Introduction to MR Physics

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What are We Imaging?

Measuring Proton Density via Net Magnetization

Bo = 1.5T
(More Align Parallel as Bo Increased)

Bo = 3T
Precessional Motion and the Larmor Frequency

\[ B_0 = 1.5T \]

\[ B_0 = 3T \]

Vector Math

• How Much Is Pointing in Each of 3 Axes?

• Add Up Components, Then Recombine

Making the Net Magnetization Detectable

Nets To This:

Appears to Rotate in Transverse Plane

(0)
Typical Field Echo Sequence

- **RF Transmit**
- **RF Receive**
- G - Slice
- G - Phase
- G - Frequency

**Fundamental Principles**

- **Protons**
  - Precession: Spinning Charge & Mass in Force Field
  - Larmor Frequency: Proportional to Magnetic Field

- **Vectors and Net Magnetization**
  - “Signal” Increases as Protons Align

- **Electromagnetism and Faraday’s Law of Induction**
  - Moving Charges/Electrical Current ➔ Magnetic Fields

- **Fourier Transform**
  - Any Signal can be Decomposed into Sinusoids

**Summary of Localization Strategy**

1. Gradient Varies Larmor Frequency along Slice Direction.
2. Transmit Coil at Desired Slice’s Larmor Frequency to Excite Desired Anatomy
3. 2nd Gradient: Temporarily Vary Precessional Frequency along PE Direction to Create Phase Distribution
4. 3rd Gradient: Vary Larmor Frequency along 3rd Direction while Receive Coil “Listens” (Echo)
5. Use Fourier Transform to Decode “Echo” into Frequency Bins (along FE)
6. Repeat for Multiple Phase Distributions along PE
7. Use Algebra to Compute Discrete Pixel Values (2D FT)
In MRI, Timing is Everything

Before 90° After 90° At Readout

Before Next 90° After 90°

(T1 Relaxation)

TR

Within View

At Readout

TR

(T2 Decay)

TE

Start of Next View

TR

Classic Image Weighting

• PROTON DENSITY
  — Long TR, Short TE

• T1 Weighted
  — Short TR (around the Tissue T1), Short TE

• T2 Weighted
  — Long TR, Long TE (around Tissue T2)

Long TR, Long TE

• T2 Weighted
• Signal Loss from Phase Dispersion
• More Loss with White/Gray Matter than CSF
• Plenty of Time for Complete T1 Recovery Each View

TR 2000, TE 120
Short TR, Short TE

- T1 Weighted
- Signal Loss from Incomplete Longitudinal Magnetization
- More Loss from CSF than Gray/White Matter

Multiple Ways to Lose Signal Through De-Phasing

- SPIN-SPIN Interaction (T2 Weighting)
  - Chemical Environment Weighs Image Intensity
- Fail to Realign to Reference Direction @ TE
  - Gradients Not BALANCED During Spatial Encoding
  - Hardware Error, OR Moving Tissue
- Magnet Inhomogeneities (Static Dephasing)
  - Larmor Frequency Variation Within a Voxel
  - "Susceptibility" affects of Tissue (eg Blood)
  - Equipment Imperfections, Implants, etc

SPIN ECHO

- Additional RF: 180°
- Reverses Static De-phasing Affects
- T2 (SE) versus T2* (FE) Contrast
Spin Echo Sequence

- RF Transmit
- RF Receive
- G - Slice
- G - Phase
- G - Frequency

Fast Spin Echo

- Multiple PE Steps per TR
- Reduces Scan Time Proportional to ETL
- Effective TE when less PE applied (center of k-space)
- Best for Long TE
- Can Blur for Short TE
- Short ETS with Wide BW, Reduces SNR

Inversion Recovery: STIR

Fat Nulled

- Apply 180°
- After TI
- After 90°

Start Imaging Sequence Here
Inversion Recovery: FLAIR CSF Nulled

IR and MagPrep Sequence

IR and MagPrep Sequence
Magnetization Preparation in Diffusion Imaging

- Starting Magnetization Less if “Dephase” ≠ “Rephase”
- Stationary Protons Retain Signal (Restricted Diffusion)

Diffusion with EPI

MRI Sequence Pearls

- SE & FSE
- FE
- EPI
- STIR
- IR
- FLAIR
- ChemSat

See www.MR-TIP.com for diagrams of other sequences
Many “Pulse Sequence” Choices

- TR/TE/TI
- Flip Angle
- Matrix
- Field of View
- Slice Thickness
- NEX
- Bandwidth
- Spin Echo
- Field Echo
- 3D
- Turbo Factor
- Echo Planar
- SENSE
- ...

