Chapter 22&25 Quantification MRI and Susceptibility in MRI

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- **Previous classes:**
  - Spin density, T1 and T2 (Chaps. 8)
  - GE and SE (chap.8)
  - Field inhomogeneity (Chap. 20)
- **Today's content**
  - Spin density, T1 and T2 quantification
  - Susceptibility, phase imaging, BOLD effects

Overview

- Why quantification?
  - Tissue characterization
  - Better understand contrast mechanisms
  - Protocol optimization / imaging post processing

- Challenges
  - Other contrast mechanism at work
  - Sequence design and scan strategy
  - Unknown baseline / Noise

Contrast mechanisms in MRI

- MRI is a multiple contrast imaging modality

Intrinsic:
- spin density
- T1/T2/T2*/T1ρ
- Diffusion
- Chemical shift
- Susceptibility
- Temperature
- …

Physiological:
- Blood flow
- Perfusion
- Blood oxygenation
- Tissue elasticity
- …

Sequence specific:
- Steady state
- Selective excitation /suppression
- Diffusion
- Flow encoded/dephase
- …

Other MRI quantification:
- B0 / B1 field variation
- Water-fat ratio
- …

- Simple spin echo signal

$$\hat{\rho}(TR, TE) = \rho_0(1 - e^{-TR/T1})e^{-TE/T2}$$

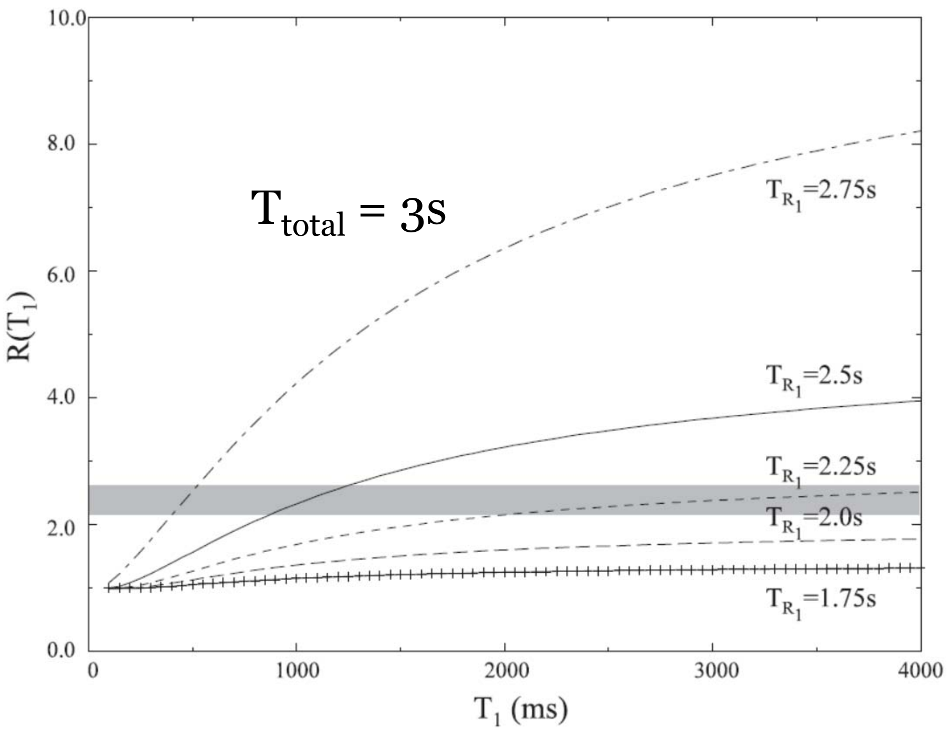
- Spin density weightings
  - TE->0, TR->∞ or TE<<T2, TR>>T1
- T1 measurement
  - TE<<T2, TR<<T1
- T2 measurement
  - TE≈T2, TR>>T1

- Latest development
  - MR Fingerprinting (Ma et al, Nature, 2013)

Signal Ratio Measurements

- T1 (Spin echo)

$$\hat{\rho}1 = \rho_0(1 - e^{-TR1/T1})e^{-TE/T2}$$
$$\hat{\rho}2 = \rho_0(1 - e^{-TR2/T1})e^{-TE/T2}$$
$$R \equiv \frac{\hat{\rho}1}{\hat{\rho}2} = \frac{1 - e^{-TR1/T1}}{1 - e^{-TR2/T1}}$$



Fixed total time constraint:
$T_{total} = N_{acq1}TR_1 + N_{acq2}TR_2$

Works best when TR1>>TR2

Fig. 22.1

Signal Ratio Measurements

- T2 (spin echo)

$$\hat{\rho}1 = \rho_0(1 - e^{-TR/T1})e^{-TE1/T2}$$
$$\hat{\rho}2 = \rho_0(1 - e^{-TR/T1})e^{-TE2/T2}$$

