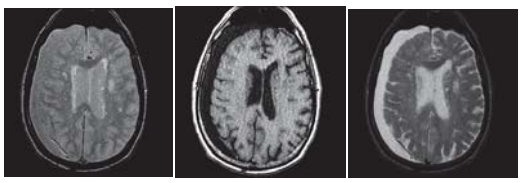
12: MRI contrast mechanisms

1. What is T_2* weighted MRI ?
2. What is the biophysical basis of T2* changes (BOLD) ?
3. How are spin echoes generated ?
4. What are the standard contrast MR sequences ?
   T_1 ,T_2 and proton-density weighted MRI
5. By which mechanism do contrast agents act ?

After this course you

1. are capable of describing the biophysical basis of BOLD contrast
2. Understand the mechanism of spin echo generation
3. Know the three contrasts that can be generated by the spin echo imaging sequence and how the timing parameters are optimized for each contrast
4. Understand why the same tissue appear bright on T2 weighted images and dark on T1 weighted images
5. Understand the mechanism by which the two principal contrast agent mechanisms lead to signal increase or decrease.

MRI: One magnet, many contrast mechanisms



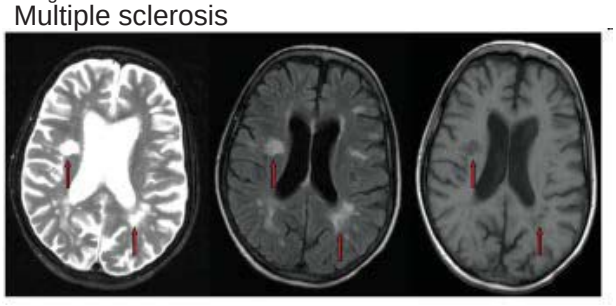
Examples of proton density, T_1, and T_2-weighted images, from the Whole Brain Atlas site at Harvard. Note fluid appearance in all images.

Proton density-weighted

T_1-weighted

T_2-weighted

Multiple sclerosis



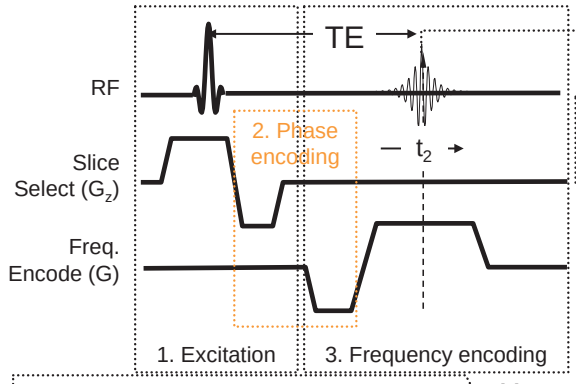
T_2-weighted
[$TE=T_2(CSF)$]

FLAIR:
T_2 and T_1 weighted (inversion recovery CSF-nulled)
[$TI=\ln 2 T_1(CSF)$]

T_1-weighted
[$TR=T_1(GM)$]

Another view on spatial encoding with MRI

Let's give it another try … (compare w. Lesson 11)



$$S(t_2) \propto \int_{object} M_\perp(x,0)e^{i\gamma G_x x t_2}dx$$

(For G along x)

$S(t_2)$ and $M(x)$ are linked by FT

$M(\omega_2) = FT\{S(t_2)\}$

$= M(x)$

M(x) is Radon transform measured along the direction of the Gradient **G**

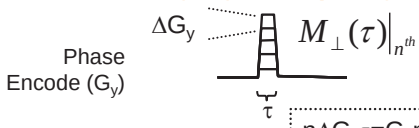
$$M(x) = \int M(x,y)dy$$

Linear combination of e.g. G_x and G_y:

G=(G_x,G_y)=cosϕG,sinϕG

Measure Radon Transforms along ϕ (as in CT) every TR s (T_1 relaxation) (→ sinogram, projection reconstruction, see also central slice theorem)

