26-11-2018

MR Basics

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Images from:
Mark Cohen's web slides
Robert Cox's web slides
Jody Culham's web slides
Karla Miller's web slides
MRI picture to Proton
Buxton's Introduction to fMRI

Spinoza FMRI Course 2018

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Learning goals

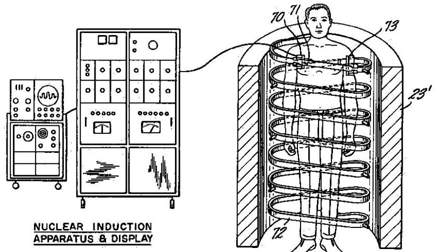
Know the basics of:

• equipment	(magnets, coils)
• image contrast	(signal differences)
• image formation	(echoes, frequencies)
• scan parameters	(repetition time, resolution)
• BOLD contrast	(blood oxygenation)
• MRI scan terminology	(kspace, SENSE, multiband)

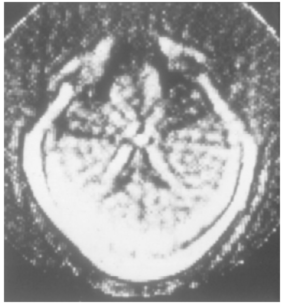
Basic fMRI physics and acquisition

- The equipment
- Image contrast
- Physics behind MRI
- How to make an MRI image - acquisition
- Blood magnetics; blood-oxygenation-level dependent (BOLD) fMRI

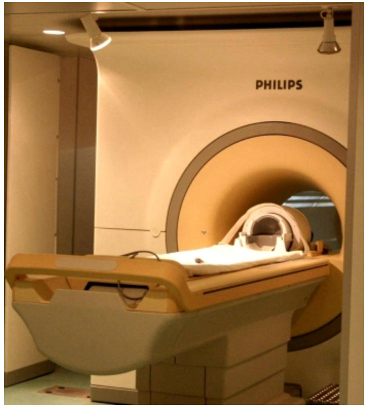
A little bit of MR history



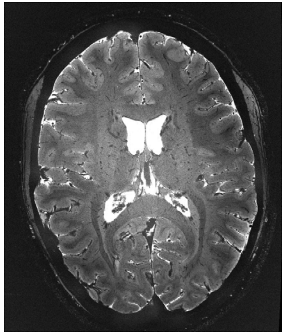
Ryamond Damadian 1974



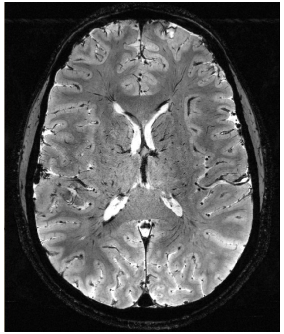
First ever human head image using MRI at 0.1 T 1978



7 Tesla MR system

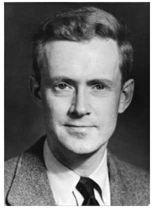


Head image 7 T (2001)

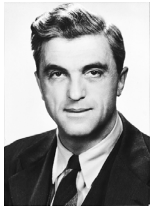


Head image 9.4 T (2009)

Nobel prize-winners

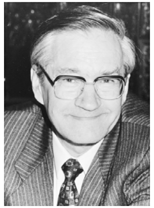


Purcell 1912–1997



Bloch 1901–1999

Bloembergen b. 1920



Ernst b. 1933

Lauterbur b. 1929

Mansfield b. 1933

Erwin Hahn 1921-2016

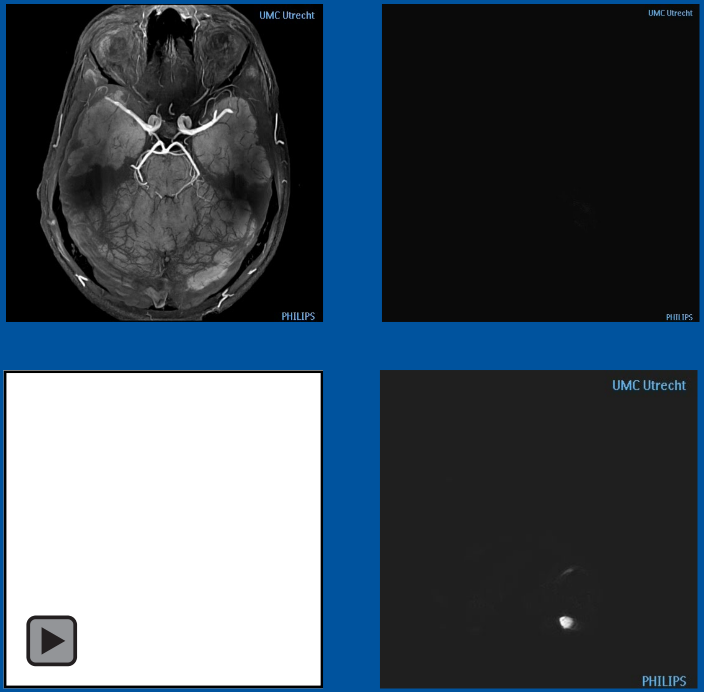
MRI data explosion

For one scan

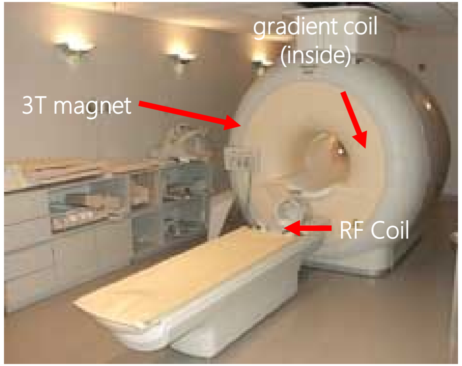
yesterday: 64^2, 32 slices
1.5Mb of data or 1 book

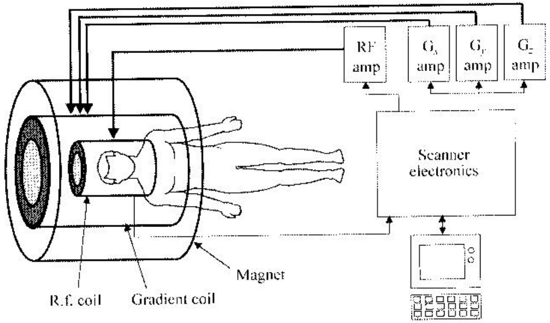
today: 128^2, 32 slices, 2s, 10min
4Gb of data or 80 books

tomorrow: 512^3 voxels, 100ms, 10min
1Tb of data or 800.000 books

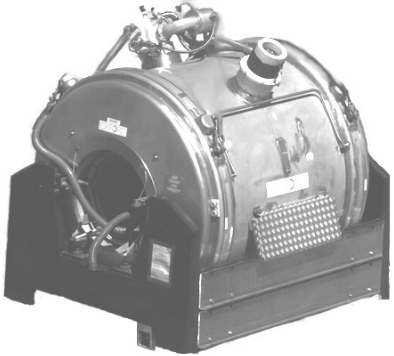


The necessary equipment



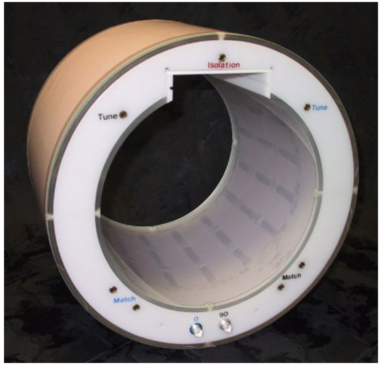


Magnet



Gradient Coils

Radiofrequency (RF) Transmit Coil



Receive Coil

Source: Joe Gati, photos

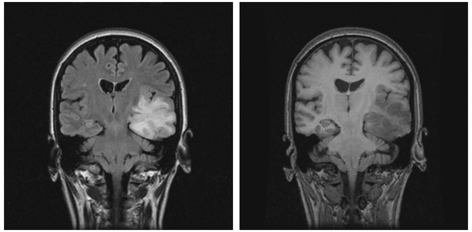
Image contrast

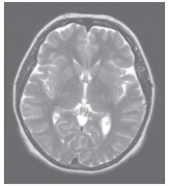
MRI: All about image contrast

Contrast: difference in signal intensity between tissues

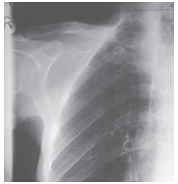
Depends on:

- **proton density** of hydrogen nuclei in tissue
- time that protons produce signal
    - **magnetization relaxation properties** of protons (T1, T2)
    - MRI specific!
- endogenous contrast: ‘fMRI’ BOLD effect
    - tissue condition (oxygenation level, T2*)
- exogenous contrast: contrast agents, perfusion
    - requires a foreign substance (e.g. Gadolinium)
- motion: flowing blood, water diffusion





MRI



Conventional X-ray

MR image
- image resolution
- voxels

MRI: All about image contrast

Different contrasts can be obtained by different imaging techniques

- *pulse sequences*: radiofrequency (RF) pulses and gradient pulses
- *duration* and *timing* influence the image contrast

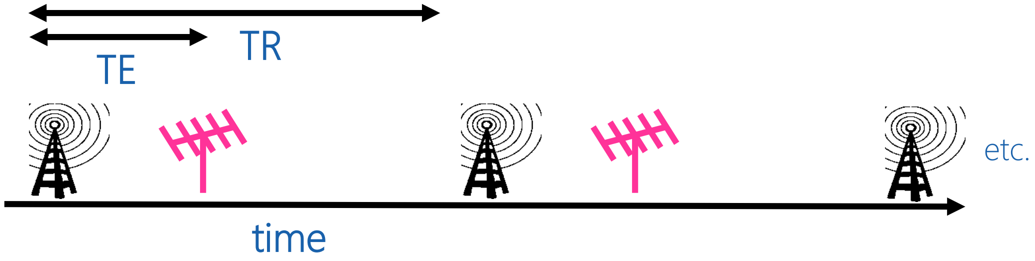
Very basic anatomy of an MRI scan:

1. place object in strong magnetic field: atoms align to field→ creating a very small magnetic field
2. transmit RF pulse: protons absorb energy
3. wait
4. 'listen' to RF emission from the protons
5. wait, Goto 2

Echo Time (**TE**): time between step 2 and 4 is our

Repetition Time (**TR**): time between step 2 and step 5

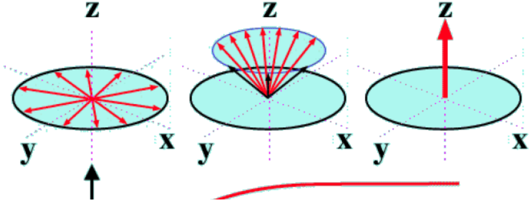
TR and TE influence image contrast

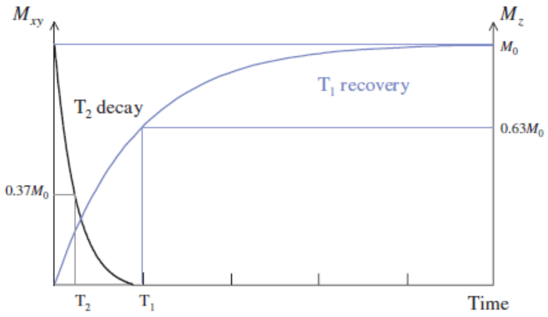


T1 (tee-one) and T2 (tee-two) definitions

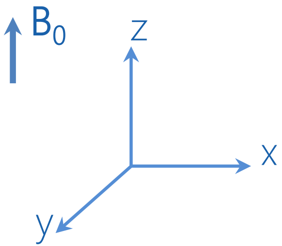
After excitation: two relaxation processes crucial for image contrast

- T1-Relaxation: Recovery
  - recovery of longitudinal magnetization M_z to equilibrium losing energy
  - spin-lattice interaction (thermal motion)
  - Very slow!





