

12: MRI contrast mechanisms

1. What is T_2^* weighted MRI ?
2. What is the biophysical basis of T_2^* 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

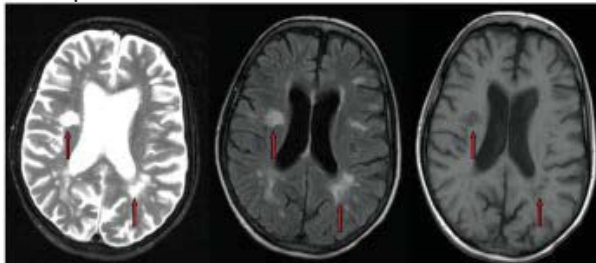
1. are capable of describing the biophysical basis of BOLD contrast
2. Understand the mechanism of spin echo generation
3. Know the three contrasts that can be generated by the spin echo imaging sequence and how the timing parameters are optimized for each contrast
4. Understand why the same tissue appear bright on T_2 weighted images and dark on T_1 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



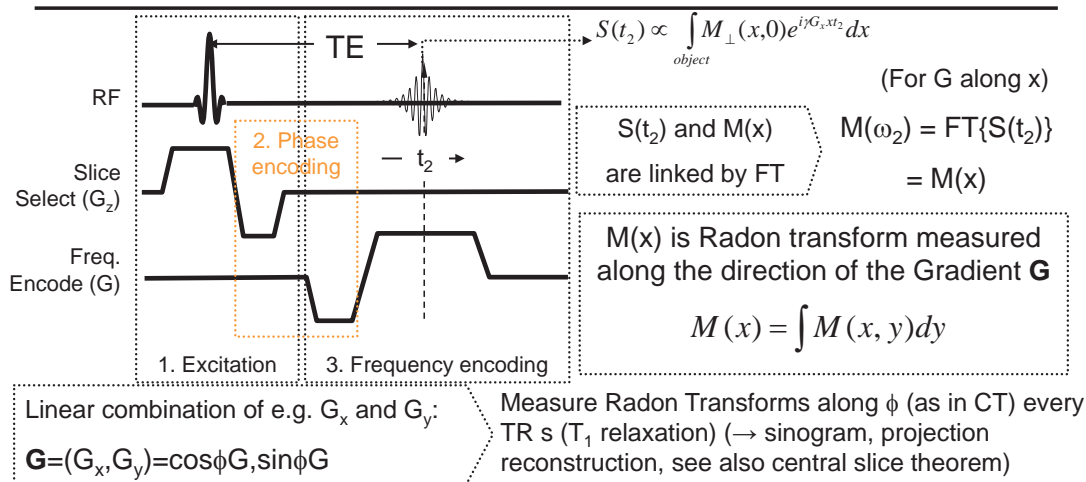
T_2 -weighted
[$TE=T_2(\text{CSF})$]

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

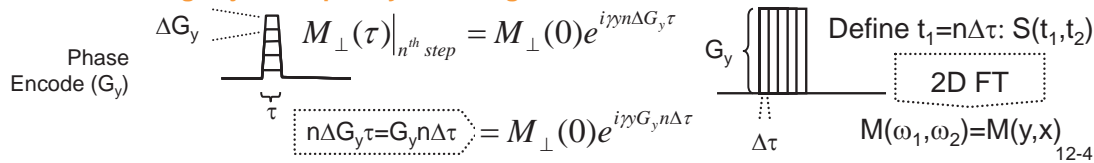
T_1 -weighted
[$TR=T_1(\text{GM})$]