$$\widehat{T_2} = \frac{TE2 - TE1}{\ln(\hat{\rho}1/\hat{\rho}2)}$$

- Similarly for T2* measurement

Multiple signal measurements

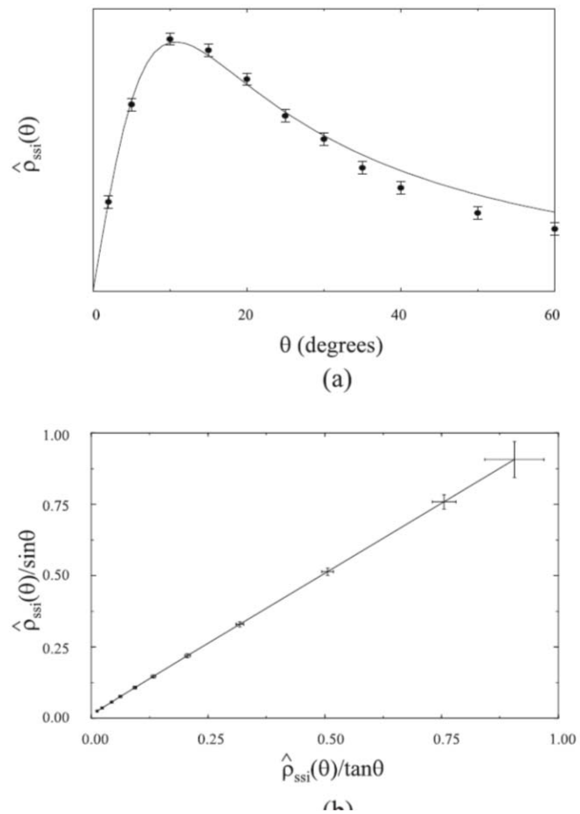
- T1
  - Multiple TR with SR (saturation recovery)
  - Multiple TI with IR (or SR)
  - Nulling point TI with IR

- T2(*)
  - Multiple TE (or echoes)
  - Different echo spacing for SE and GE
  - Partial volume effects or Water exchange effects (dual exponential model)

Misc QMRI methods

- Misc QMRI methods
  - Look locker
  - SSI with multiple flip angle
  - Fingerprinting
  - …

- Practical issues
  - 2D vs. 3D (time)
  - Slice profile
  - B1 inhomogeneity (esp. FSE)
  - Partial volume effects
  - Noise



Susceptibility

- Or magnetic susceptibility, χ, describes the extent of a substance gets magnetized in an external magnetic field

$$\chi = \frac{\mu}{\mu_0} - 1$$

*μ and μ_o are magnetic permeability of the substance and vacuum

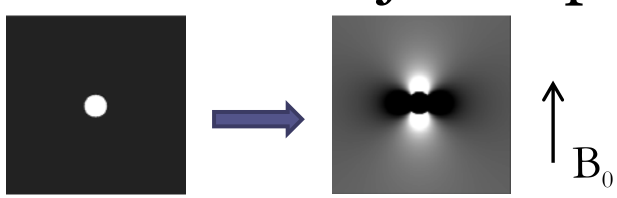
* χ is defined relative to vacuum in physics

* χ is defined relative to water in MRI

*χ is of ppm/ppb scale

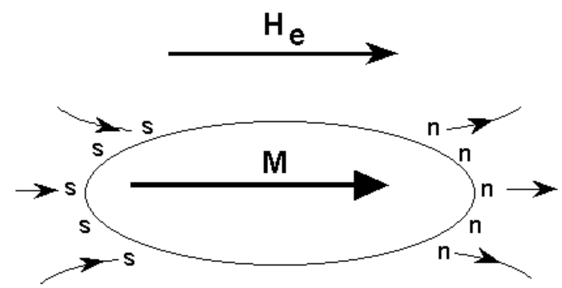
$$\vec{B} = \mu\vec{H}$$
$$\vec{M} = \chi\vec{H}$$

- The magnetic field around the object depends on many factors

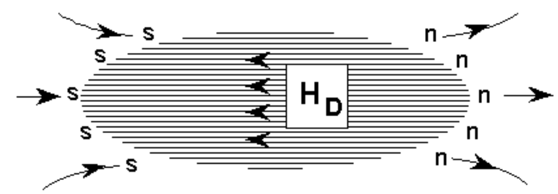


Susceptibility properties

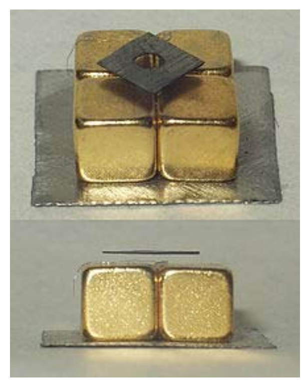
- Paramagnetism / Superparamagnetism
  - $\chi > 0$, i.e. attracted to external magnetic field
  - Increase surrounding fields
  - Iron, magnesium, Aluminum
- Diamagnetism
  - $\chi < 0$, i.e. repulsed by external magnetic field, usually very week
  - Decrease surrounding fields
  - Calcium, water, diamond
- Ferromagnetism
  - $\chi > 0$, and retain magnetization
  - iron, nickel, cobalt, gadolinium, dysprosium, and various alloys and oxides
  - Fridge magnets, Neodymium



Magnetization Produces Apparent Suface Pole Distribution



Demagnetizing Field Due to Apparent Surface Pole Distribution



$H_i = H_e - H_D$

$H_D = NM$

N= demagnetizing factor

Objects in External Fields

- Sphere (e.g. microbleeds)

$$\vec{B}_{out} = [\frac{\chi}{3+\chi}\frac{a^3}{r^3}\left(3\cos^2\theta\,\hat{r} - 1\right) + \hat{z}]B_0 \quad \Longrightarrow \quad \Delta\vec{B}_{out} \approx \frac{\Delta\chi}{3}\frac{a^3}{r^3}\left(3\cos^2\theta - 1\right)\vec{B}_0$$

$$\vec{B}_{in} = 3B_0\frac{1+\chi}{3+\chi}\hat{z} \quad \Longrightarrow \quad \Delta\vec{B}_{in} \approx \frac{2\Delta\chi}{3}B_0$$