- T2-Relaxation: Decay (dephasing)
  - loss of transverse magnetization M_{xy} losing coherence
  - spin-spin interaction
  - Very fast!



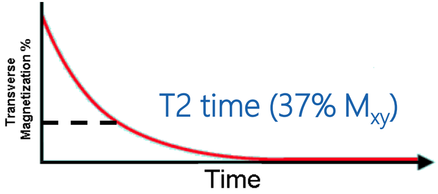
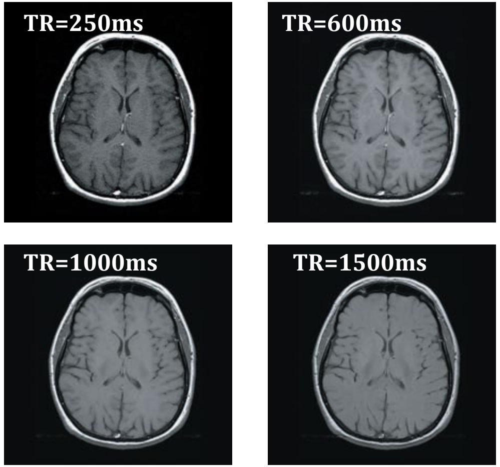


Image contrast: T1 and T2 Effects

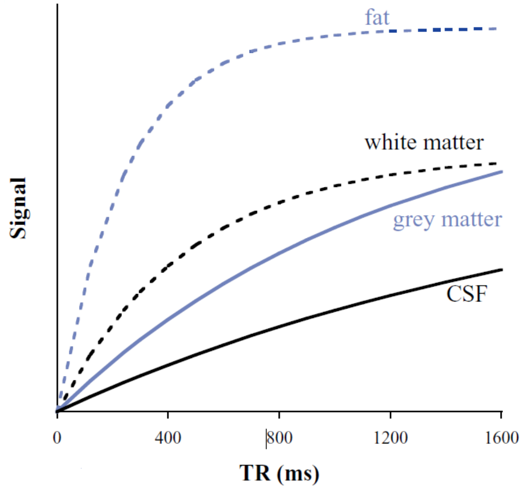
- T1 effects measure recovery of longitudinal magnetization
- T2 refers to loss of transverse magnetization
- **T1 and T2 vary for different tissues (T1>T2, factor 10 for brain)**

For example, fat has very different T1 and T2 than CSF
This difference causes these tissues to have **different image intensities.**

- **T1 weighting** (T1w) is primarily influenced by **TR**
- **T2 weighting** (T2w) by **TE**

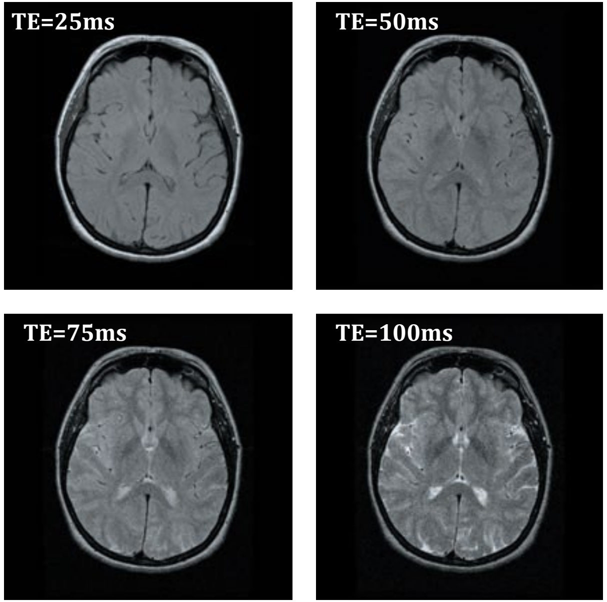


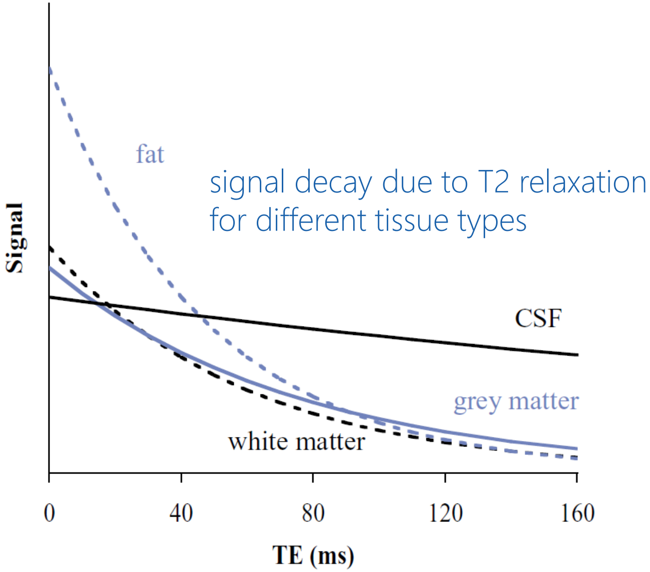
Changing repetition time (TR): different T1 contrast



T2-weighted contrast

changing the echo time: different T2 contrast





T1- and T2-weighted contrast

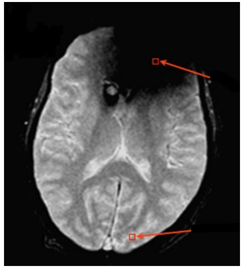
- Every scan is influenced by both T1 and T2 effects
- Adjusting scan parameters, TE and TR, determines which effect dominates:
  - T1-weighted images use short TE and short TR.
    - fat bright (fast recovery), water dark (slow recovery)
    - anatomy scans
  - T2/T2*-weighted images use relatively long TE and long TR:
    - fat dark (rapid dephasing), water bright (slow dephasing)
    - functional BOLD scans (T2* weighted)

flip angle
preparation pulses

T1 weighted image

T2 weighted image

T2* weighted image



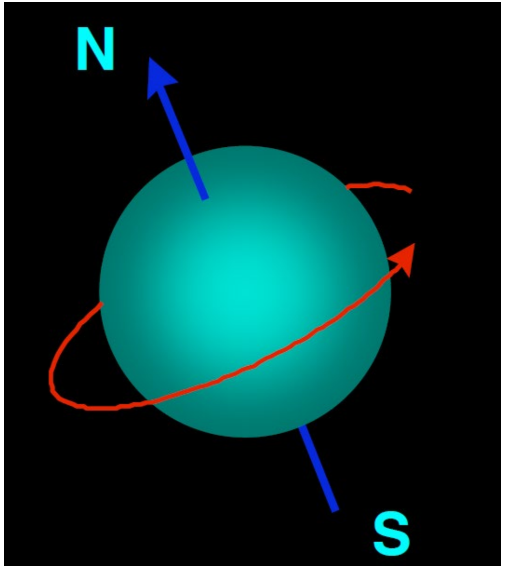
metal artifact above (obvious)
BOLD effect (subtle version)

