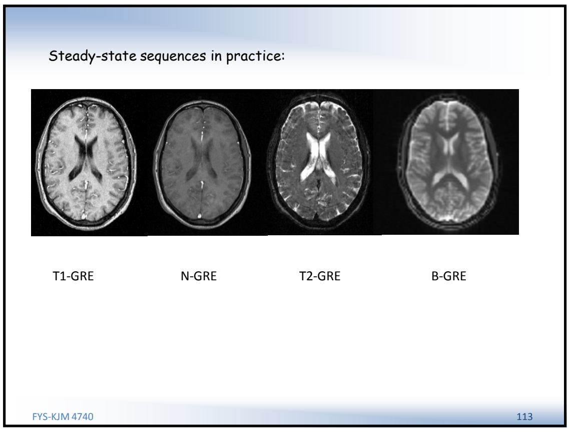
Next lecture: transient GRE and approach to steady-state

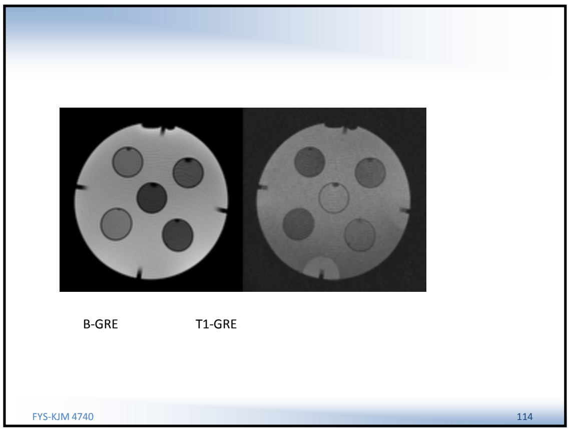


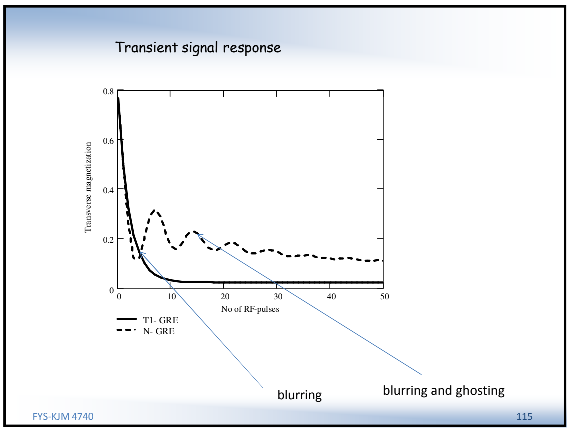







Steady-state sequences in practice:





Transient signal response

blurring

blurring and ghosting

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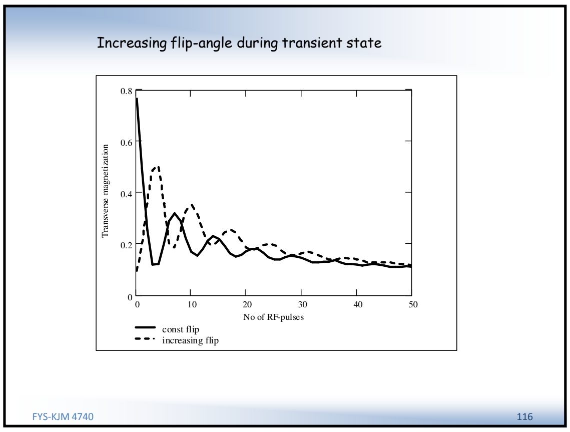

Increasing flip-angle during transient state

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