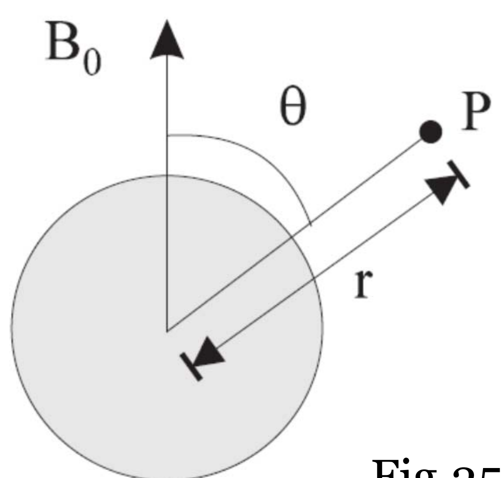


Fig.25.2

Objects in External Fields

- Infinite Cylindrical Body (e.g. vessels)

$$\vec{B}_{out} = \left(\frac{\frac{\chi}{2}}{1+\frac{\chi}{2}} \frac{a^2}{\rho^2} (\hat{x} cos2\phi + \hat{y} sin2\phi) \right) sin\theta B_0 + cos\theta \hat{z} B_0$$

$$\vec{B}_{in} = cos\theta(1+\chi)\hat{z}B_0 + \frac{1+\chi}{1+\chi/2} sin\theta \hat{x} B_0$$

$$\chi_{water} \simeq -9\,ppm$$
$$\Delta\chi_{vein} \simeq 0.45ppm$$

$$\Delta B_{out} = \frac{\Delta\chi}{2} \frac{a^2}{\rho^2} \sin^2 \theta \, cos2\phi B_0$$

$$\Delta B_{in} = \frac{\Delta\chi}{6} \left(3\cos^2 \theta - 1\right) B_0$$

(With $\vec{B}_{int} = -\frac{2\mu_0}{3}\vec{M}$)

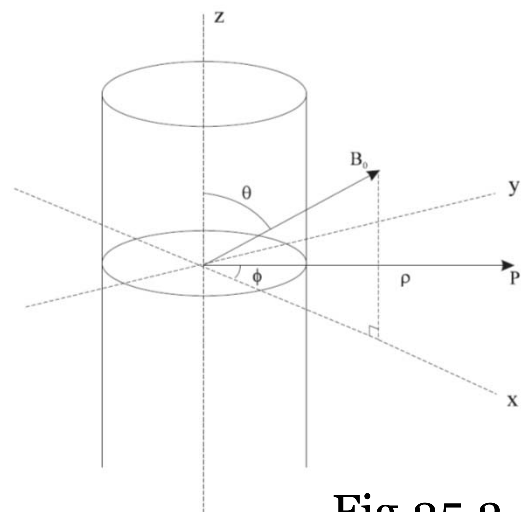
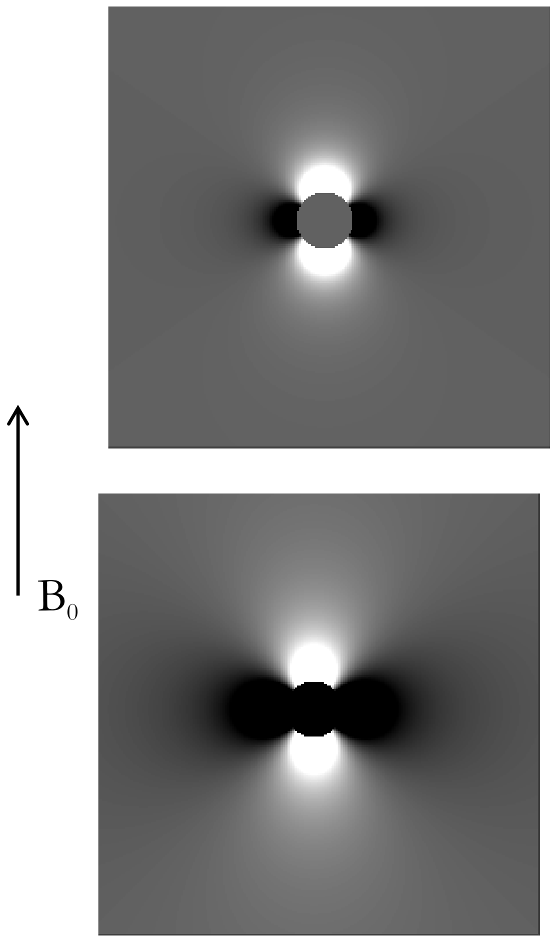
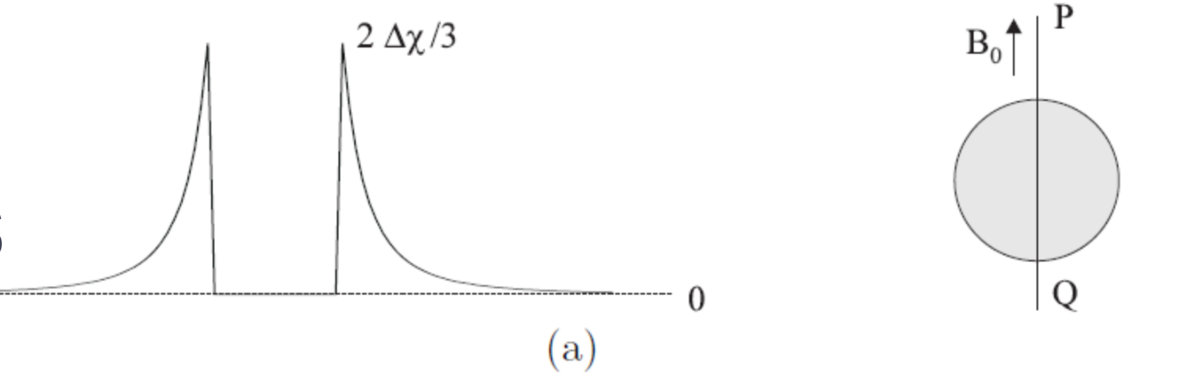