Another view on spatial encoding with MRI

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



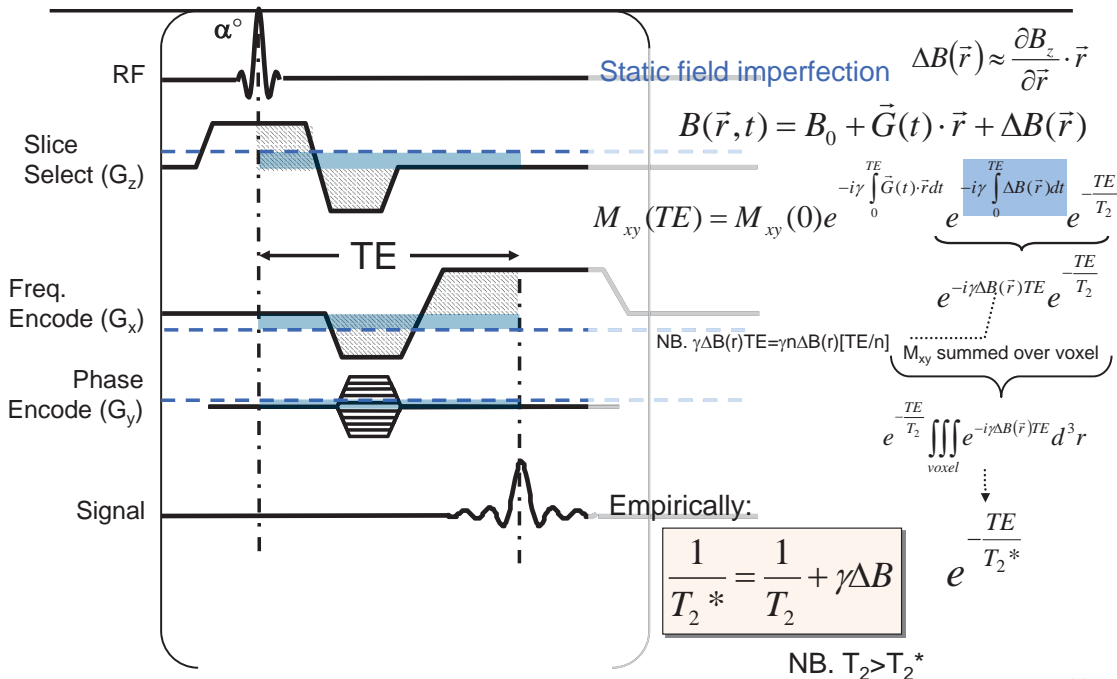
Phase encoding is just frequency encoding in a 2nd time dimension



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

T_2^* weighting – static dephasing



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12-5

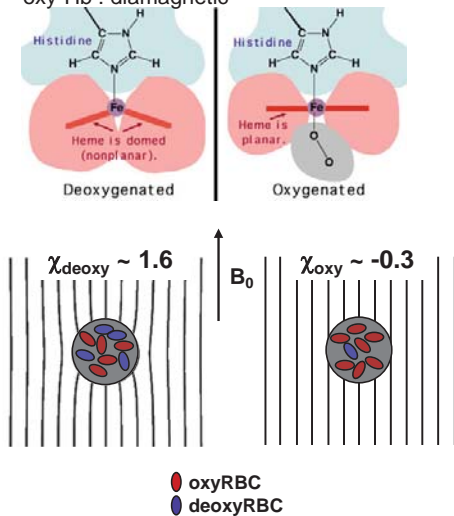
12-2. What is the Biophysical basis of T_2^* changes ?

Blood Oxygenation Level Dependent (BOLD)

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

Deoxy-hemoglobin : paramagnetic

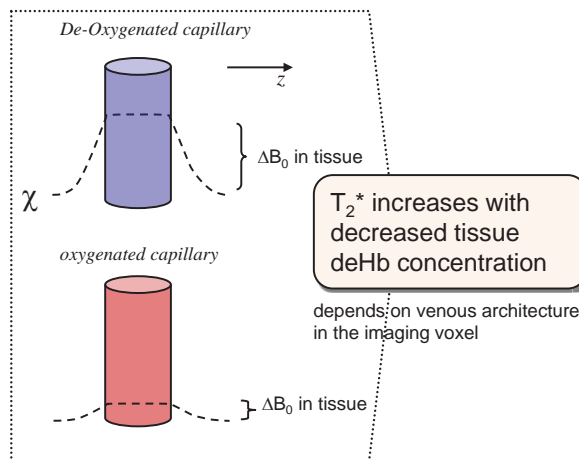
oxy-Hb : diamagnetic



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

$\chi < 0$: diamagnetism (repelling force)

$\chi > 0$: paramagnetism (attracting force)



12-6

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

deHb content

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

What is the consequence?