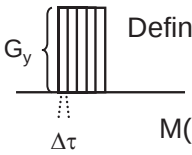
Phase encoding is just frequency encoding in a 2nd time dimension



$$M_\perp(\tau)\big|_{n^{th}\ step} = M_\perp(0)e^{i\gamma n\Delta G_y \tau}$$

$n\Delta G_y\tau = G_y n\Delta\tau$

$$= M_\perp(0)e^{i\gamma G_y n\Delta\tau}$$



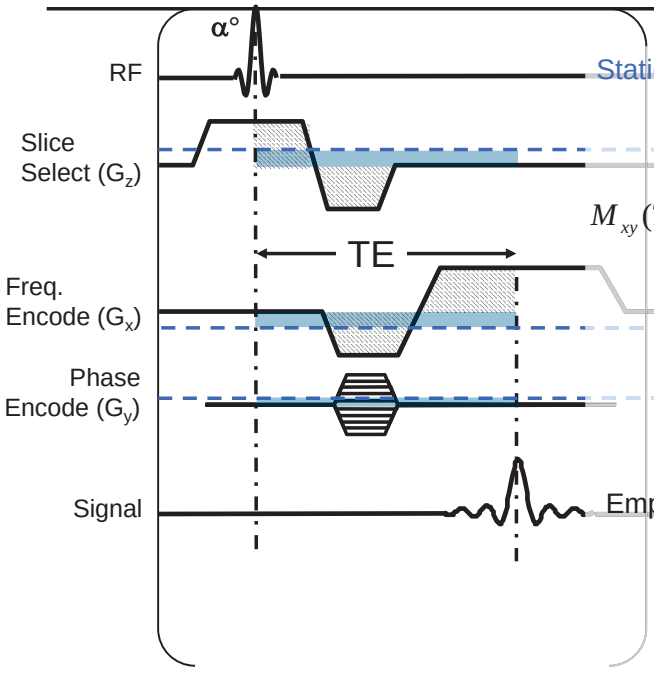
Define $t_1=n\Delta\tau$: $S(t_1,t_2)$

2D FT

$M(\omega_1,\omega_2)=M(y,x)$

12-1. What is the contrast in gradient echo imaging ?

T_2* weighting – static dephasing



Static field imperfection

$$\Delta B(\vec{r}) \approx \frac{\partial B_z}{\partial \vec{r}} \cdot \vec{r}$$

$$B(\vec{r},t) = B_0 + \vec{G}(t)\cdot\vec{r} + \Delta B(\vec{r})$$

$$M_{xy}(TE) = M_{xy}(0)e^{-i\gamma\int_0^{TE}\vec{G}(t)\cdot\vec{r}dt}\ e^{-i\gamma\int_0^{TE}\Delta B(\vec{r})dt}\ e^{-\frac{TE}{T_2}}$$

$$e^{-i\gamma\Delta B(\vec{r})TE}\ e^{-\frac{TE}{T_2}}$$

NB. γΔB(r)TE=γnΔB(r)[TE/n]

M_{xy} summed over voxel

$$e^{-\frac{TE}{T_2}}\iiint_{voxel} e^{-i\gamma\Delta B(\vec{r})TE}d^3r$$

Empirically:

$$\frac{1}{T_2*} = \frac{1}{T_2} + \gamma\Delta B$$

$$e^{-\frac{TE}{T_2*}}$$

NB. $T_2 > T_2$*

12-2. What is the Biophysical basis of T_2* changes ?

Blood Oxygenation Level Dependent (BOLD)

Magnetic susceptibility χ: magnetic field in object depends on object properties

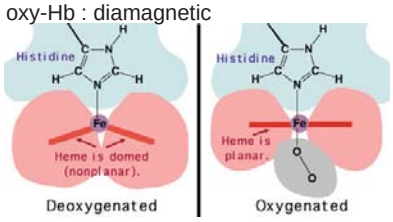
$$B(\vec{r}) = (1 + \chi(\vec{r}) \cdot 10^{-6}) B_0$$