Some Physics

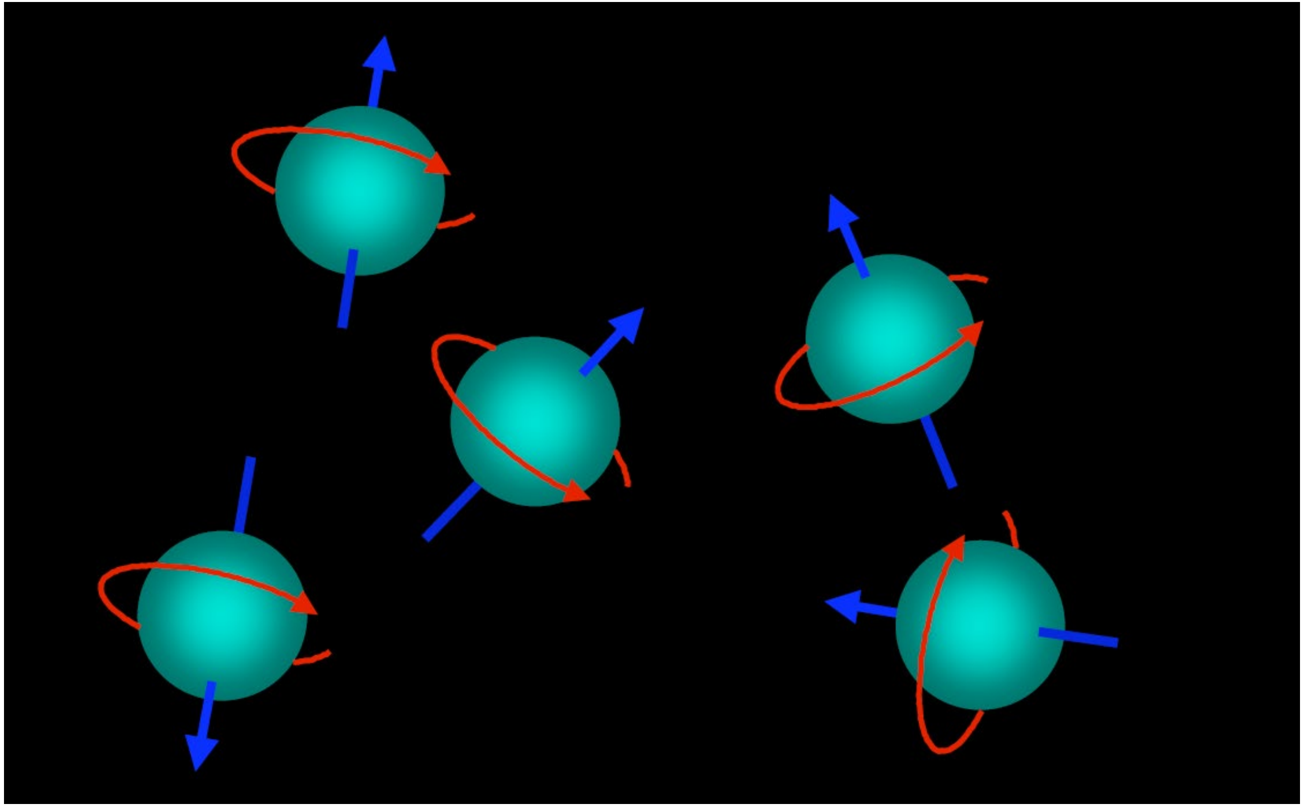
Physics of Nuclear Magnetic Resonance

Hydrogen nuclei: protons
very abundant in human body

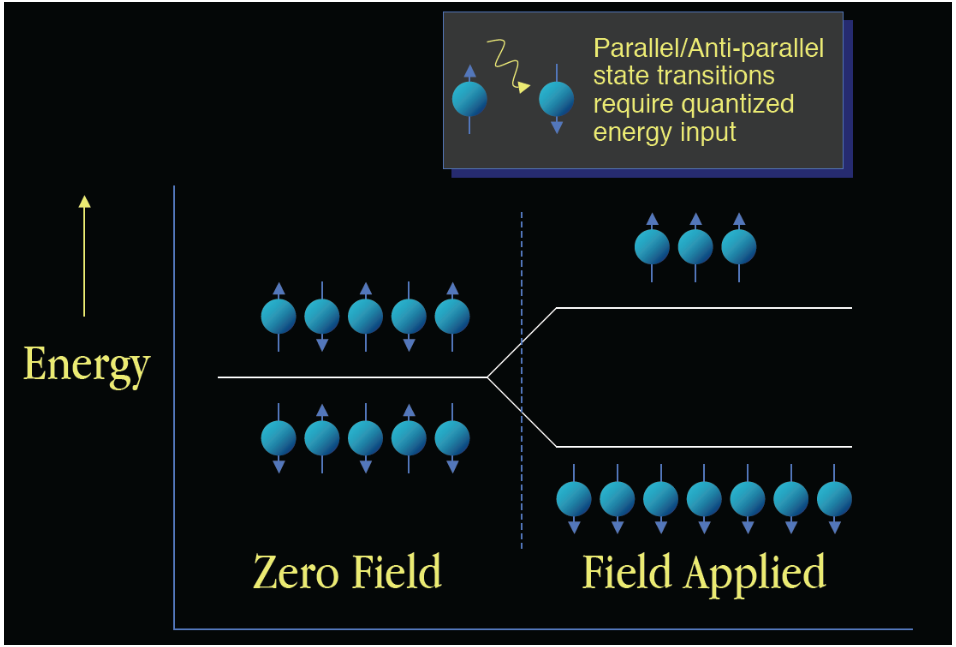
proton SPIN and MAGNETIC moment (like a compass needle)



Free protons



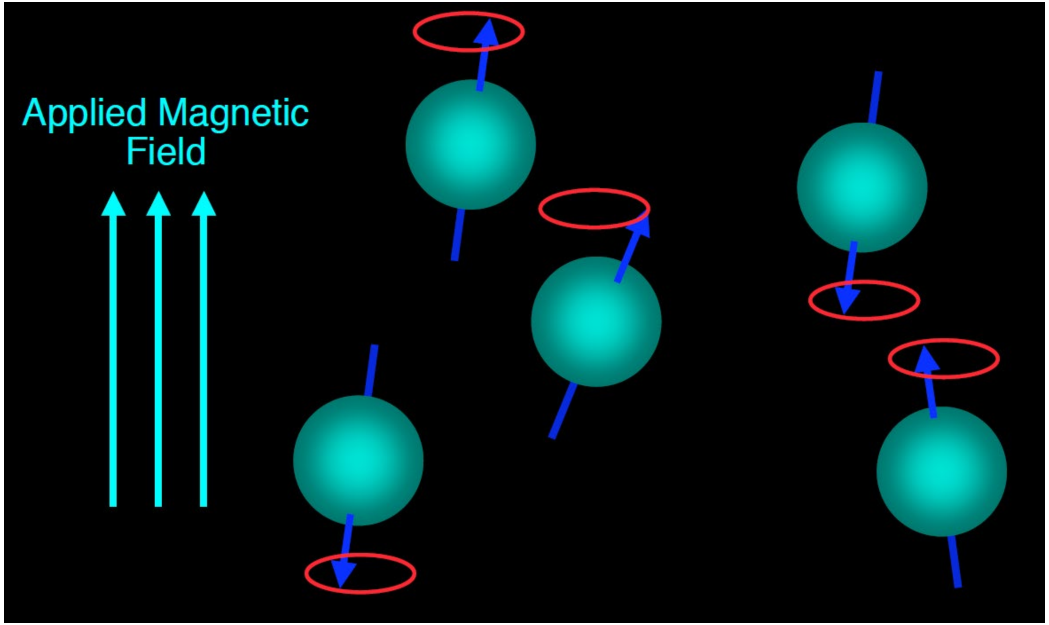
Transition to equilibrium

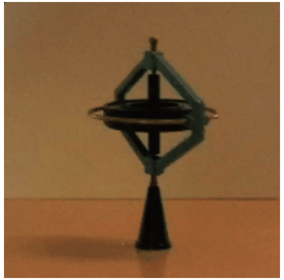


very small net magnetic field M_0 from all the protons

water contains 6.67×10^{22} protons per ml
human head contains ≈ 1500 ml of water
then $M_0 \approx 0.00002$ Tesla
very small compared to main field (1.5 T) but measurable!

Protons in Applied Field: Precession





due to their magnetic moment, Protons precess in the magnetic field at the **Larmor frequency**

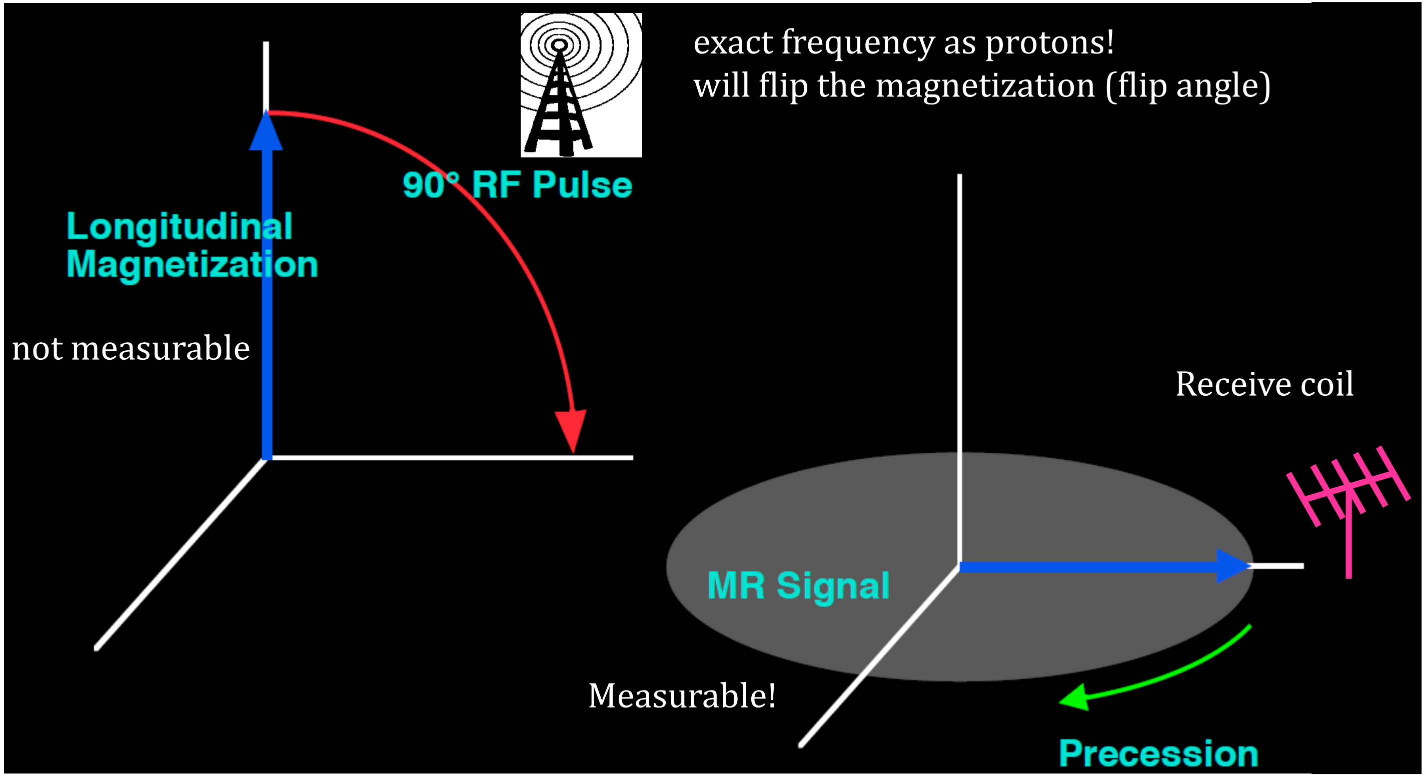
$$f_{Larmor} = \frac{\gamma}{2\pi} B_0$$

1.5Tesla = 63.8MHz

3.0Tesla = 127.7MHz

7.0Tesla = 298.2MHz

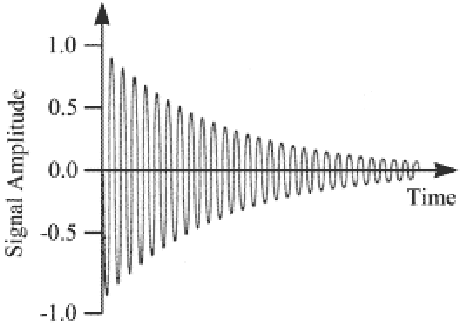
Getting a signal: radiofrequency pulse flips proton spins



Signal decay analog

After RF transmission, we can detect RF emission

- Emission at **Larmor frequency:**
- Emissions amplitude decays over time, because of:
  - spin-spin interactions (T2)
  - local & global magnetic field disturbances (BOLD effect, magnet imperfections (T2’)
  - combined effect is called T2* (tee-two-star) relaxation
- Analogous to tuning fork: frequency constant, amplitude decays

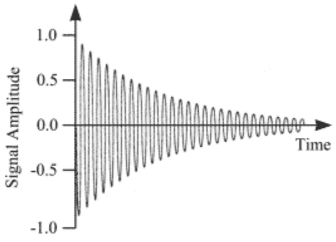


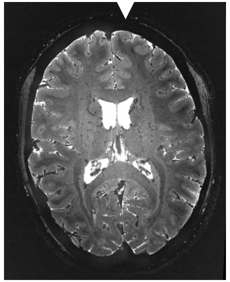
Making an image: spatial encoding

Create a signal

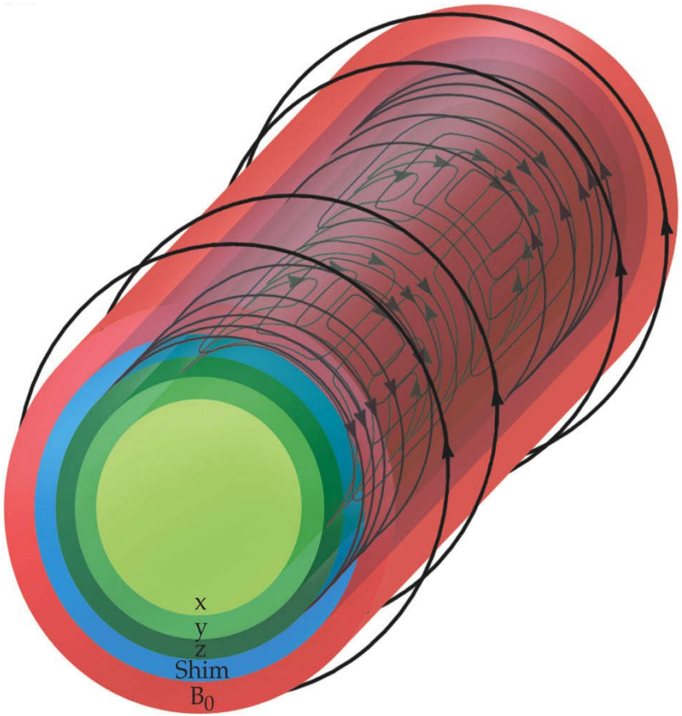
To create an image we need localization: spatial encoding