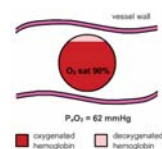
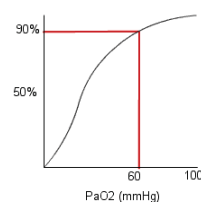
steady-state hemodynamic response

\uparrow cerebral blood flow (CBF) : \downarrow dHb : \uparrow BOLD

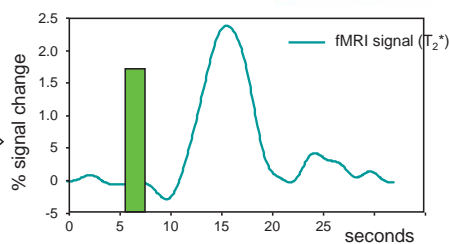
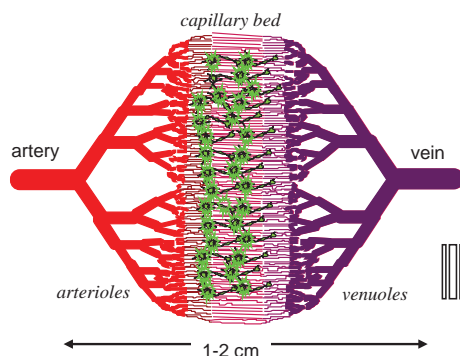
\uparrow cerebral blood volume (CBV) : \uparrow dHb : \downarrow BOLD

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

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



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



12-7

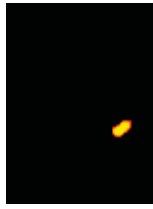
How is brain function imaged using functional MRI (fMRI) ?

Brain Activation Analysis

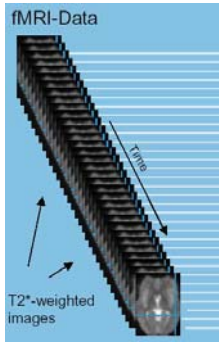
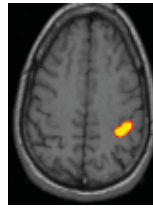
T₂*-weighted Image



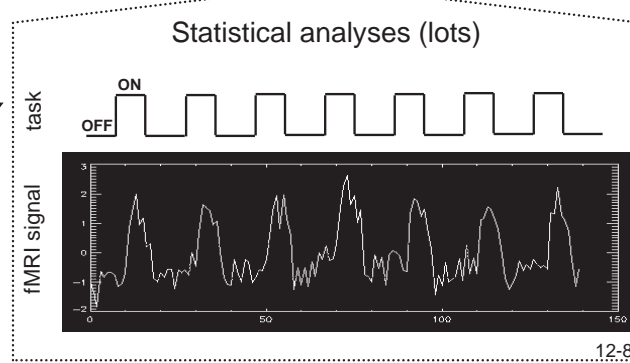
Thresholded Statistical Image



Overlay on Anatomic Image



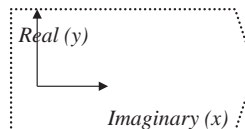
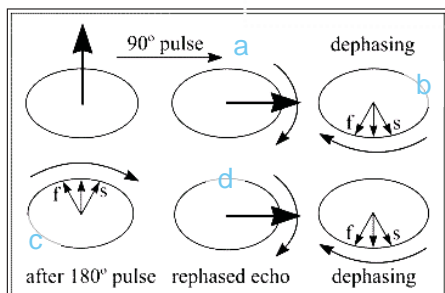
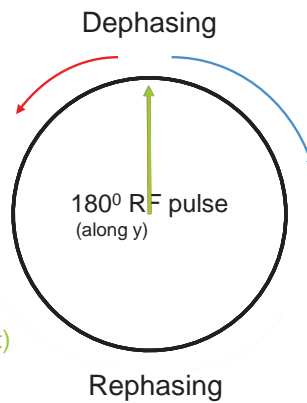
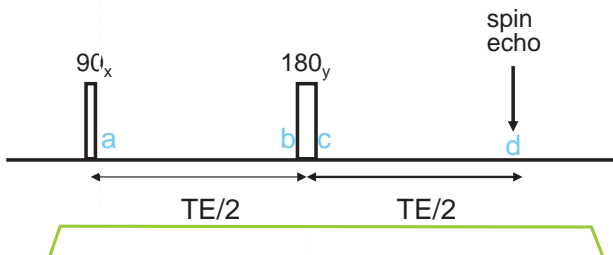
Time series



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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).