Fig.25.3

Objects in External Fields





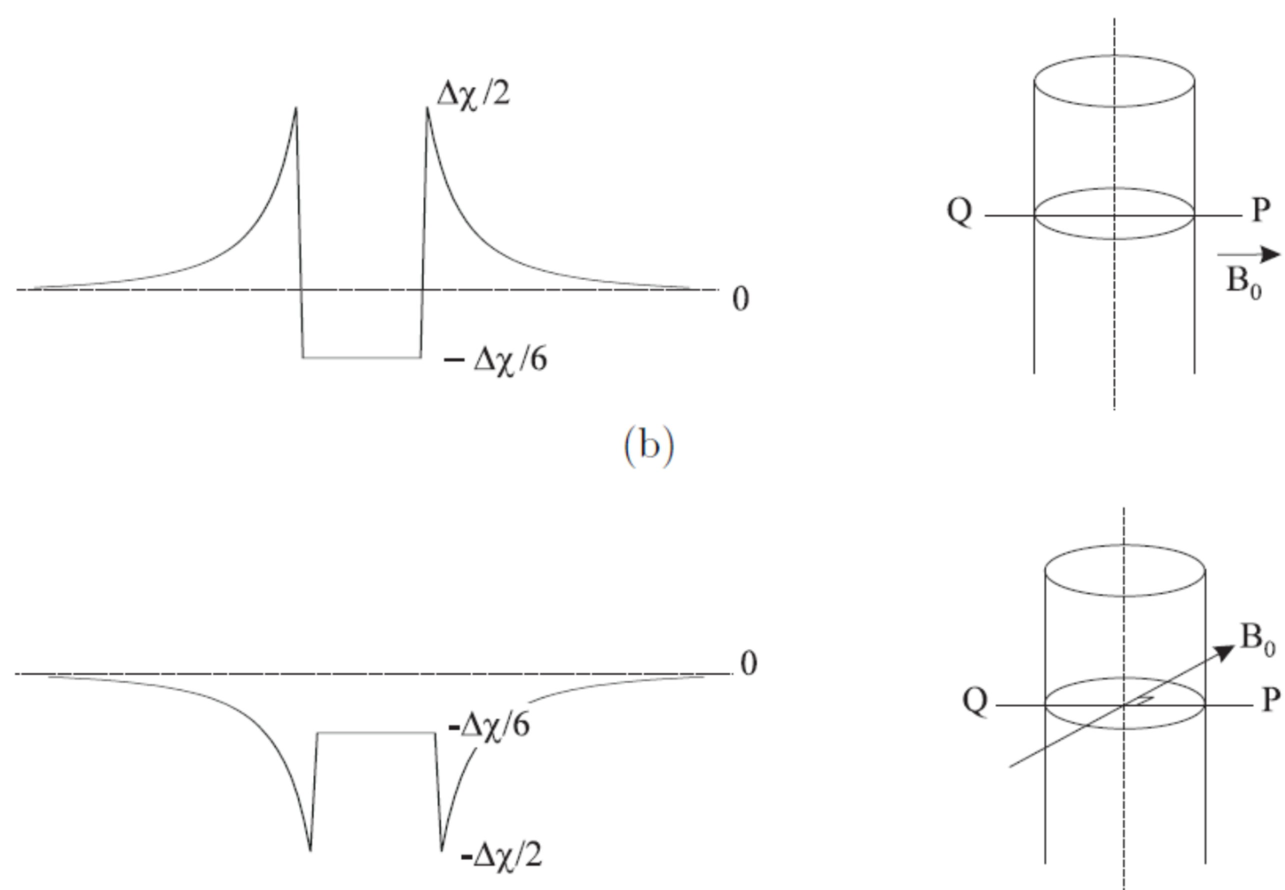


Fig.25.4

Susceptibility effects in MRI

- Effect 1
  - Dipole effect

Sphere

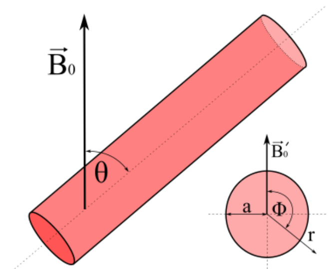
$$\Delta B_{in} = 0$$

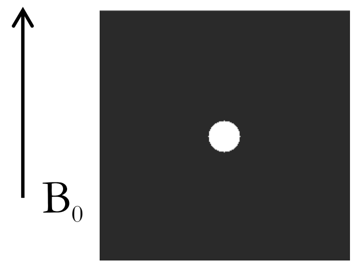
$$\Delta B_{out} = \frac{\Delta\chi}{3}\frac{a^3}{r^3}\left(3\cos^2\theta - 1\right)B_0$$

Cylinder

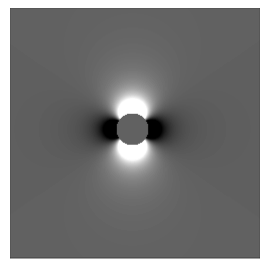
$$\Delta B_{in} = \frac{\Delta\chi}{6}\left(3\cos^2\theta - 1\right)B_0$$

$$\Delta B_{out} = \frac{\Delta\chi}{2}\frac{a^2}{\rho^2}\sin^2\theta\, cos2\phi B_0$$

