MR physics and safety for functional MRI

Lawrence L. Wald, Ph.D.

Robert L. Savoy, Ph.D.
MRI in a Slide: 8 Magnetic Fields and Relaxation

- To Obtain the NMR Signal: Three Magnetic Fields
  - $\mu$: The magnetic field of a nucleus with spin
  - $B_0$: The main magnetic field, used to align nuclei
  - $B_1$: The radio-frequency field, used to flip nuclei

- Relaxation: Two ways for the signal to go away
  - $T_1$: Longitudinal: The nuclei re-align with $B_0$
  - $T_2$: Transverse: The nuclei get out-of-phase

- To Select Slices and Make Images: Three More Fields
  - $G_x$, $G_y$, $G_z$: The gradient fields

- Shim Fields: To make better images

- Shielding Fields: To protect us from all of the above!
Outline:

Part 1:
MR signal
MR contrast
fMRI contrast

Part 2:
Image encoding (10 minute version)
Imaging considerations for fMRI

Part 3:
MR Safety
What is NMR?

NUCLEAR
MAGNETIC
RESONANCE

A magnet, a glass of water, and a radio wave source and detector….

Almost every idea in MRI is easy... but the combined collection is complicated.
Gyroscopic motion

- Proton has magnetic moment
- Proton has spin (angular momentum)

$\nu = \gamma B_0$

Larmor precession freq. = 42.58 MHz/T
EXCITATION: Displacing the spins from Equilibrium (North)

Problem: It must be moving for us to detect it.

Solution: knock out of equilibrium so it oscillates

How?
1) Tilt the magnet or compass suddenly

2) Drive the magnetization (compass needle) with a periodic magnetic field
Excitation: Resonance

Why does only one frequency efficiently tip protons?

Resonant driving force.
It’s like pushing a child on a swing in time with the natural oscillating frequency.
z is "longitudinal" direction
x-y is "transverse" plane

The RF pulse rotates Mo the about applied field
The NMR Signal

Voltage (Signal)

RF

time

\[ V(t) \]

Bo

Mo

90°

V(t)

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Magnetization vector during the NMR experiment

\[ \omega = \gamma B_1 \]

B1 RF Field (from RF excitation pulse)
Magnetization vector during MR

$M_0 \rightarrow M_z$, $B_0$

$\omega = \gamma B_1$

B1 RF Field (from RF excitation pulse)

$M_{xy}$

Voltage (Signal)

$T_2^*$

$T_{2*}$

$M_z$

$M_{xy}$

RF encode

TE

Time
Three places in the process to make a measurement (image)

0) Equilibrium (magnetization points along Bo)

1) RF Excitation (tip magnetization away from equilibrium)

2) Precession induces signal, allow to dephase for time TE.

3) Return to equilibrium (timescale = T1).

proton density weighting

T2 or T2* weighting

T1 Weighting

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Contrast in MRI: proton density

Form image immediately after excitation (creation of signal).

Tissue with more protons per cc give more signal and is thus brighter on the image.

No chance to dephase, thus no differences due to different tissue T2 or T2* values.

Magnetization starts fully relaxed (full Mz), thus no T1 weighting.

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Contrast in MRI: proton density

Image immediately after excitation

No time for relaxation!

Signal proportional to 
# of spins in voxel

All MRI images have proton density weighting underlying them…

CSF > gray > white

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T2*-Dephasing

Wait time \textbf{TE} after excitation before measuring M.

Shorter T2* spins have dephased

Initially

\textbf{at } t= \textbf{TE}

\textit{vector sum}

Is smaller...
T2* Dephasing

Just showing the tips of the vectors…

in the laboratory frame … and in the rotating frame
T2* Weighting

Phantoms with four different T2* decay rates...

There is no contrast difference immediately after excitation, must wait (but not too long!).

Choose TE for maximum intensity difference.
Spin Echo (T2 contrast)

Some dephasing can be refocused because it's due to static fields.

Blue arrows precess faster due to local field inhomogeneity than red arrow.
Spin Echo

180° pulse only helps cancel static inhomogeneity

The “runners” can have static speed distribution.

If a runner trips, he will not make it back in phase with the others.

Shown in Laboratory Frame

Shown in Rotating Frame
T2 weighed spin echo image

NMR Signal

Time to Echo, TE (ms)

gray

white

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Other contrast for MRI

In brain: (gray/white/CSF/fat)

- Proton density differences ~ 20%
- T1 relaxation differences ~ 2000%

How to exploit for imaging?