Gradient coil



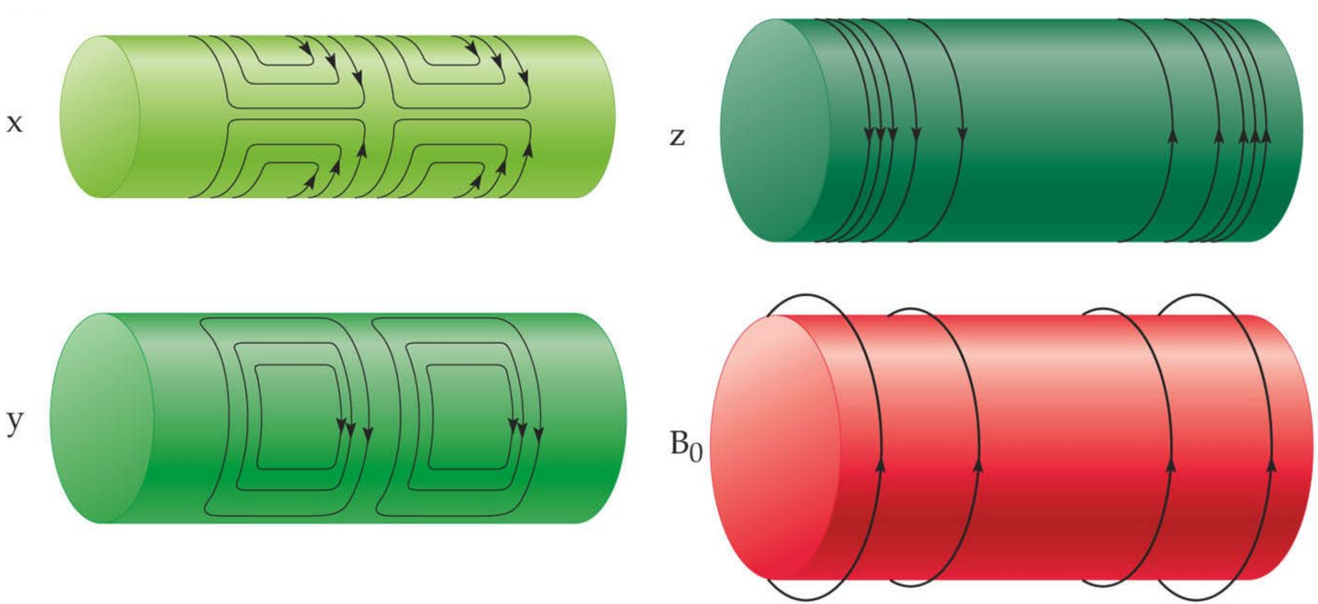


The Gradients

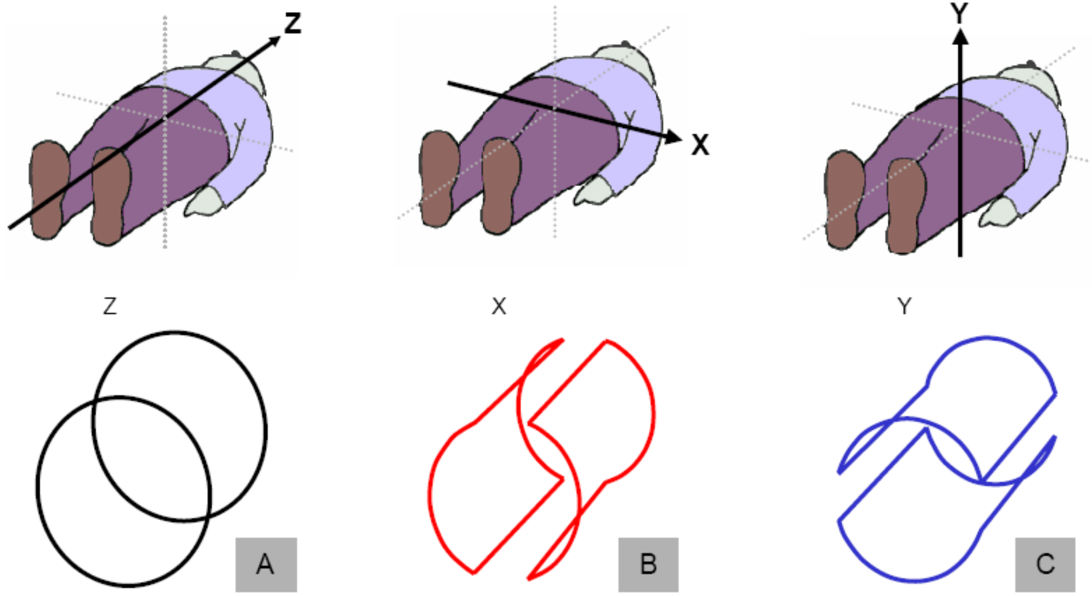


The Gradients

Gradients are magnets that apply changes to the main magnetic field (B_0) which depend on the **location** in the scanner

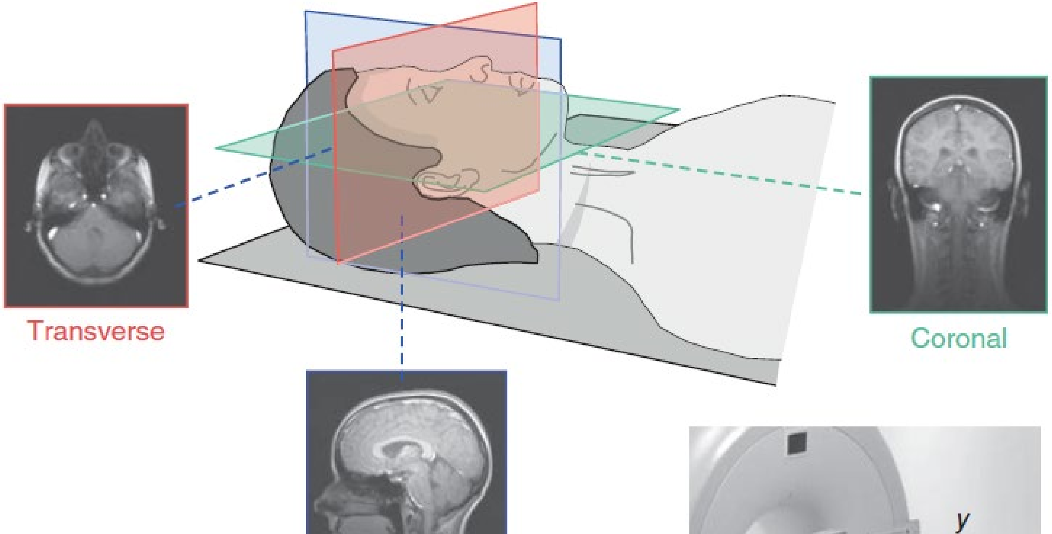


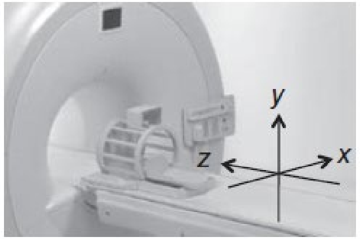
The Gradients



Precession of hydrogen nuclei will depend on location!

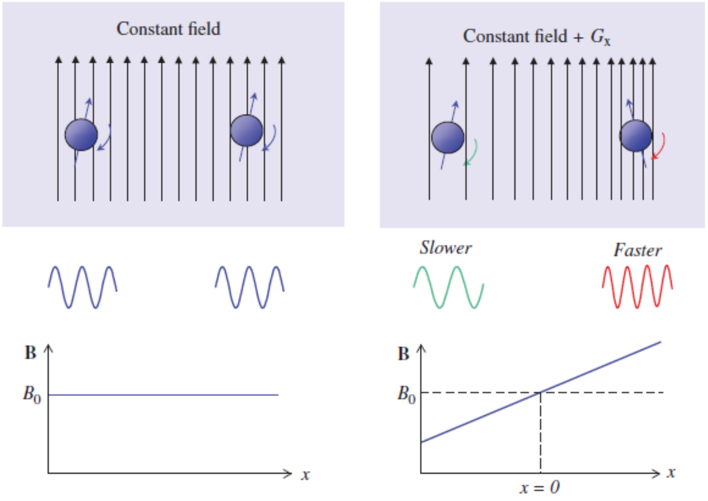
Example: Slice selection

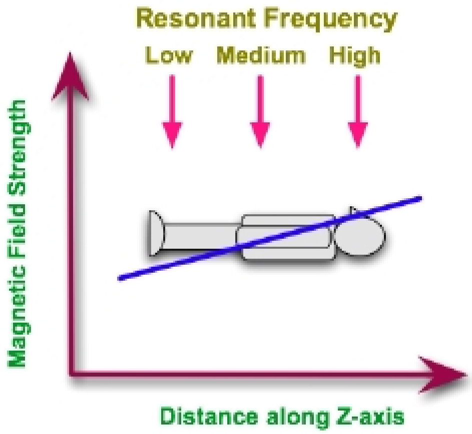




Example: Slice selection

constant magnetic field: Larmor frequency is equal for all locations

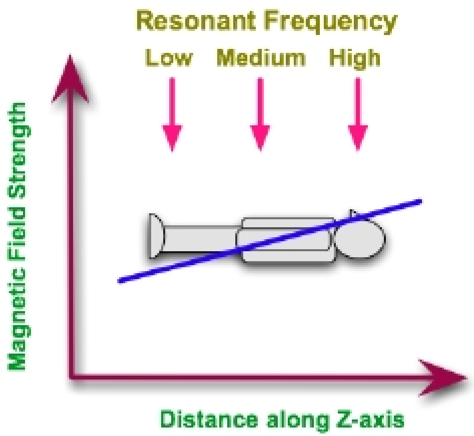


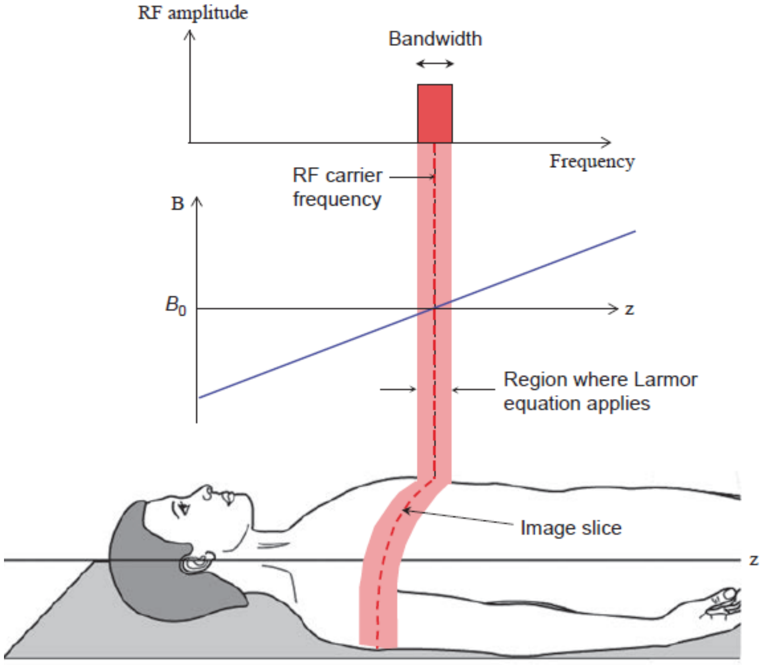


Switch on a gradient: Larmor frequency now depends with position along gradient axis