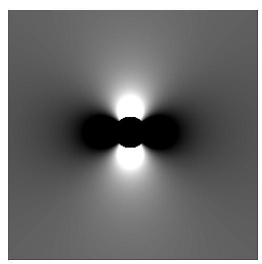




$\chi(r)$

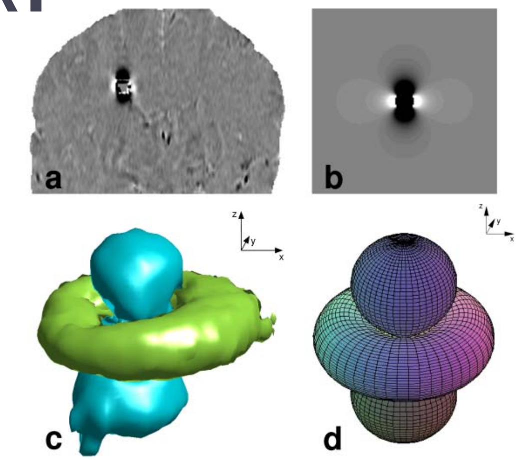


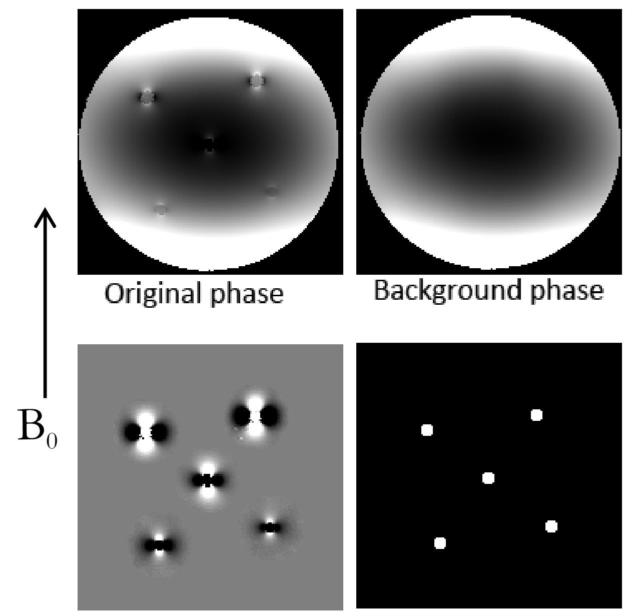
$B(r)$



$B(r)$

Right handed system
$\Delta\chi > 0$





Original phase

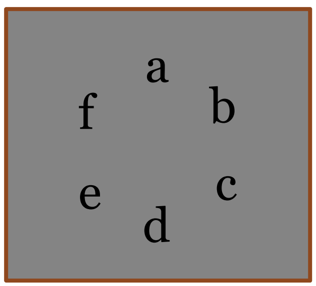
Background phase

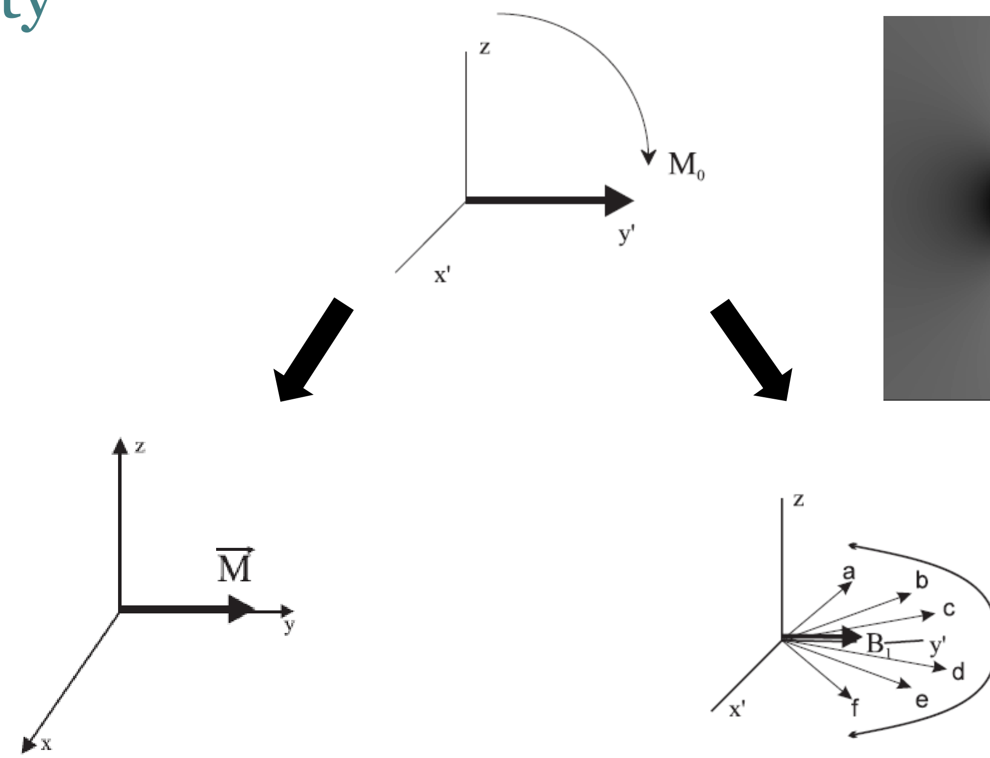
Phase induced by Ferritin samples

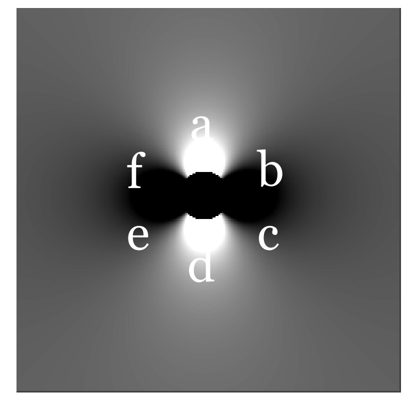
Ferritin samples

Susceptibility effects in MRI

- Effect 2
  - Reducing T2* by increasing local field inhomogeneity





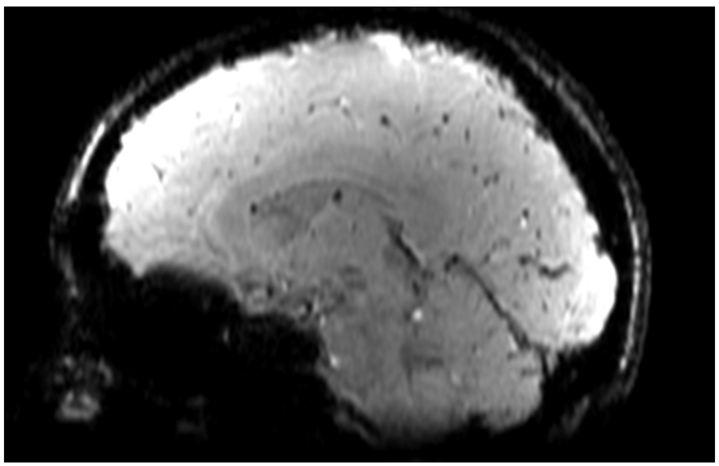


T2 decay (ideal)

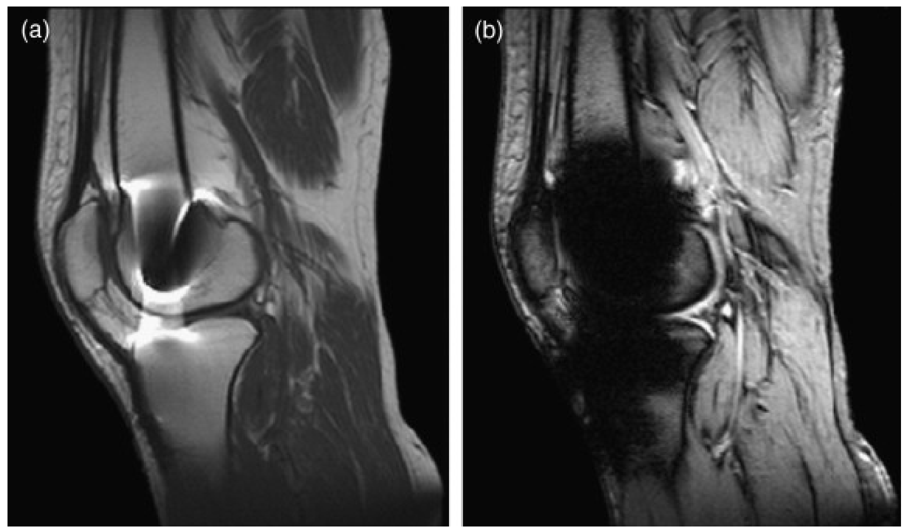
T2* decay (actual)

Susceptibility effects in MRI

- Effect 3
  - Signal dropouts and distortion at boundary with large susceptibility difference (global)