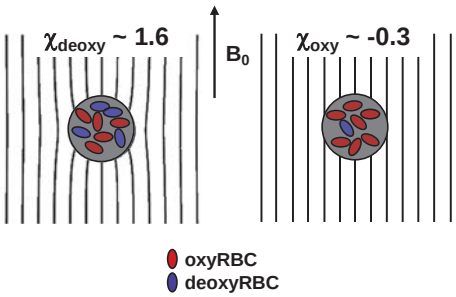
Deoxy-hemoglobin : paramagnetic

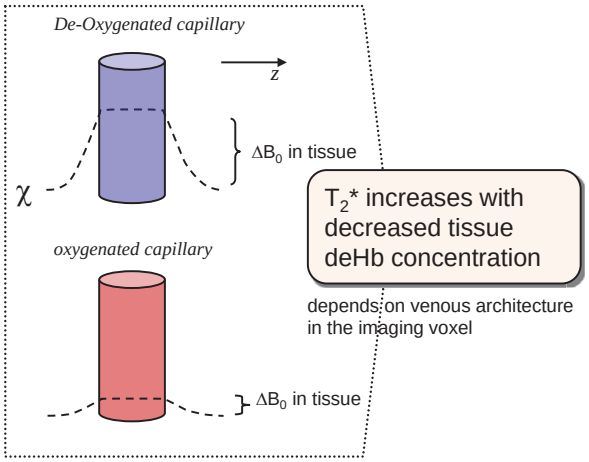
oxy-Hb : diamagnetic

χ<0: diamagnetism (repelling force)

χ>0: paramagnetism (attracting force)







T_2* increases with decreased tissue deHb concentration

depends on venous architecture in the imaging voxel

What does Blood oxygen level dependent (BOLD) contrast measure ?

deHb content

Brain physiology: O_2 consumption increases less than Flow during "thinking"

$$[O_2]_{in} - [O_2]_{out} = \frac{\text{rate of O2 consumption}}{\text{Flow}}$$

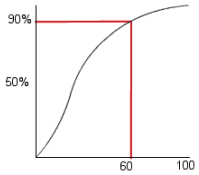
What is the consequence?

steady-state hemodynamic response

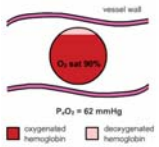
↑ cerebral blood flow (CBF) : ↓ dHb : ↑ BOLD

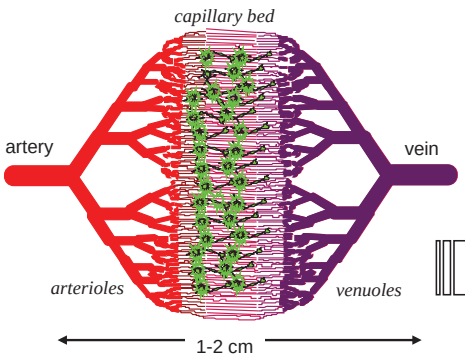
↑ cerebral blood volume (CBV) : ↑ dHb : ↓ BOLD

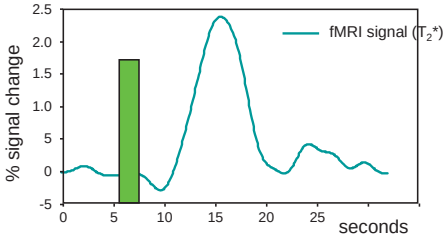
Saturation=%oxy-Hb
(deHB=100%-saturation)



$$BOLD \propto \frac{\Delta CBF}{\Delta CBV \cdot \Delta CMRO_2}$$





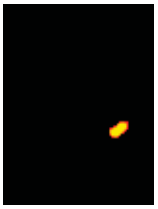


How is brain function imaged using functional MRI (fMRI) ?