Example: Slice selection

Tune your slice exitation RF pulse to match range of Larmor frequencies

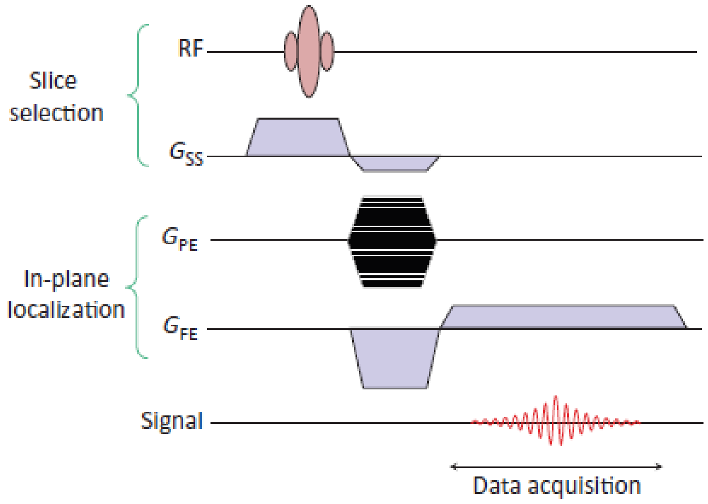




Scanning sequence

Pulse sequence diagrams show the rf pulses and activity of the gradients

- slice excitation RF pulse →
- slice selection gradient →
- encoding (phase) Gradient →
- encoding (frequency) Gradient →
- getting your signals →



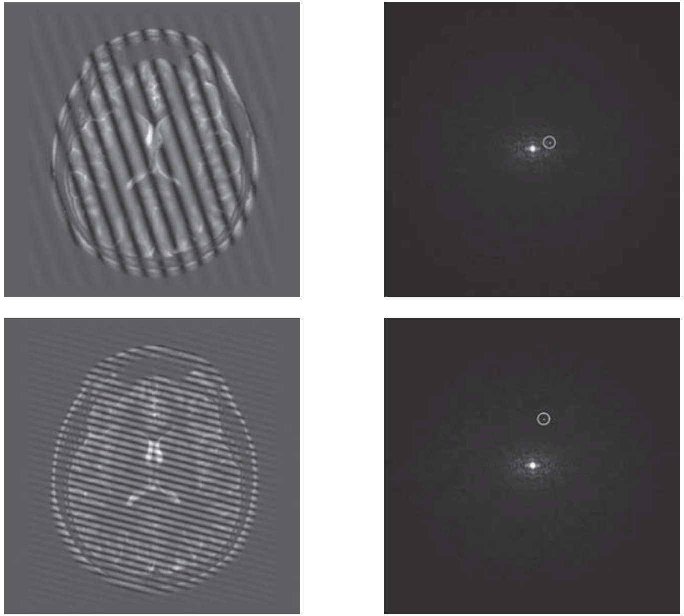
Data represent ‘spatial frequencies’ of the image

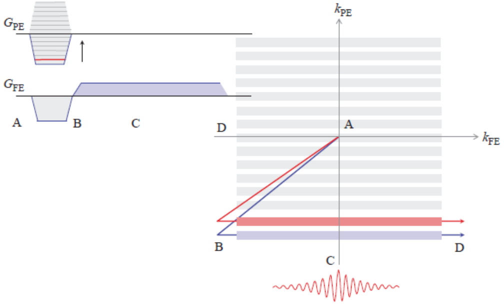
frequency space - ‘k’-space

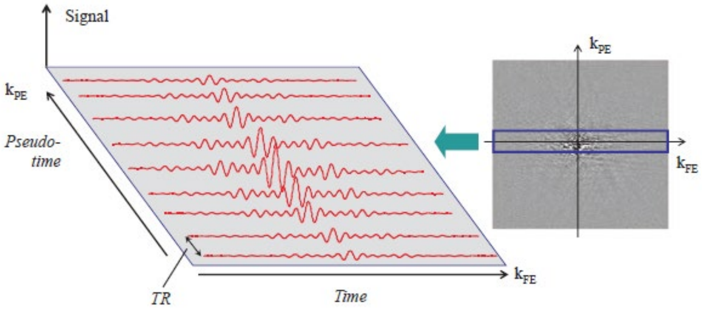
music analog (bass, mid, treble)

image space

frequency space
‘k’-space







Data represent 'spatial frequencies' of the image

frequency space
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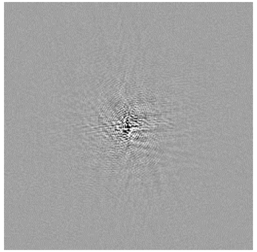
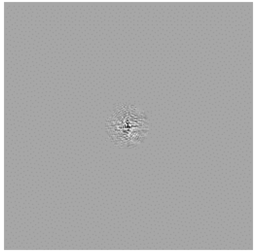
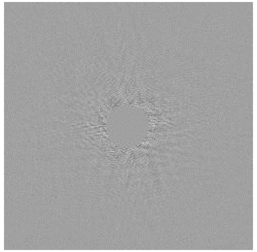
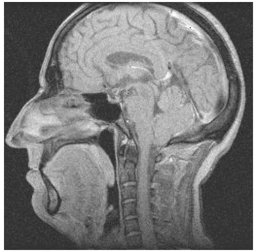


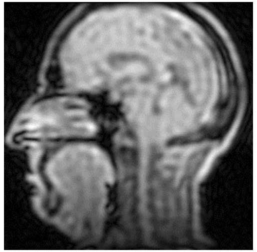


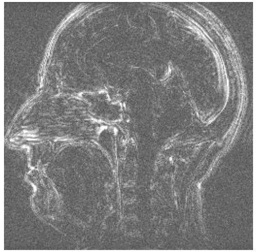


mathematics! Fourier transform
we want to see brains not frequencies

image space

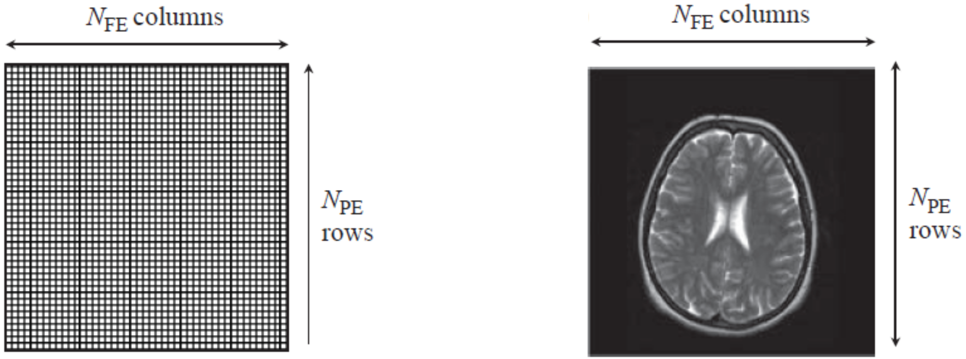


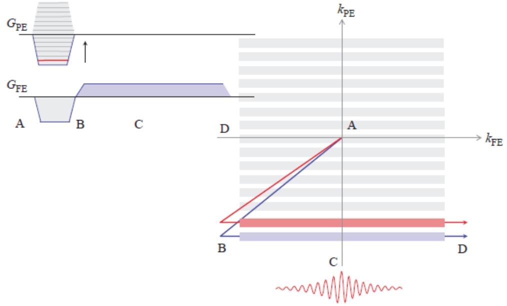


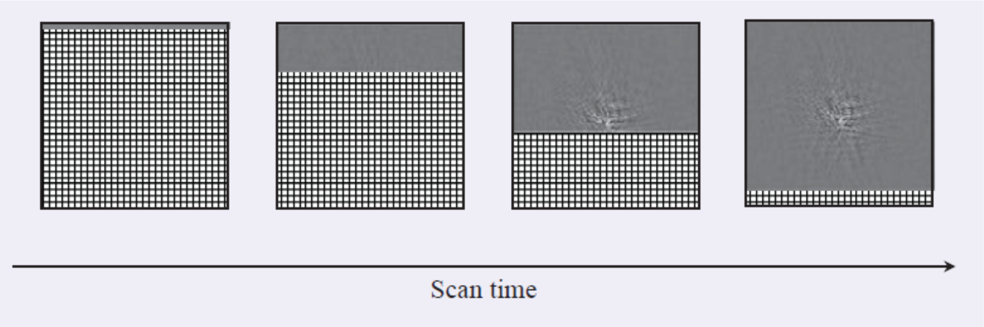


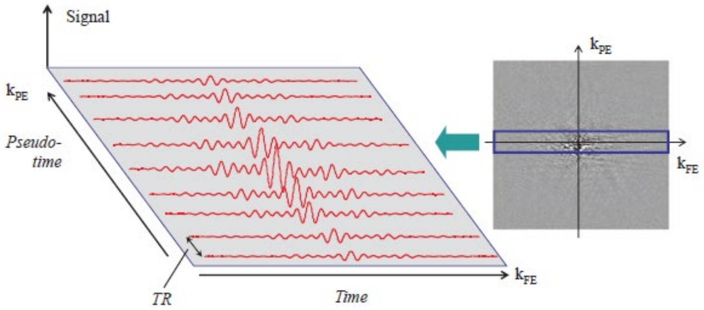
Filling kspace: collecting echoes

Kspace: raw data space
One echo (length of frequency encode) for each phase encode step