Magnetization before & after 180:

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

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

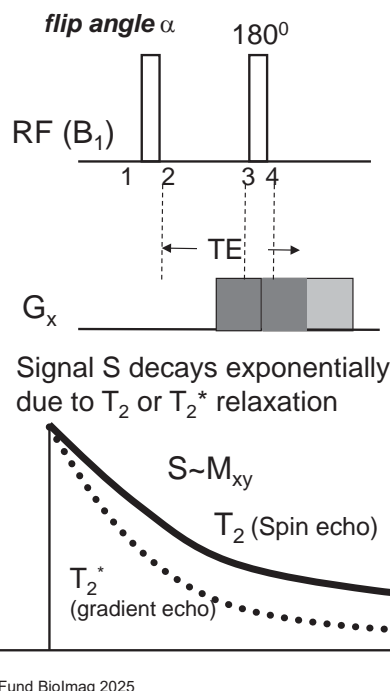
$$M_{\perp} e^{i\Phi} \xrightarrow{180^\circ \text{ along } y} M_{\perp} e^{-i\Phi}$$

12-10

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Spin echo formation revisited

Mathematical formulation



Magnetization at the time points specified:

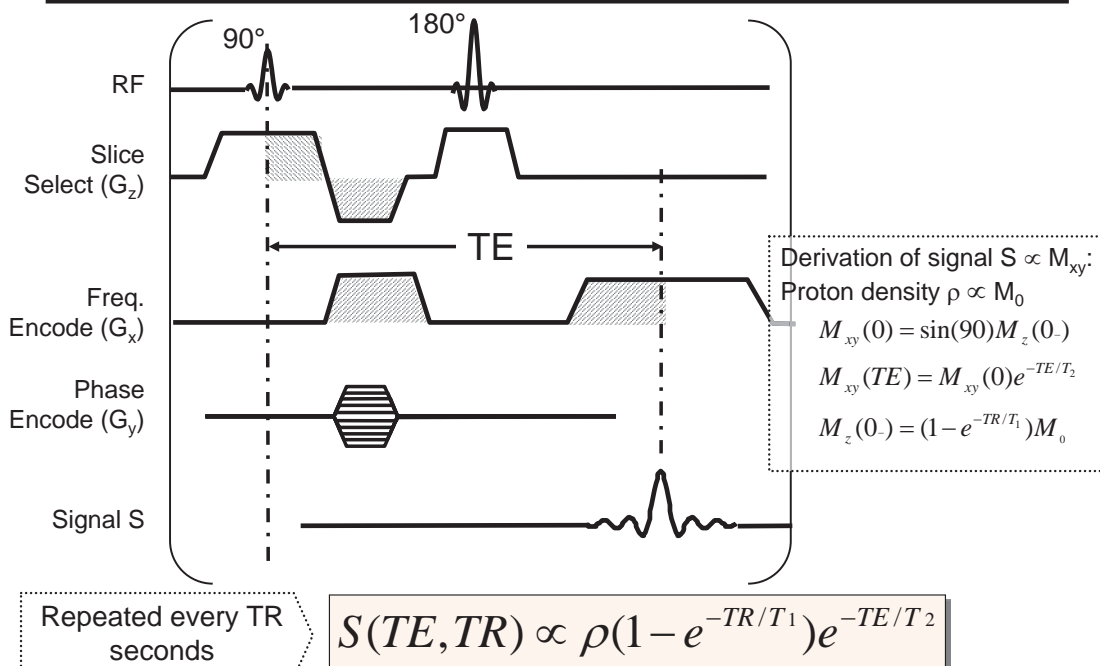
- 1: $(0, 0, M_z)$
rotated by α degrees (RF pulse):
- 2: $(0, M_z \sin \alpha, M_z \cos \alpha) \equiv (0, M_y, \dots)$
- [only consider M_{xy} , precesses with $B = \pm \gamma G_x x$]
- 3: $M_y (\cos[(+\gamma G_x x)t], \sin[(+\gamma G_x x)t])$
 $\equiv M_y [\cos(+\phi_x), \sin(\phi_x)]$
 180° pulse about x inverts y component of M_{xy} :
 $M_y \rightarrow -M_y$
- 4: $M_y [\cos(+\phi_x), -\sin(\phi_x)] \equiv M_y [\cos(\phi_x), \sin(-\phi_x)]$
 \Rightarrow identical to the effect of a negative gradient (see previous lecture) \rightarrow **echo formation**

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

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

12-11

The spin echo imaging sequence



12-12

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

I. Proton density weighted MRI

Minimize effects of relaxation:

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

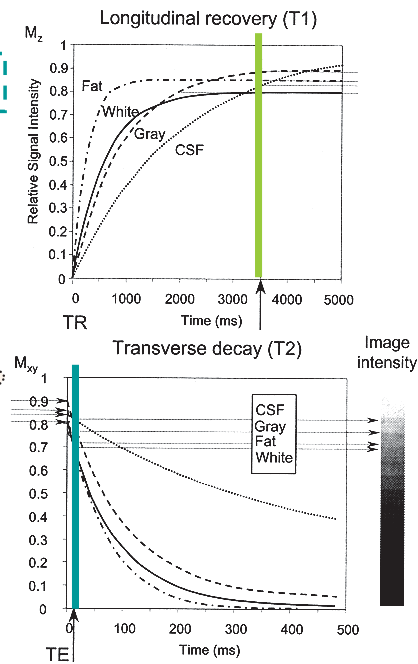
long TR:
minimize effect of T_1 differences

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)



12-13

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

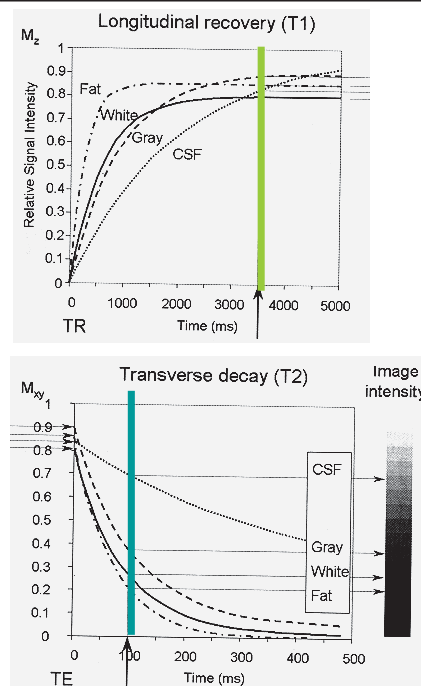
longer TE : accentuate T_2 differences

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 $dM_{xy}/dT_2 = \text{maximal}$

$$TE = T_2$$

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



12-14

III. How is MRI T_1 -weighted ?

contrast based on differences in T_1

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

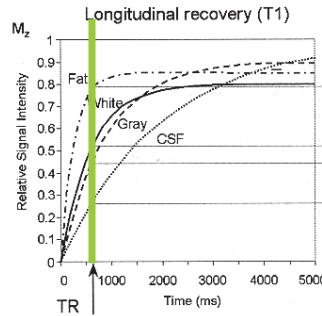
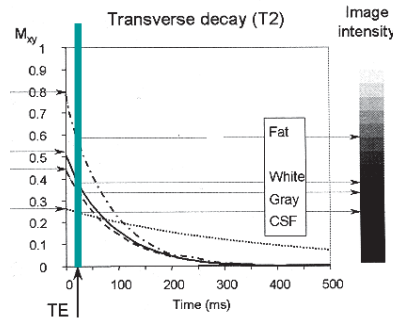
T_1 weighting: **short TE** → minimize T_2 effects

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)



12-15

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

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

Mechanism: (interaction with water & molecular tumbling)

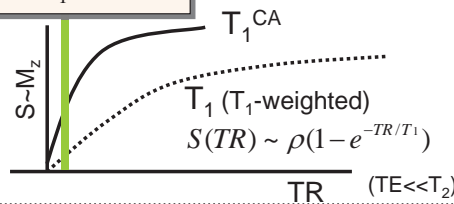
$$\frac{1}{T_1^{CA}} = \frac{1}{T_1} + r_1 [CA]$$

Example:

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

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

brighter signal
on T_1 -weighted images



2) T_2 – Paramagnetic and Susceptibility agents

$[T_2^* - \text{Susceptibility agents}]$

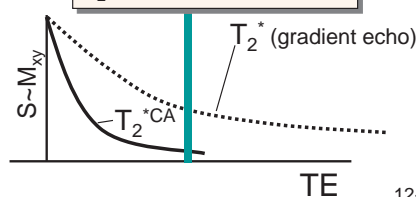
$$\frac{1}{T_2^{*CA}} = \frac{1}{T_2^*} + r_2^* [CA]$$

Example:

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

$1/T_2^{*CA} = 20 + 50 = 70 \rightarrow T_2^{*CA} = 14 \text{ ms}$

Reduced (removed) signal
on T_2 or T_2^* -weighted images



12-18