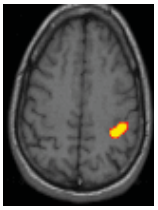
Brain Activation Analysis

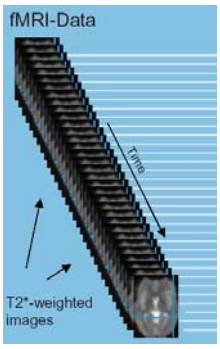
T_2*-weighted Image

Thresholded Statistical Image



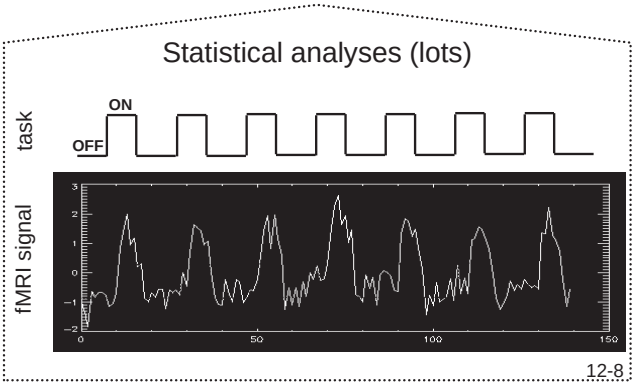
Overlay on Anatomic Image





Time series

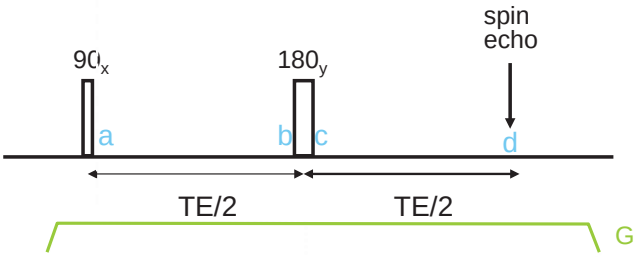
Statistical analyses (lots)



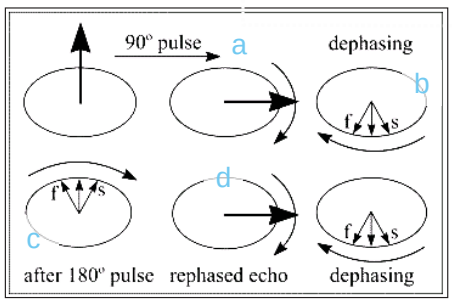
12-3. How can a π RF pulse form an echo ?

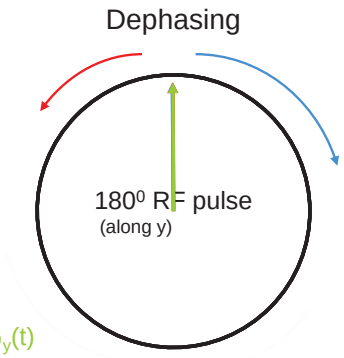
(Hahn) spin echo

Observation: When using two RF pulses, echo occurs at twice the time difference between the RF pulses (constant gradient G).



Gradient $G_y(t)$

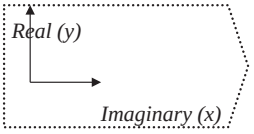




Magnetization before & after 180:

$M_\perp(\sin\Phi, \cos\Phi,) \rightarrow M_\perp(-\sin\Phi, \cos\Phi)$

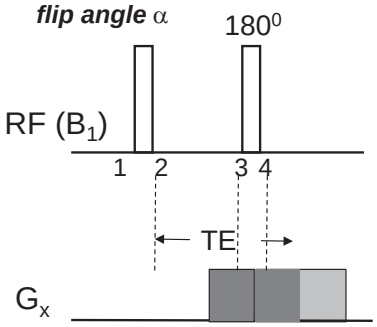
$(\Phi=\gamma G_y y TE/2)$



$M_\perp e^{i\Phi} \xrightarrow{180^0 \text{ along } y} M_\perp e^{-i\Phi}$

Spin echo formation revisited

Mathematical formulation



Magnetization at the time points specified:

1: $(0,0,M_z)$

rotated by α degrees (RF pulse):

2: $(0,M_z\sin\alpha,M_z\cos\alpha)\equiv(0,M_y,\ldots)$

[only consider M_{xy}, precesses with B = $+\gamma G_x x$

3: M_y (cos[$(+\gamma G_x x)t$], sin[$(+\gamma G_x x)t$])

$\equiv M_y$ [cos($+\phi_x$), sin(ϕ_x)]

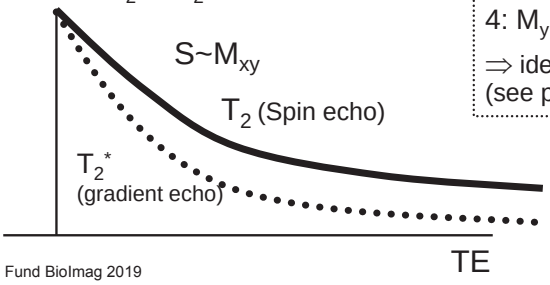
180^0 pulse about x inverts y component of M_{xy} :