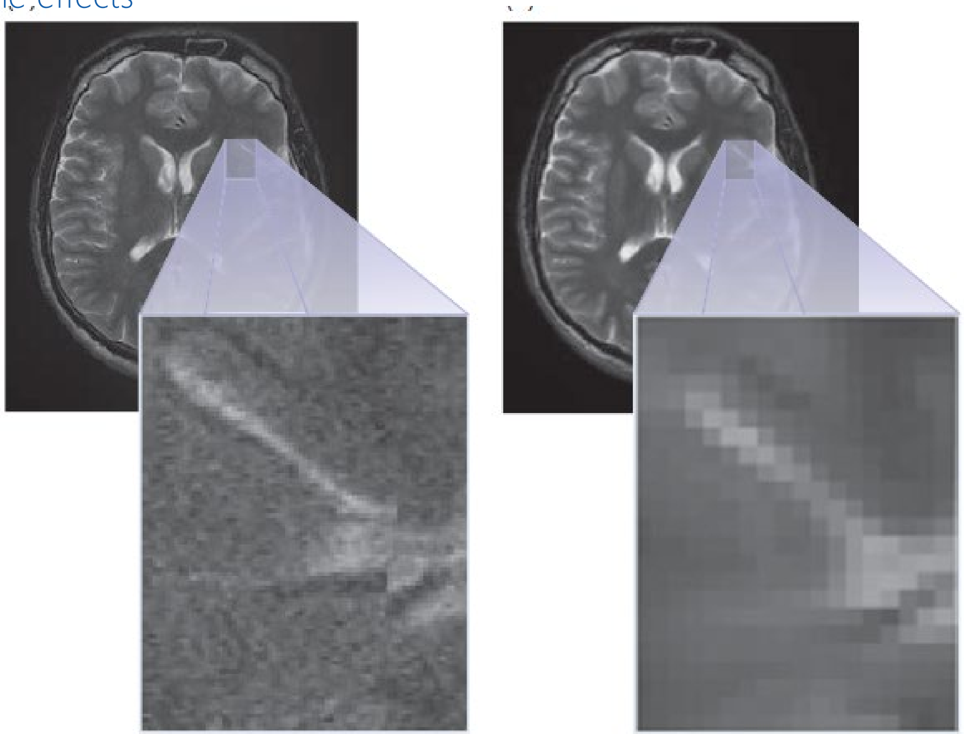






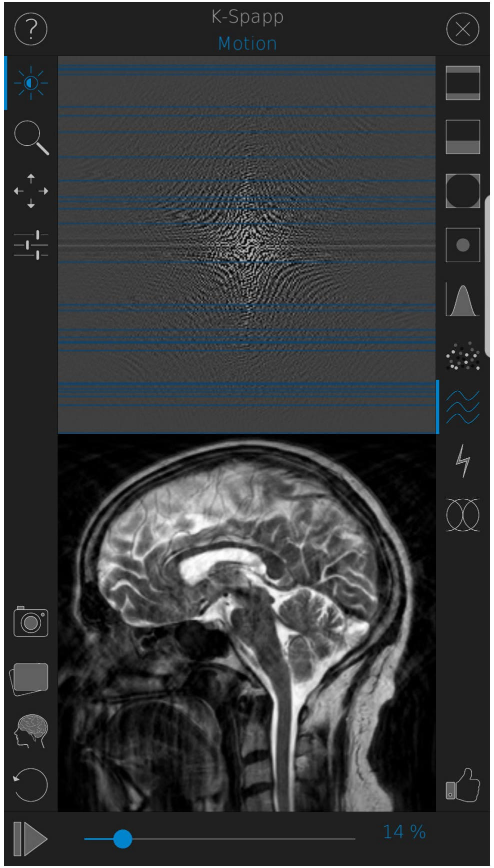
Resolution

- determined by highest spatial frequency: k_{max}
- Increases scan time, reduces signal-to-noise ratio (SNR)
- partial volume effects



scan with $0.25 \times 0.25 \times 3.00$ mm^3 voxels. (b) The same slice position with $1 \times 1 \times 3$ mm^3 voxels showing the partial volume effect.

Data represent 'spatial frequencies' of the image

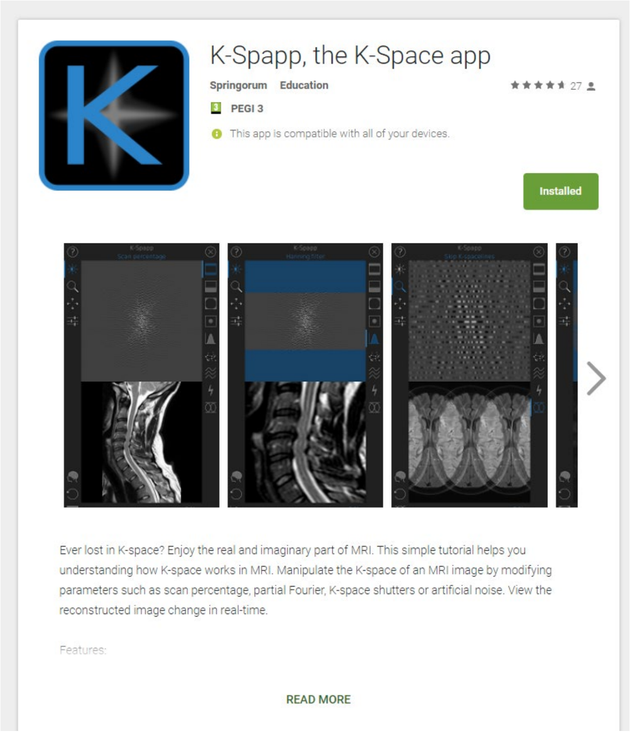


a K-space app!

K-space

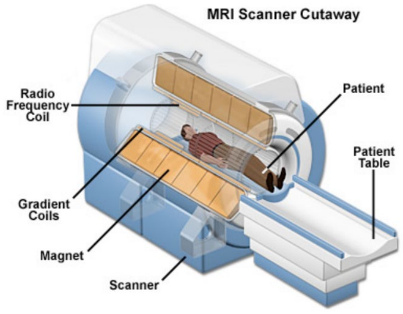
<- playing with some motion

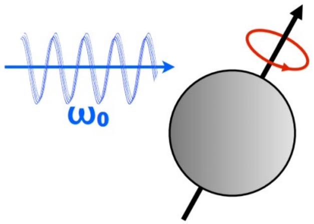
image space



Summary MRI

1. Nuclear magnetic moments align with strong field (a bit)
2. RF pulses cause excitation
   when at resonance frequency (e.g 128 MHz. for 3 Tesla)
3. Magnetization precesses and relaxes after RF pulses
4. Detect transverse magnetization that is spatially encoded
5. Repeat with different gradients applied
6. Reconstruct image





Sequence jungle functional MRI

BOLD

3D T2prep-GE

3D GRASE

2D SE-EPI

3D GE-EPI

3D PRESTO

2D GE-EPI

3D FLASH

3D bSSFP

cerebral
blood flow
blood volume

VASO (SS-SI)

PCASL

PASL

acceleration
methods

SENSE/GRAPPA/iPAT

multiband/
simultaneous multislice

CAIPIRINHA

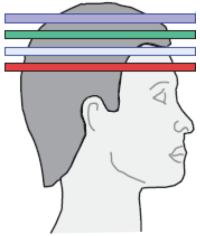
Gradient-echo Echo Planar Imaging (EPI)

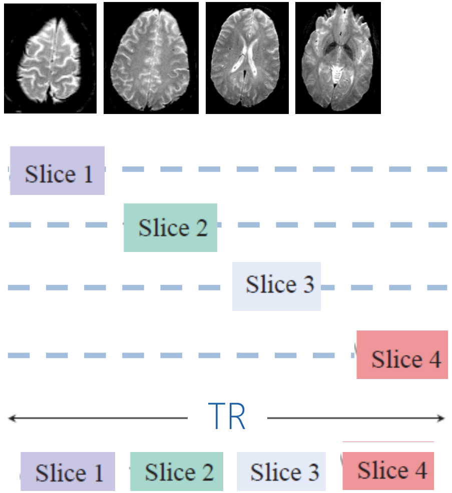
Very typical whole brain BOLD fMRI at 3T:

- workhorse for fMRI
- **multi-slice** 2D acquisition
- ~30-50ms per slice! – but a 'bit' distorted
- voxel size = 2.5 mm isotropic
- field of view = 224 x 224 mm^2
- 50 slices
- echo time = 35 ms
- **repetition time (TR) = 2-3s**
- flip angle = 90^0

The need for speed: scan efficiency, head motion

Noise considerations! (thermal, physiological)





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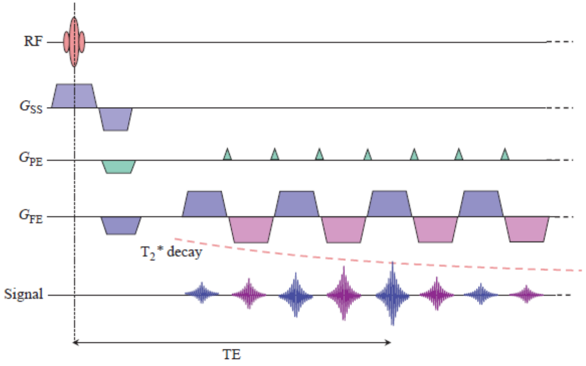
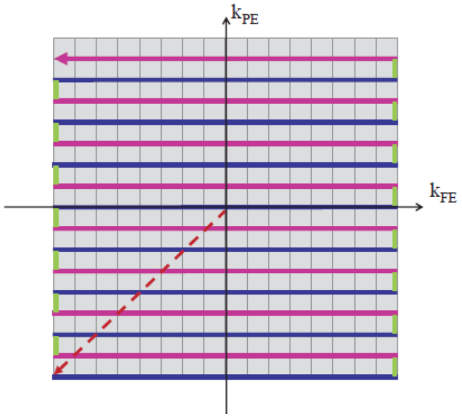
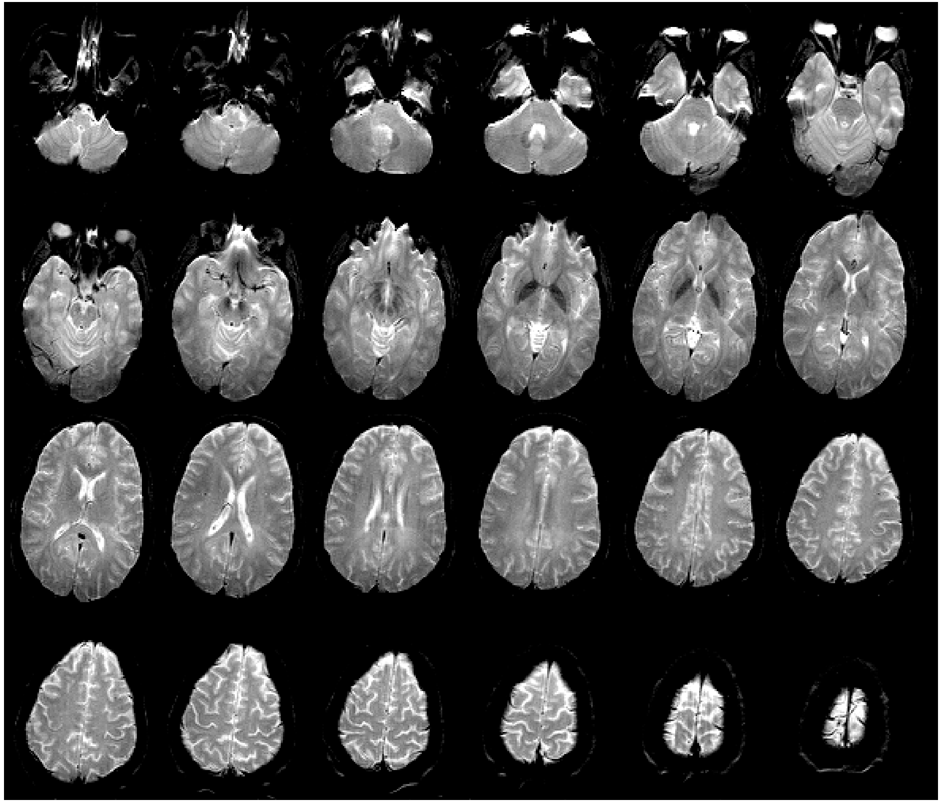