Sagittal GRE image with long TE

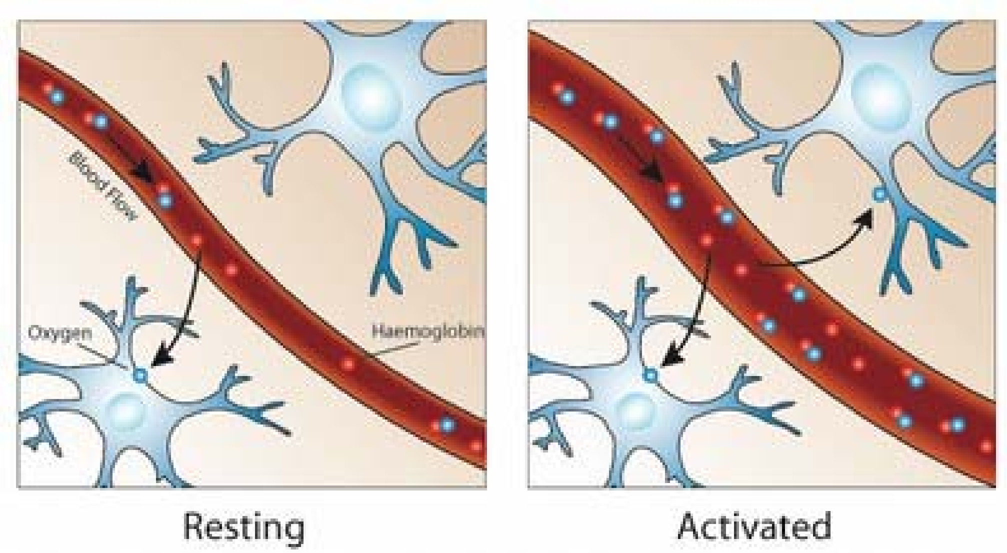


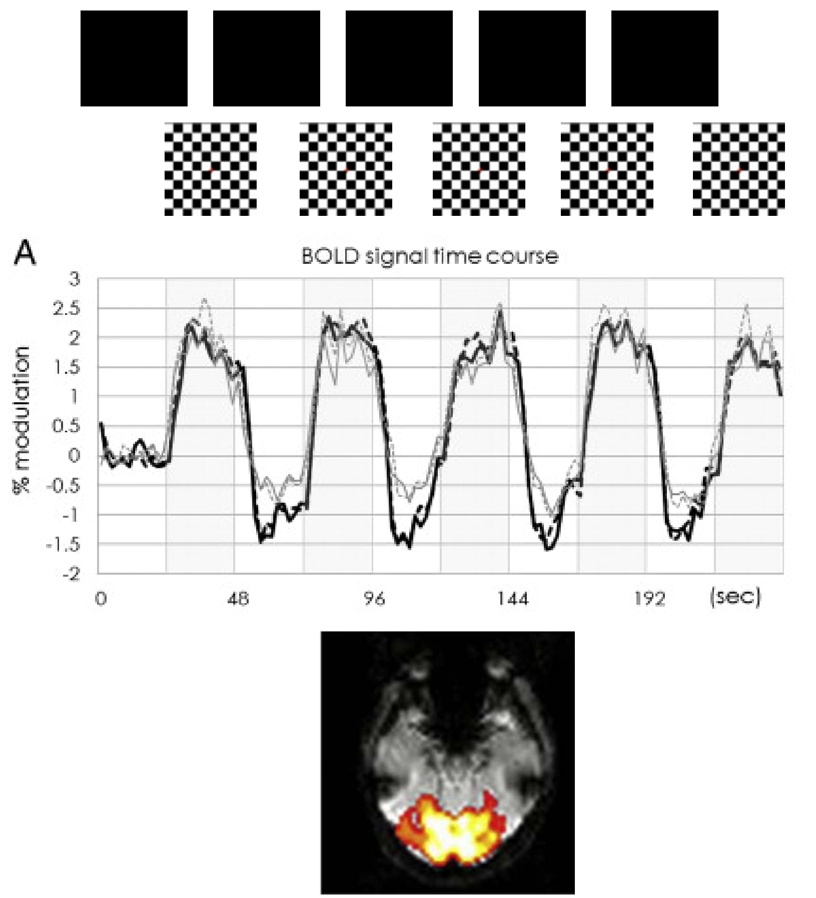
(a) Ferromagnetic artifact seen in a T2 TSE sagittal image of the knee joint due to fixation screws in the femur.
(b) A corresponding T2 GRE image was unreadable due to blooming effect in a GRE pulse sequence.

(Kaur et al. Radiography, 2007)

Susceptibility effects in MRI

- Effect 4:
  - BOLD effects





Susceptibility and BOLD effects

- Venous blood susceptibility is related to oxygen saturation, hematocrit (HCT) and blood flow