$M_y \rightarrow -M_y$

4: M_y [cos($+\phi_x$), -sin(ϕ_x)] $\equiv M_y$ [cos(ϕ_x),sin($-\phi_x$)]

$\Rightarrow$ identical to the effect of a negative gradient (see previous lecture) $\rightarrow$ ***echo formation***

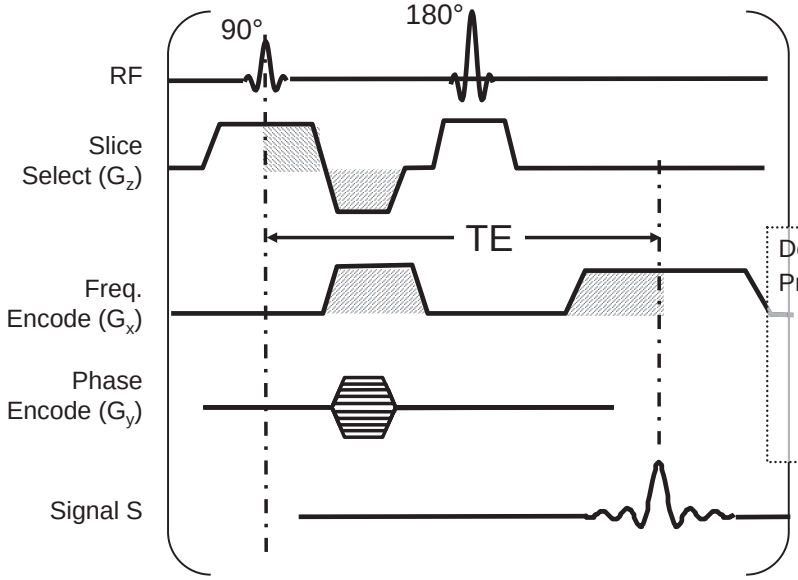
Signal S decays exponentially due to T_2 or T_2* relaxation



$$\frac{1}{T_2*} = \frac{1}{T_2} + \gamma\Delta B$$

Unavoidable
(B_0 is never homogenous in space)
exploited in BOLD fMRI

The spin echo imaging sequence



Derivation of signal S $\propto$ M_{xy}:

Proton density $\rho \propto M_0$

$$M_{xy}(0) = \sin(90) M_z(0_-)$$

$$M_{xy}(TE) = M_{xy}(0) e^{-TE/T_2}$$

$$M_z(0_-) = (1 - e^{-TR/T_1}) M_0$$

Repeated every TR seconds

$$S(TE,TR) \propto \rho(1 - e^{-TR/T_1}) e^{-TE/T_2}$$

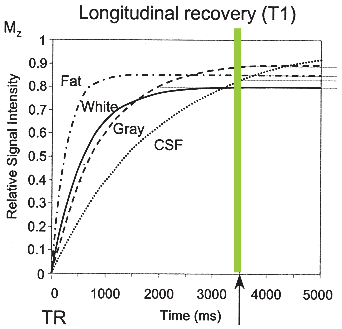
12-4. How are the basic MRI contrasts generated ?

I. Proton density weighted MRI

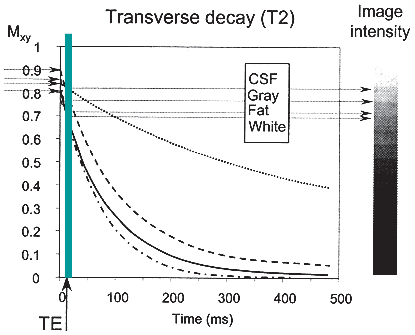
Minimize effects of relaxation:

$$S(TE,TR) \propto \rho(1-e^{-TR/T_1})e^{-TE/T_2}$$

long TR:
minimize effect of T_1 differences



Short TE:
minimize influence of T_2



Imaging the number of protons per voxel

⇒ Tissues with higher spin density (e.g., fat, CSF) have higher image intensity

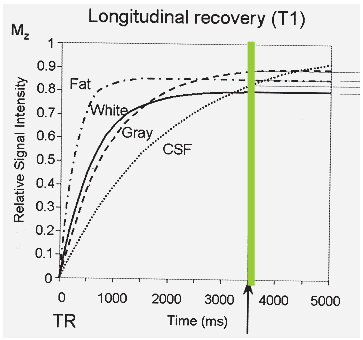
Water content: only ~70-100% (poor contrast)