Single-shot EPI, one slice is acquired in one go
64-128 echoes are acquired

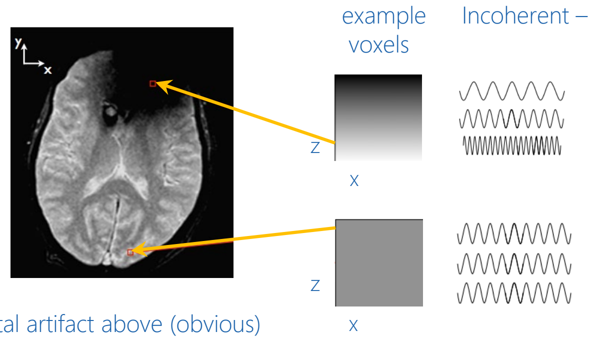


Kspace trajectory of one slice

Image of the whole brain within 1 s



A T2* weighted image - T2* effects



Incoherent – dephases

coherent – stays in phase

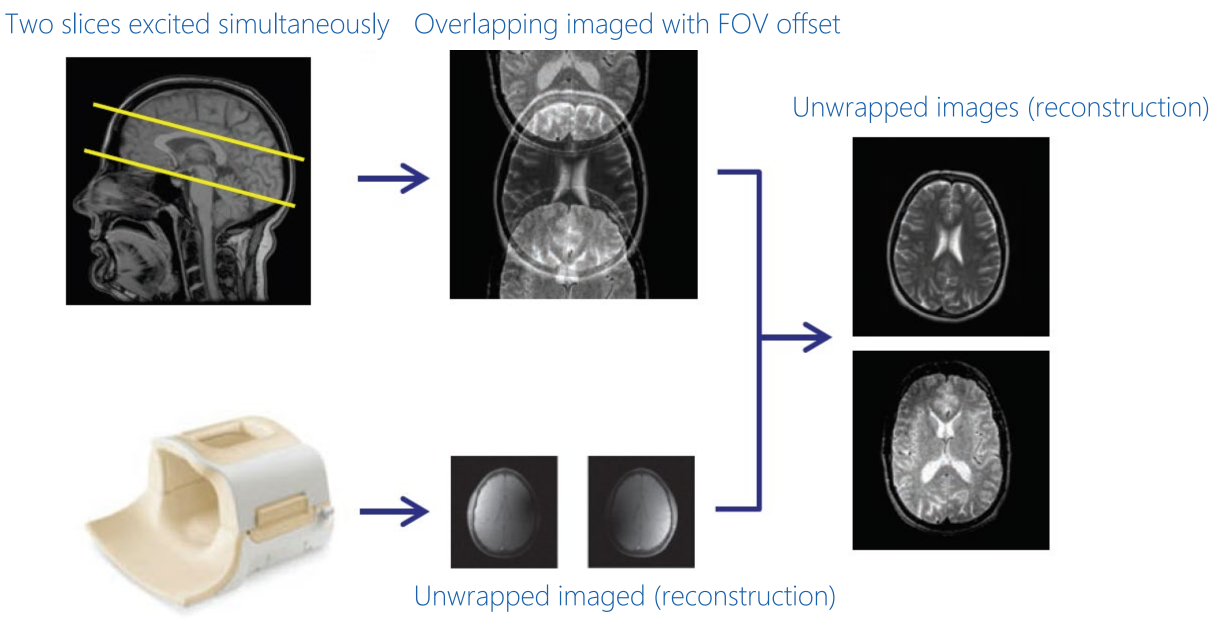
metal artifact above (obvious)
BOLD effect (subtle version)

The need for speed: parallel and multiband imaging

Known as:

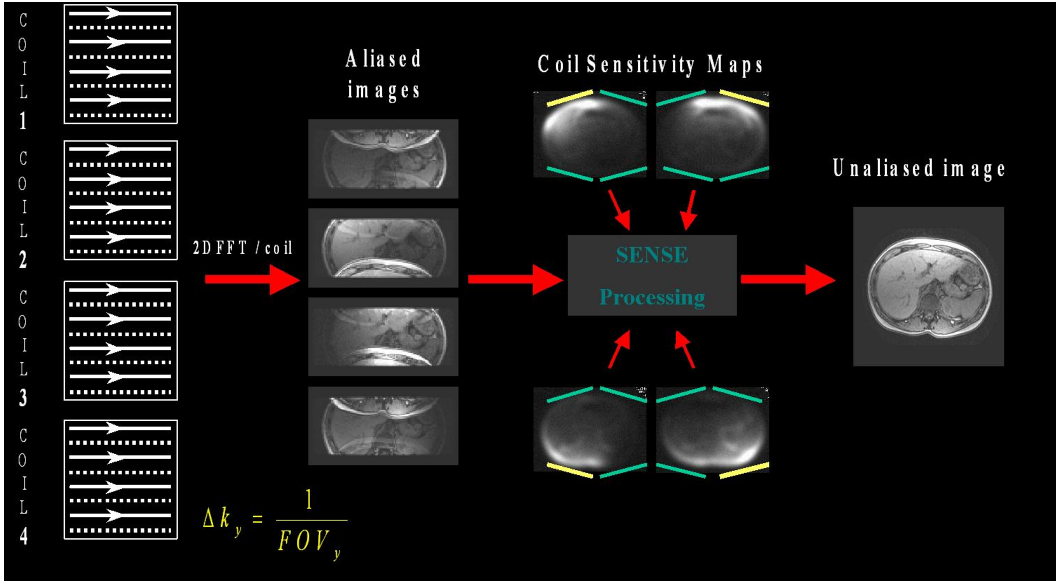
Multi-Band SENSE (MB-SENSE, Philips)

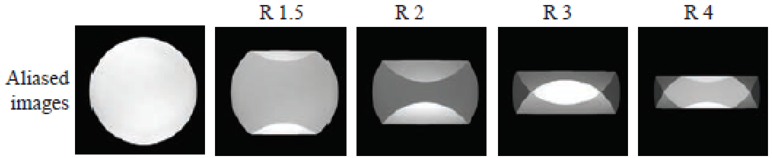
Simultaneous Multi-Slice (SMS, Siemens)



The need for speed: parallel and multiband imaging

Parallel imaging:
- SENSE/GRAPPA
- In plane acceleration
- Skip kspace (phase encode) lines
- Unfold using known coil sensitives
- Reduced image distortions in EPI
- Shorter echo times



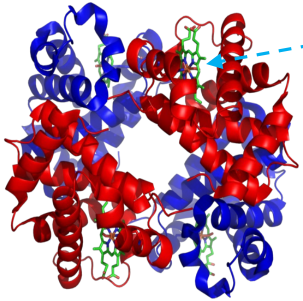


https://wiki.biac.duke.edu/biac

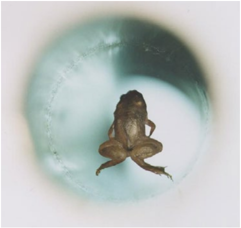
Blood magnetics

Oxygen and hemoglobin

Hemoglobin (Hb): Protein contained in red blood cells



iron containing heme group



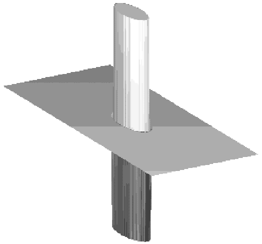
diamagnetic levitation

Can bind (four) oxygen molecules (O_2) for transport

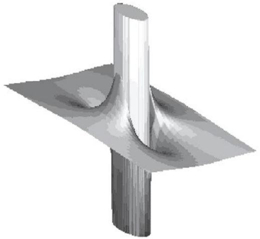
Oxygenation level influences **magnetic properties** of Hb:

- Oxyhemoglobin; diamagnetic, same as tissue, $\Delta\chi = 0$ ppm
- Deoxyhemoglobin; paramagnetic, $\Delta\chi \approx 0.2$ ppm

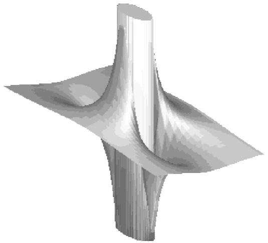
Blood oxygenation influences T2/T2* relaxation



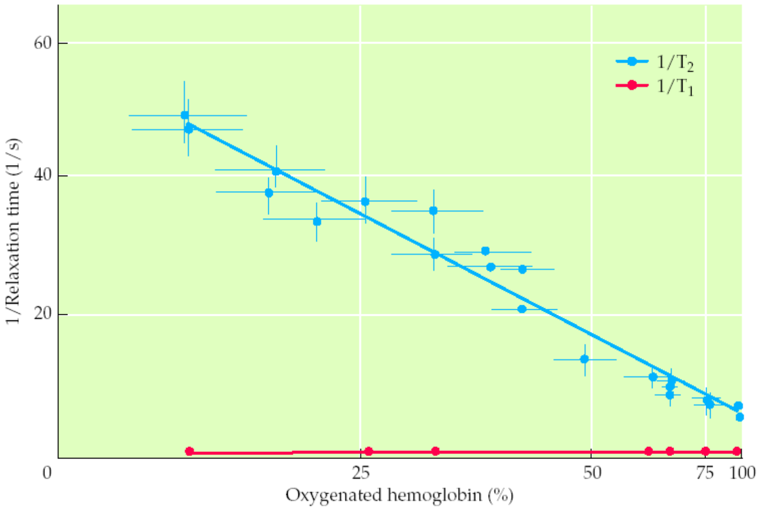
0% Deoxy-Hb



20% Deoxy-Hb



40% Deoxy-Hb

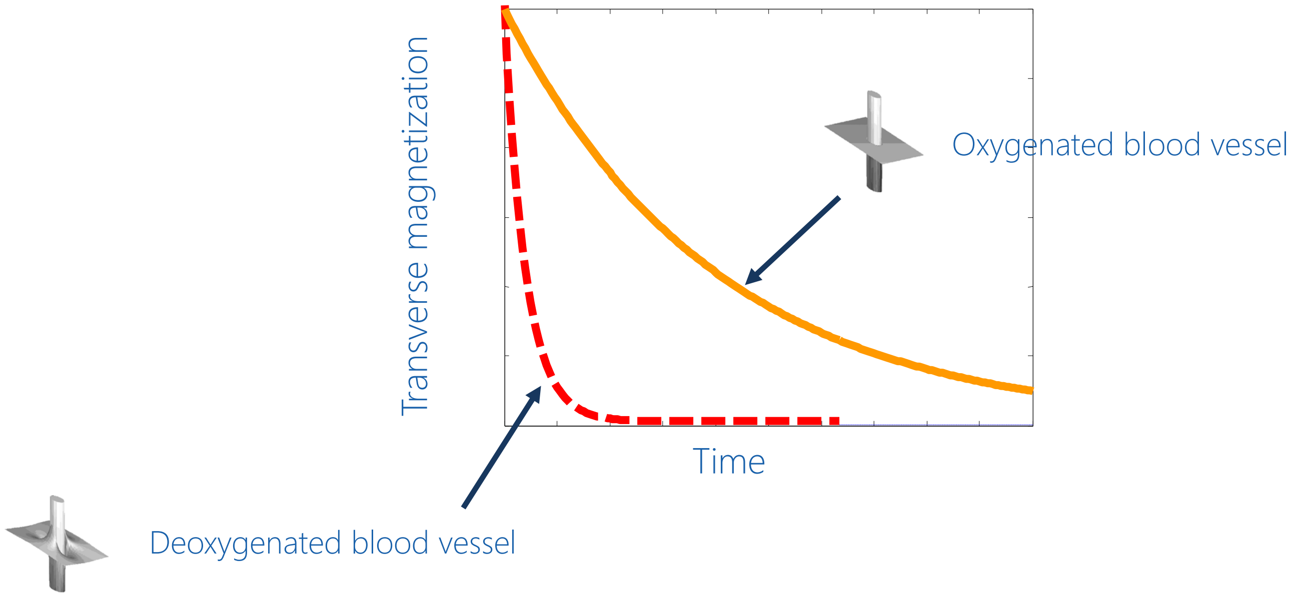


Deoxy-Hb causes a distortion of the magnetic field surrounding the blood vessel
→ faster decay of transverse magnetization (T2/T2* effect)