Fundamental Tradeoffs: Resolution – SNR – Speed

- Resolution Increases with:
  - More Voxels in FOV (Bigger Matrix, Small FOV, Thin Slice)
- SNR Increases with:
  - More data, Listen Longer, Less Resolution
  - Field Strength (More Net Protons, ... consider Safety, Artifacts, T1 Contrast)
  - Receive Coil Matched to Anatomy
- Time Decreases with:
  - Collecting Less Data (eg Less Resolution, Fewer Averages)
  - Shorter TR (contrast)
  - More Data per TR (eg FSE, EPI, GRASE, Parallel Imaging)
    Careful with Blurring, J-coupling, distortion, Aliasing

Example Images and Parameters
Artifacts

- Partial Volume
- Motion, Flow
- Wrap (Aliasing)
- Gibbs (Ringing)
- Susceptibility (including Intentionally creating SWI)
- Chemical Shift
- Cross Talk

Partial Volume

Motion
Motion Compensation
(BLADE, PROPELLER, MultiVANE, JET, RADAR)

T2 Weighted Fast Spin Echo + Motion Compensation

CSF Flow, Gradient Moment Nulling

Parallel Imaging

If Reduce FOV by half...
Half Scan time but Aliasing

Unfolding
(Post processing)

Full FOV
No wrap around
Half scan time

Multiple receiver coils
Coil #1
Coil #2

Sensitivity Distribution

Courtesy Toshiba Medical Systems

Susceptibility vs. Parallel Imaging


No PI

PI x 3
Chem-Sat Fat Suppression

DWI/ADC & T2 Shine Through

Specialized Sequences
**Diffusion Tensor Imaging: Fractional Anisotropy**

- Determine the Direction and Shape of Diffusion
- Repeat Diffusion “Probe” in at least 6 Directions

\[(D_x, D_y, D_z) \implies \text{Isotropic Blob of Protons Going That Way}
\]
\[(D_x, D_y, D_z) \implies \text{Linear Blob of Protons Going That Way}
\]

\[\text{FA} = 0 \implies \text{FA} \approx 1\]

**Resulting Graphics of White Matter**

- FA = Brightness
- Color = Direction
- Connect Similar Dots = Representation of Tracts that Linearly Restrict Diffusion

**Functional Imaging: BOLD**

- Blood Oxygenation Level Dependent Imaging
- Oxy vs. De-oxy Hg Changes Iron Environment
- Iron Affects Nearby Magnetic Field
- Variation in Larmor Frequencies within Voxel Changes Net Magnetization
Simple Paradigm to Tag Function

- Scan Entire Brain Every Couple Seconds
  - FE-EPI = fast single shot, & susceptibility weighted
- Do Something that Affects Local O2 Uptake
- Continue Scanning While Interleaving Another Task With Different O2 Affect
- Subtract Image Sets (after a lot of averaging)
- Threshold “Meaningful” Differences
- Overlay on a Registered Anatomic Image

Surgical Guidance Using Combined FiberTracts and fMRI

Arcuate Fasciculus (DTI)
Broca & Wernicke (fMRI)

AvM on T2
Perfusion abnormality

Very Basic MR Spectroscopy

- eg Fat and Water 3.5 ppm Separation
- Larmor Frequency of Protons in Water = 1.5T x 42.58 MHz/T = 64MHz
  Fat = 3.5 ppm slower due to e- shielding
  = about 220 Hz Lower

Fat
64 MHz
0.00220 MHz (3.5ppm)
Water

Water – Fat Shift

Chemical Shift due to Shielding => Different Larmor f’s

• Tune “RF Slice Select” or “Sat Bands” to Excite or Destroy Fat or Water

• Phase Cycling: Fat & Water Precess In and Out of Phase (Another Fat Suppression Method)

• Different Frequency => Chem Shift Artifact Misplaces Fat (Incorrect Frequency Encoding)