II. How is T_2 contrast generated ?

contrast based on differences in T_2

$$S(TE,TR) \propto \rho(1-e^{-TR/T_1})e^{-TE/T_2}$$

T_2 weighting: long TR → reduced T_1 effects



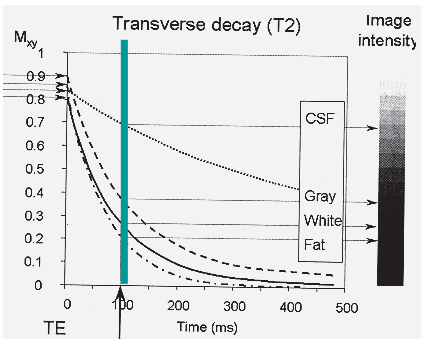
longer TE : accentuate T_2 differences

What TE is optimal?

1. Find TE at which M_{xy} is most strongly affected by T_2 differences
2. Solution (variational calculus, Lecture 1):
3. Find TE at which dM_{xy}/dT_2=maximal

$$TE = T_2$$

4. For tissues with different T_{2a} and T_{2b}: Use TE between the two T_2 values.



III. How is MRI T_1-weighted ?

contrast based on differences in T_1

$$S(TE,TR) \propto \rho(1-e^{-TR/T_1})e^{-TE/T_2}$$

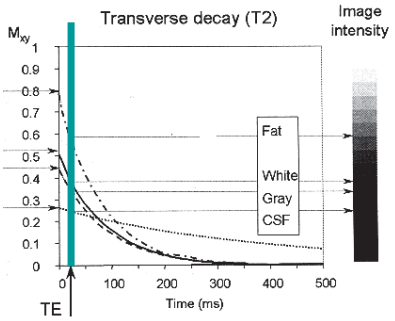
T_1 weighting: *short* TE → minimize T_2 effects

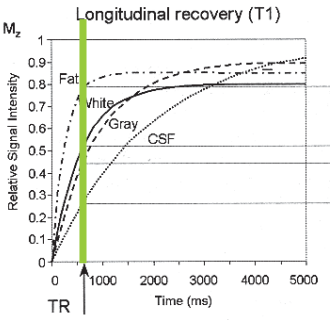
short TR → accentuate T_1 effects

1. use short TR to maximize the differences in longitudinal magnetization during the return to equilibrium
2. Tissues with shorter T_1 have higher image intensity
3. **Question:** When is the signal maximally sensitive to changes/differences in T_1?

   Answer: TR=T_1

   (see 9-17)





12-5. What are the mechanisms of MRI Contrast Agents ?

Relaxation times are shortened by relaxivity r_1, r_2*

1) T_1 – Paramagnetic agents

Mechanism: (interaction with water & molecular tumbling)

Contrast agent w. concentration. [CA] shortens T_1:

$$\frac{1}{T_1^{CA}} = \frac{1}{T_1} + r_1[CA]$$

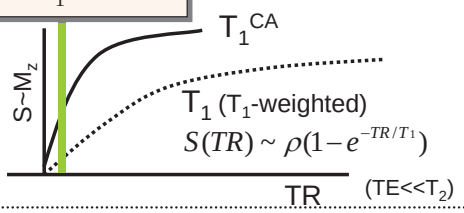
brighter signal

on T_1-weighted images

Example:

[CA]=1mM, r_1=3 $mM^{-1}s^{-1}$ and T_1=1s:

$1/T_1^{CA}=1+3=4 \rightarrow T_1^{CA}=0.25s$



2) T_2 – Paramagnetic and Susceptibility agents

[T_2* – Susceptibility agents]

$$\frac{1}{T_2^{*CA}} = \frac{1}{T_2^{*}} + r_2^{*}[CA]$$

Reduced (removed) signal

on T_2 or T_2*-weighted images

Example:

[CA]=1mM, r_2*=50 $s^{-1}mM^{-1}$ and T_2*=50ms:

$1/T_2^{*CA}=20+50=4 \rightarrow T_2^{*CA}=14ms$