- Vary repetition rate - TR
T1 weighting in MRI

Voltage (Signal) From Mxy

Mz

time

RF

TR

encode

encode

encode

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grey matter (long T1) (long T2*)
white matter (short T1) (short T2*)
T1 weighting in MRI

Grey matter (long T1) (long T2*)
White matter (short T1) (short T2*)
T1 weighting in MRI

Voltage (Signal) From Mxy

Mz

encode

encode

encode

grey matter (long T1) (long T2*)

white matter (short T1) (short T2*)

time
T2* weighting in MRI

Voltage (Signal) From Mxy

Mz

encode

encode

grey matter (long T1) (long T2*)

white matter (short T1) (short T2*)
T2 weighting in MRI

- 90° RF
- 180° RF
- TR: MUCH LONGER

Voltage (Signal) From Mxy

Mz

grey matter (long T1) (long T2*)
white matter (short T1) (short T2*)
time
TE: Time to “Echo” or “Encode”? 
TE: Time to “Echo” or “Encode”? 

Spin Echo Imaging
Gradient Echo Imaging
Echo Planar Imaging

Gradient Echo Imaging

Spin Echo Imaging

Echo Planar Imaging

Wolbarst Fig. 43-11; Physics of Radiology, A.R. Wolbarst; First Edition
T1-Weighting

TR (milliseconds)

Signal

white matter
T1 = 600

grey matter
T1 = 1000

CSF
T1 = 3000

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Image contrast summary: TR, TE
Basis of fMRI: BOLD contrast

Qualitative Changes During Activation

Observation of Hemodynamic Changes

- Direct Flow effects
- Blood oxygenation effects
Blood cell magnetization and Oxygen State

\[ B_0 = 0 \]

\[ M = \chi_B \]

Oxygenated Red Cell

de-Oxygenated Red Cell
Addition of paramagnetic compound to blood: T2* effect

Local field is heterogeneous
- Water is dephased
- T2* shortens,
  Signal goes down on EPI

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Addition of paramagnetic compound to blood

Signal from water is dephased

$T2^*$ shortens, Signal goes down on $T2^*$ weighted image
Neuronal Activation . . .

Produces *local* hemodynamic changes
(Roy and Sherrington, 1890)

Increases local blood flow
Increases local blood volume
BUT, relatively little change in oxygen consumption
Deoxyhemoglobin concentration goes down when flow goes up

Flow (4 balls/sec.)

Venous out

Consumption = 3 balls/sec.

Flow (6 balls/sec.)

Venous out

Consumption = 3 balls/sec.
Activation

- Increases blood flow ($F \uparrow$)
- Increases blood volume ($V \uparrow$)
- Small increase in oxygen consumption

So:

venous O2 $\uparrow$

deoxy Hb concentration $\downarrow$

less magnetic stuff

less dephasing

MR signal increases on T2* weighted image
Other MR methods for detecting activation

Any one of the following can be detected with MR:

Flow $\uparrow$ increases signal on Spin Labeled flow scans

DeoxyHb $\downarrow$ increases signal on “T2/T2*-weighted” scans ("BOLD" method)

Blood Vol. $\uparrow$ Decreases signal when contrast agent is on board (IRON method).
Brain vessels range in size from capillaries (6-10um) to sagittal sinus (5mm).

Relative volumes: 5% arterial, 45% capillary, 45% vein.

The BOLD signal comes from water inside vessels (intra-vascular) and outside vessels (extra-vascular).

While there is 20x more extra-vascular water, the vessel water is in better contact with the deoxyHeme.
Paramagnetic compound in blood: T2 also changes.

- Diffusion through local fields gives dynamic phase changes not refocused by spin echo
  - T2 shortens, S goes down on spin echo EPI
  - T2 effect increases with $B_o^2$
Why does T2 in extravascular water not change for large vessels?

Field outside large “magnetized” venule is approx. constant on length scale of water mean path (~25um)

Field is constant over water path, but magnitude depends on vessel orientation. Thus T2* effect only.
Extravascular T2 does not change for large vessels

Field outside large “magnetized” venule is approx. constant on length scale of water mean path (~25um)
MR pulse sequences to see BOLD

Considerations:
Signal increase = 0 to 5% (small)
Motion artifact on conventional image is 0.5% - 3%
=> need to “freeze motion”
Need to see changes on timescale of hemodynamic changes (seconds)

Requirement: Fast, “single shot” imaging, image in 80ms, set of slices every 1-3 seconds.
Part II
MR imaging methods for fMRI
Single shot SE-EPI, with and without 4x GRAPPA