Detecting Metabolite Concentrations

• Metabolites “Shielded” Differently

• Protons “See” Different Bo Field

• Just Excite One Big Voxel

• Frequency Variation = Metabolites instead of Spatial Location

• Fourier Transform = Plot MR Spectrum

Example Proton Spectra

• Long TE Clean, Basic
  — NAA, Cr, Cho: Hunter’s Angle
  — Lactate, Lipid

• Short TE Methods
  — Add mi, Glx, etc

• Multivoxel
  — Time Efficient
  — Longer TE, Purists Object

Hunter’s Angle
The High Field Trend

- 0.015T → 0.35T → 1.0T → 1.5T → 2T → 2.9T → 3T → 7T —— and still climbing
- More Net Protons: SNR Increases Linearly
  - Trade for Cleaner Images, Higher Resolution, Faster Acquisition
- Greater Chemical Shift
  - MRS Peak Separation, Susceptibility, Magnetization Transfer Contrast
- Greater SAR and Dielectric Effects
  - Reworked Sequences, Different Contrast, Safety Issues
- Equipment and Siting Expensive
  - Superconducting Material, Iron to Contain Field

Why Higher Field Strength?

- Higher SNR → Better Resolution and Scan Time
- Better Contrast
- Higher Sensitivity for Susceptibility Contrast
- Increased Chemical Shift
Physical Components, Options, Financial Insights

Components of MRI

- Superconducting Electro-Magnet
  - Align protons in Longitudinal Direction
- RF Transmit Coil (Typically Built In)
  - Flip protons + force coherence
  - Rotating Transverse Magnetization
- RF Receive Coil (Several Supplied)
  - Detect Transverse Magnetization
- 3 Sets of Gradients
  - Vary Magnetic Field to Spatially Encode
- Sequencer and Image Reconstruction

Inside an MRI Scanner
Various Magnet Designs

Siting an MRI

• Scanner Room
• Equipment Room
• Tech Area
• Outside
• Equipment
• Fringe Fields
• Power
• Vibration
• Security

MRI System Cost Examples

• Low Field Open $400,000 (avail?)
• New 1T Open $1.5M

• Refurb 1.5T $600,000
• New 1.5T $1.2M

• Refurb 3T $900,000
• New 3T $1.9M

• 7T $6M, plus $1M siting
Example MRI Proforma (monthly)

- Equipment (MRI, PACS, etc) $21,000
  - eg $1.5M operating lease
- Service $12,000
- New Installation $7,500
  - eg $400,000 5yr capital lease
- Rent $2,000
  - eg $200/sf x 1000sf
- Staff $10,000
  - eg RT@$25, clerical@$15
- Legal, Management, Physicist $1,000
- Technical Margin per scan $200
- Breakeven (Costs/margin) 270 scans per month = 14 scans per day

Total $53,000

Example MR Profitability

- Operate 40hrs/week, 1/2 hr per patient
- 320 scans per month = 50 scans beyond breakeven
  - TC profit = $200 x 50 = $10,000 monthly
  - Annual PC Revenue = $60/scan x 320 x 12 (about 80hrs/mo) = $200K

- Generally,
  - New scanner justified at 10-15/day
  - 1 scan per day beyond b.e. = $60-$100K annual profit
  - New Neuro Patient 50% need MRI
    - 20-30 new patients/d
    - >4 MDs + PAs

Some Educational Resources

- https://www.youtube.com/watch?v=Ok9IUyZmaY
- Society of Magnetic Resonance Technologists
- Joe Hornack Web Site
  - http://www.cis.rit.edu/htbooks/mri/
- Wikipedia
- Manufacturer Web Sites and Operator Manuals
- MRI Safety by Frank Shellock, PhD
- Simply Physics, Moriel Nessaiver
- Medical Imaging Consultants, Inc
- jfritz@dentinstitute.com, www.Dentinstitute.com
Some Additional Details

K-Space vs. Image Space

Indexed Collection of Echoes
Indexed Collection of Protons

K_y (PE Direction)

FT

K_x (FE Direction)

Some Characteristics of K-space

- One Point in K-Space Affects Entire Image, One Pixel formed from All of K-Space
- Center = Contrast, Edges = Resolution
- If Do Not Collect Periphery ➔ Blurry, Ringing
- If Too Few Echoes Sparsely Separated ➔ Wrap-Around (Aliasing)
- If Physical Motion Between PE Steps ➔ Ghosting (Misaligned “Plane Waves”)
Walking Through K-Space To Collect My Echoes

- An Easy Way to Understanding Many Sequences
- Start at Center
- Use PE and FE Gradients to “Steer” and “Accelerate”
- Think “Etch-a-Sketch” or “Pac-Man”
- “Receiver Bandwidth” = Speed of Collecting Echoes while Traveling

Walking Through K-Space Illustration

Fast Spin Echo