  - Oxyhemoglobin – diamagnetic
  - De-oxyhemoglobin – paramagnetic

- Oxygen saturation level (Y) estimation

$$\chi_{blood} = Hct\left(Y\chi_{oxy} + (1 - Y)\chi_{deoxy}\right) + (1 - HCT)\chi_{plasma}$$

$$\Delta\chi_{blood} = -\Delta Y\left(\chi_{deoxy} - \chi_{oxy}\right)HCT$$

$$\chi_{do} \equiv \chi_{deoxy} - \chi_{oxy} = 4\pi \cdot 0.18\, ppm/HCT$$

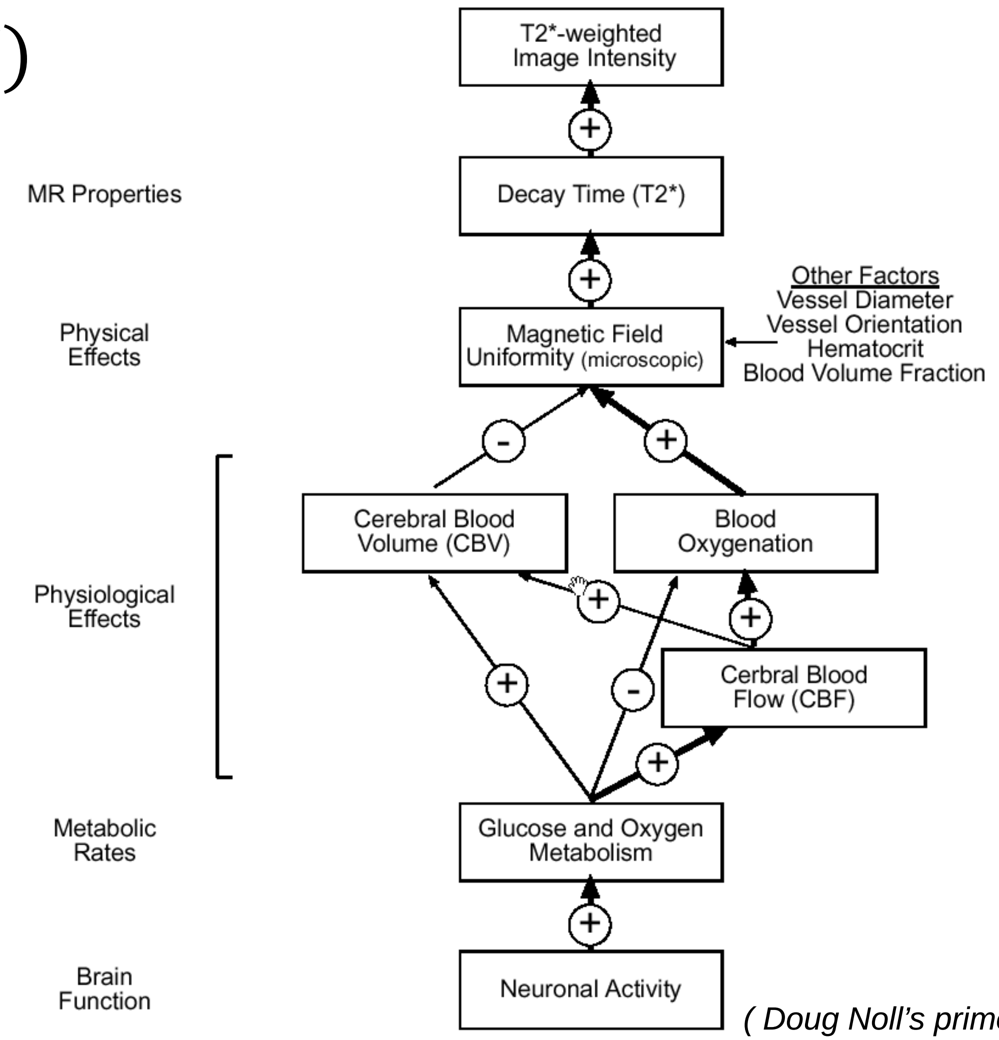
$$\chi_{blood,relative} \cong \chi_{blood} - \chi_{oxy}$$
$$= 0.72\pi \cdot HCT(1 - Y)ppm$$