23 Channel array at 1.5T
With and without 4x Accel.
Single shot EPI,
256x256, 230mm FOV
TE = 78ms

R=1x
Single shot SE-EPI, with and without 4x GRAPPA

23 Channel array at 1.5T
With and without 4x Accel.
Single shot EPI,
256x256, 230mm FOV
TE = 78ms
Image SNR Maps

Birdcage

Matrix 12Ch

32Ch Array

1x1x3 mm³, Gradient Echo single-shot EPI, TE=30ms

C.Triantafyllou, ISMRM 2009, Hawaii
Its all about trade-offs

Reduce image distortions (fast gradients, parallel imaging)

Maximize sensitivity to T2* changes…

Having enough sensitivity in the image time-series

Have enough resolution to:
  localize activation as well as you need.
  reduce partial volume with unactivated tissue.
  reduce thru-plane dephasing.

Be aware that noise in timeseries is both from image and from physiological fluctuations.
Two big messages:

1) Look at the images! Try different orientations, resolutions….

2) Plot time-series SNR (tSNR) map for every run as QA check

\[ tSNR = \frac{\text{pixel mean}}{\text{pixel SD over timeseries}} \]
Magnetic field gradient: the key to image encoding

Uniform magnet

Field from gradient coils

Total field

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The magnet’s field is homogeneous.

A gradient coil is a spool of wire designed to provide a linear “trim” field.

Gradient coil in magnet
A gradient causes a spread of frequencies

**MR frequency of the protons in a given location is proportional to the local applied field.**

\[ v = \gamma B_{TOT} = \gamma (B_0 + G_z z) \]
Step one: excite a slice

While the grad. is on, excite only band of frequencies.
Step two: encode spatial info. in-plane

\[ B_{\text{TOT}} = B_0 + G_z x \]

"Frequency encoding"

with gradient

without gradient

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‘Pulse sequence’ so far

RF

“slice select”

“freq. encode” (read-out)

\[ S(t) \]

\[ G_z \]

\[ G_x \]

Sample points
“Phase encoding”

“slice select”

“phase encode”

“freq. encode” (read-out)

RF

G_z

G_y

G_x

S(t)
“Spin-warp” encoding

one excitation, one line of kspace...
“Spin-warp” encoding mathematics

Keep track of the phase...

Phase due to readout:

\[ \theta(t) = \omega_0 t + \gamma G_x x t \]

Phase due to P.E.

\[ \theta(t) = \omega_0 t + \gamma G_y y \tau \]

\[ \Delta \theta(t) = \omega_0 t + \gamma G_x x t + \gamma G_y y \tau \]

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What’s the difference?

conventional MRI

“slice select”

“freq. enc” (read-out)

“fast” imaging

eq...
“Echo-planar” encoding

Observations:

- Adjacent points along $k_x$ are taken with short $\Delta t (= 5 \text{ us})$. (high bandwidth)
- Adjacent points along $k_y$ are taken with long $\Delta t (= 500\text{us})$. (low bandwidth)
- A given line is read quickly, but the total encode time is longer than conventional Imaging.
- Adjacent lines are traversed in opposite directions.
Drawbacks of Single Shot Imaging

• Require high gradient performance to eliminate susceptibility induced distortions.

• Susceptibility in the head is worse at 3T than 1.5T.
BOLD and Field Strength

Increasing Field strength increases BOLD fMRI CNR:

1. SNR of images improves
2. Increases $\Delta T2^*$ with $\Delta O2$ → more bang for buck
3. But caution, increases susceptibility artifact, so increased care required to perform good whole brain
Enemy #1 of EPI: local susceptibility gradients

Orbitofrontal susceptibility region

Lateral temporal susceptibility region

$B_0$ field maps in the head

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Susceptibility in MR

Gives us BOLD
(i.e., The Good)

Gives us dropouts
(i.e., The Bad)

Gives us distortion
(i.e., The Ugly)
What do we mean by “susceptibility”?  

In physics, it refers to a material’s tendency to magnetize when placed in an external field.  

In MR, it refers to the effects of magnetized material on the image through its local distortion of the static magnetic field $B_o$. 
What is the source of susceptibility?

1) deoxyHeme is paramagnetic
2) Water is diamagnetic ($\chi = -10^{-5}$)
3) Air is paramagnetic ($\chi = 4 \times 10^{-6}$)

The magnet has a spatially uniform field but your head is magnetic…
Susceptibility effects occur near magnetically dis-similar materials

Field disturbance around air surrounded by water (e.g. sinuses)
$B_0$ map in head: it’s the air tissue interface…

Sagittal $B_0$ field maps at 3T
Susceptibility field (in Gauss) increases w/ $B_0$.