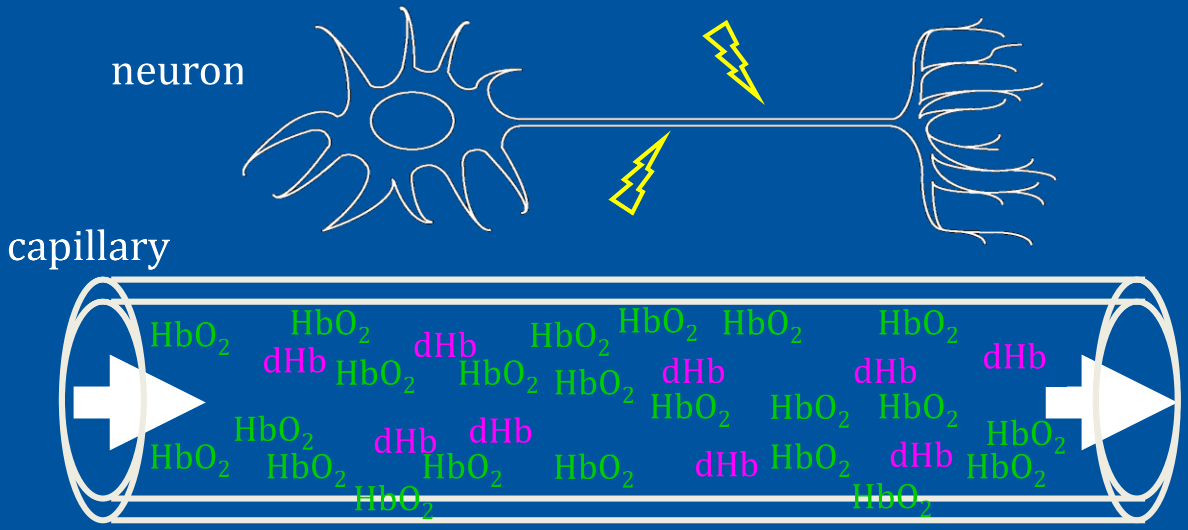
Oxygenated and deoxygenated blood

deoxygenated blood influences local magnetic field inhomogeneities,
signal decays faster than **oxygenated** blood

Blood Oxygenation Level Dependent (BOLD) contrast



BOLD signal

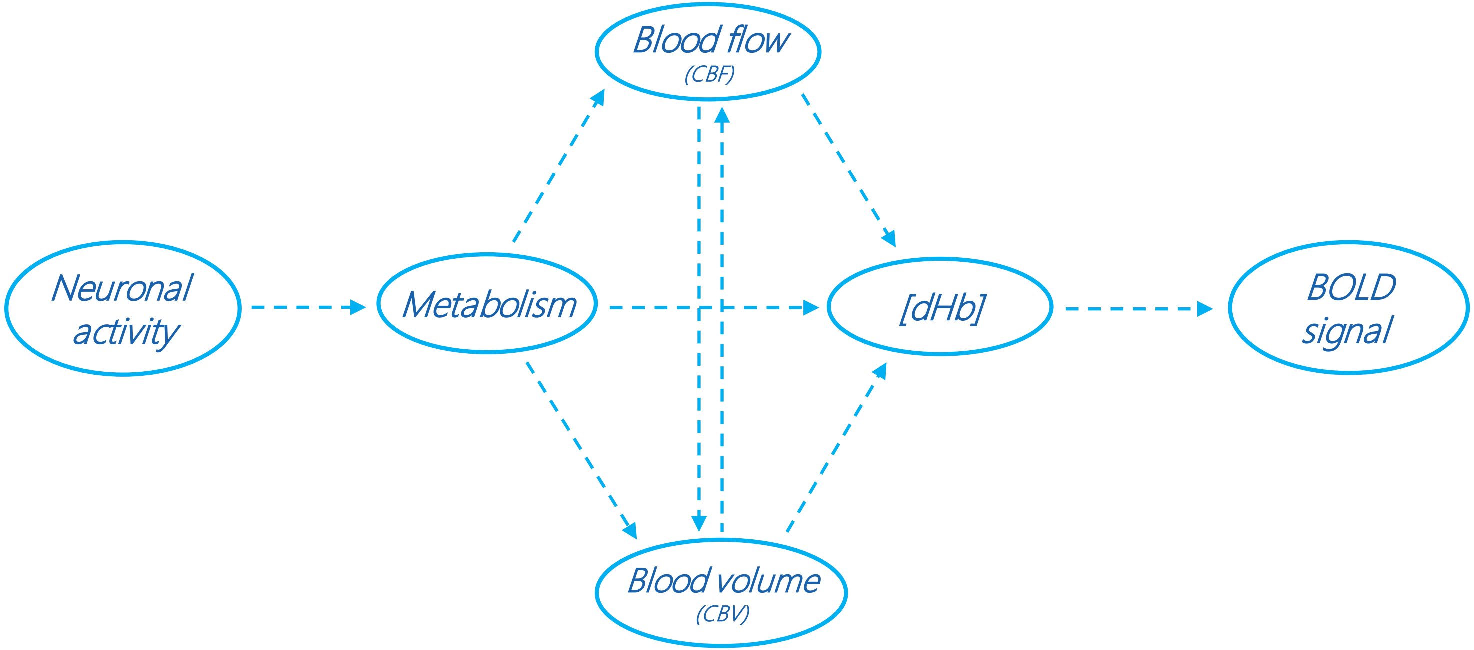


HbO_2 = oxyhemoglobin
dHb = deoxyhemoglobin

↑ O_2 metabolism ↑ dHb
↑ blood flow ↑ HbO_2
↑ blood volume ↑ HbO_2

↓ [dHb] ↓ $\Delta\chi$ signal ↑

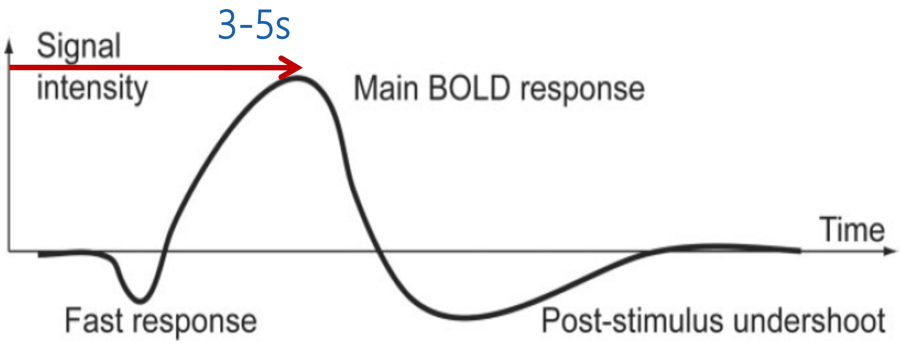
Neurovascularcoupling



- very indirect measure of activity (via hemodynamic response to neural activity)!
- complicated dynamics lead to reduction in [dHb] during activation
- signal increase → BOLD response

Hemodynamic BOLD response

- Peak response 1-5 % w.r.t. baseline
- Peak time 3-5 s
- Shape varies with
    - stimulus
    - cortices
    - vasculature



BOLD specificity (microvasculature)

Increased oxygen demand starts in capillary bed (deep gray matter)

BOLD response from capillary bed most specific

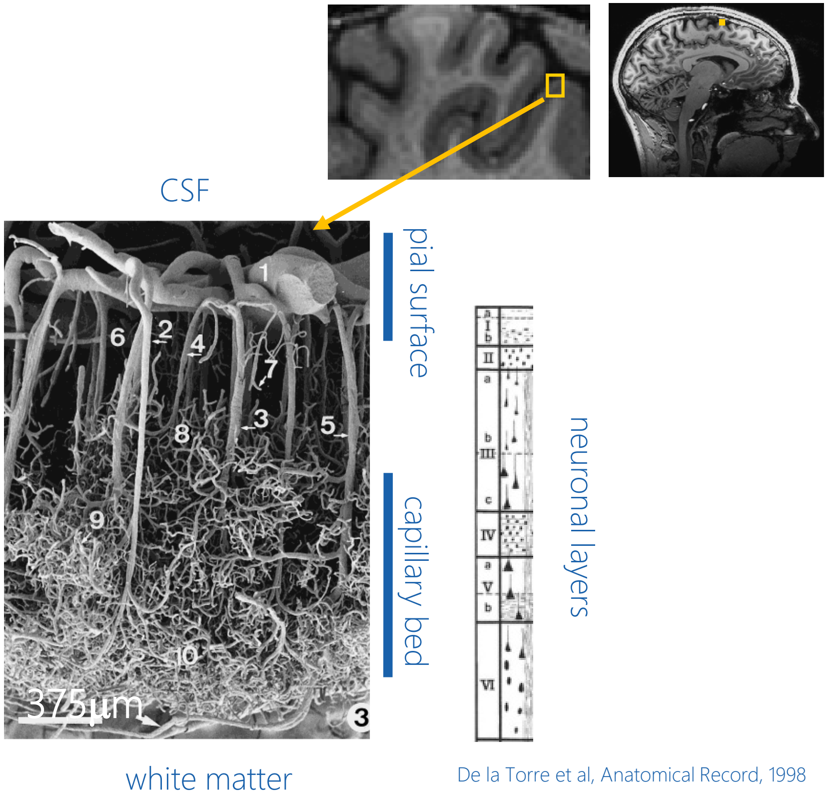
- small fast narrow response

BOLD response from draining veins least specific

- strong delayed broad response

Improve specificity by:

- remove signals from larger veins
- different scan sequences
- ultra high field MR systems
- high spatial resolution – laminar BOLD imaging!
- exploit timing differences in BOLD response
- Fast sampling!! MRI acceleration methods



De la Torre et al, Anatomical Record, 1998

Quick recap

Know the basics of:

- equipment (magnets, coils)
- image contrast (signal differences)
- image formation (echoes)
- scan parameters (repetition time), resolution,
- BOLD contrast (blood oxygenation)
- MRI scan terminology (kspace, SENSE/iPAT, multiband/SMS)

Suggested references

- MRI from picture to proton, 3rd edition, D.W. McRobbie et al., Cambridge University Press, 2017
- Introduction to Functional Magnetic Resonance Imaging – Principles and Techniques, R.B. Buxton, 2nd edition, Cambridge University Press, 2009
- Functional Magnetic Resonance Imaging, 2nd edition, S.A. Huettel et al. Sinauer Associates, 2009
- Magnetic Resonance Imaging Physical Properties and Sequence Design, 2nd edition, R.W. Brown, Wiley Blackwell, 2014
- Youtube channel: Principles of fMRI
- Youtube channel: Layer fMRI