Oxygen saturation level and blood low

$$\Delta Y = \left(1 - \frac{\beta}{1+\alpha}\right)(1-Y)$$

$$\overset{\beta=1}{\Longrightarrow} \Delta Y = \frac{\alpha}{1+\alpha}(1-Y)$$

α: relative blood flow change
β: relative metabolic rate change



(Doug Noll's primer)

Measuring local magnetic field variations

- Phase imaging

$$\phi(\vec{r}, TE) = -\gamma \Delta B(\vec{r}) TE + \phi_0$$

- Note: susceptibility is only one of the properties that affect image phase, others include
  - chemical shift
  - motion (e.g. blood flow)
  - field inhomogeneity
  - RF pulses
  - Gradients, eddy currents, etc.

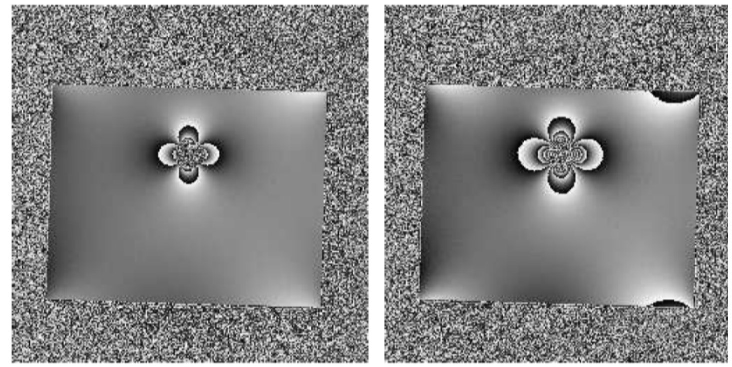


Fig. 25.5

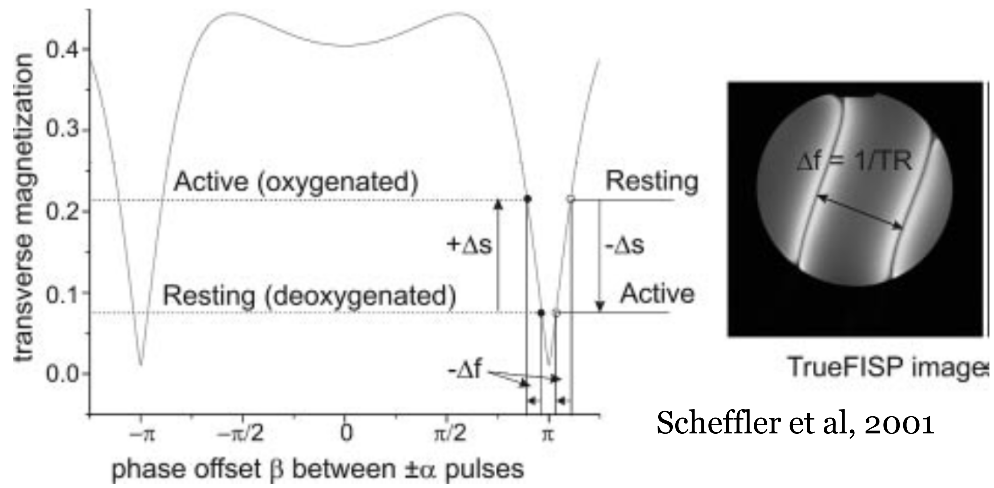
- Only susceptibility variation can lead to dipole effects outside of the source

- Phase information is best revealed by high resolution gradient echo sequence

- MRI images only stores phase in a 2π range, thus phase wrapping can occur

Measuring local magnetic field variations

- Magnitude imaging
  - SSFP (SSC)
  - T2* mapping (ME GRE)
  - T2 mapping (FSE)



Scheffler et al, 2001

- Phase imaging
  - GRE
  - Shift echo SE

Homework

- *22.2, 22.3, 22.4, 22.6*
- *25.2, 25.5, 25.10, 25.11*

Next Session

Chapter 23