Ping-pong ball in $H_2O$:
Field maps ($\Delta TE = 5ms$), black lines spaced by 0.024G (0.8ppm at 3T)
What is the effect of having a non-uniform field on the MR image?

Local field changes with position.

To the extent the change is linear, => local suscept. field gradient.

We expect uniform field and controllable external gradients…
Local susceptibility gradients: two effects

1) Local dephasing of the signal (signal loss) within a voxel, mainly from thru-plane gradients

2) Local geometric distortions, (voxel location improperly reconstructed) mainly from local in-plane gradients.
1) Non-uniform Local Field Causes Local Dephasing

Sagittal $B_0$ field map at 3T

5 water protons in different parts of the voxel...

$\begin{align*}
T = 0 \\
T = TE
\end{align*}$
Thru-plane dephasing gets worse at longer TE

Orbitofrontal susceptibility region

3T, TE = 21, 30, 40, 50, 60ms
Mitigation: thru-plane dephasing; easy to implement

1) Good shimming. (1st and 2nd order)
2) Use thinner slices, preferably with isotropic voxels.
   *Drawback: takes more slices to cover the brain.*
3) Use shorter TE.
   *Drawback: BOLD contrast is optimized for $TE = T2^{*_{local}}$. Thus BOLD is only optimized for the poor susceptibility regions.*
Mitigation: thru-plane dephasing; harder to implement

1) Bo correction.

2) “Z-shimming” Repeat measurement several times with an applied z gradients that rewind the dephasing, Pick the right gradient afterward on a pixel by pixel basis. (Drawback: multi shot or longer encode). *MRM 39 p402, 1998.*

2) Use special RF pulse with built-in prephasing in just the right places. (Drawback: long RF pulse, pre-phasing differs from person to person.)


3) The “mouth shim” paramagnetic material in roof of mouth.

*Wilson, Jenkinson, Jezzard, Proceed. ISMRM p205, 2002.*
Part III
Safety issues in MRI
Safety issues in MRI

**Bioeffects versus. Bioconcerns versus Biohazards**

3 electromagnetic fields, 3 issues; Plus other issues

1) Static $B_0$ Field $\rightarrow$ projectiles *Deadly*
2) RF Field $\rightarrow$ heating of tissue
3) Gradient fields $\rightarrow$ stimulating periph. Nerves acoustic noise
4) Cryogens $\rightarrow$ Loss of O2 in room *Deadly*

**IRB considerations**

*Informed Consent* with “normal” subjects
Static Magnetic Field

“Projectiles” **Enormous force** on magnetic objects.

- Study operator must make sure ferris objects are not brought into scan room.
- One mistake can kill your subject!

**Bioeffects:** Does the big magnetic field affect you?
Forces on ferris objects

Bigger magnets = bigger forces

1.5T magnet meets anesthesiology cart. Subject in magnet would likely have been killed.
Forces on ferrous objects

Subject must be screened for non-MR compatible implants (pacemaker, aneurism clips etc.)

Research must be risk free; “probably okay” NOT Good enough!
Implants: you can’t assume anything

MGH clinical Case study:

Drunken man in ER, unable to provide MR screening info

Smart MR tech did not assume anything...
Implants: you can’t assume anything

MGH clinical Case study:
Drunken man in ER, unable to provide MR screening info
Smart MR tech did not assume anything...
Commercial scanners monitor average power delivered. Less than 3 W/kg to whole head.

This limits some applications at 3T and 4T.
The switching gradient fields

Nerve stimulation (electrical currents in body)
Acoustic trauma (noise from forces on coil)
Burn from looped cables

\[ V \sim (\text{Area}) \times (\text{dB/dt}) \]
Safety at 3T and 4T

• Scanning at higher fields:
• Poses some safety challenges (implanted objects not confirmed)
• Challenges are incremental
  Most are same as any MRI, must be handled with same techniques, **routine** key to safety

• Not near safety limit of MRI
IRB Considerations
(Institutional Review Board)

• Informed **consent** (and informed **assent**)
  • Adults; Children; D.I.D.

• Special considerations for **MRI**
  • Why we now reward patients with money in stead of a print-out of their brain…

• Special considerations for **functional MRI**
  • NeuroEthics
  • Upsetting the subject at the start