High Field MRI Technology, Applications, Safety, and Limitations

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The promise of high-field MRI

• Trade SNR increase into higher resolution/speed
  • Higher resolution imaging
    • More detail
    • Less partial volume averaging
  • Faster imaging
    • Higher throughput
    • Breath hold
• Exploration of new/alternated contrast mechanisms
• Potential to significantly advance anatomic, functional, metabolic and molecular MR imaging

High-field Scanners

• 3.0T whole body scanners
  – Commercial since 2002
  – Accounted for 8.5% of high-field revenue in 2003
• Whole body 4-8T scanners: in evaluation
• Whole body 9.4T scanners: in the queue

A brief overview of high-field MRI

• Technical/Safety Issues
  – Main field
  – RF Field
  – Gradients
• Contrast changes
  – Spin lattice relaxation (T1)
  – Spin-Spin relaxation (T2)
  – Transverse relaxation (T2*)
  – Spectral Resolution
• Applications

Note:
7T: MGH and NIH also have
8T: Ohio State University

University of Minnesota CMRR
(www.cmrr.umn.edu)
The Main Field ($B_0$)
- Modern superconducting magnet design
  - Type II superconductors
  - Niobium titanium (NbTi) windings
    - Critical field limits upper field (< 10 T)
    - Bypass by cooling < 4.2 K
  - Niobium tin (Nb3Sn) for higher fields
    - Brittle and difficult to wind
    - Expensive to use
  - Fields above 10 T likely to interleave both

Magnetic Field Homogeneity
- Often stated as the $\Delta \nu$ (in Hz or ppm) across a given diameter of spherical volume (DSV).
- Homogeneity desired is often application dependent:
  - Routine imaging: < 5 ppm at 35 cm DSV
  - Fast imaging (EPI): < 1 ppm at 35 cm DSV
  - Spectroscopy: < 0.5 ppm at 35 cm DSV

High-field siting challenges
- With constant homogeneity, as field is increased
  - Magnet size increases
  - Overall weight increases
  - Cryogen volume and consumption increased
  - Energy stored in windings is increased
  - Stray field lines
- Costs and siting concerns can be significant
  - Modern 3T scanners weigh 2x as much as 1.5T
  - Higher-fields: 20 tons with cryogens + 100 tons shielding

Shimming
- Need higher performing, automated shims to maintain homogeneity
- Several stages
  - Magnet $\Rightarrow \delta < 125$ ppm
  - Superconducting shims: $\delta < 1.5$ ppm
  - Passive + Room Temperature: $\delta < 0.2$ ppm

Magnet Shielding
- Reduces problems of siting MRI in a confined space
  - 5 G line reduced from 10-13 m => 2-4 m
- Passive Shielding
  - High permeability material, such as iron, provides return path for stray field lines of $B_0$ decreasing the flux away from the magnet.
  - Can be quite heavy and expensive
- Active Shielding
  - Secondary shielding coils produce a field canceling fringe fields generated by primary field coils
  - Typically coils reside inside the magnet cryostat
  - Commercial 3T scanners rely on this to minimize weight
Fringe Fields: 1.5T versus 3.0T

FDA $B_0$ Field Safety limits

$B_0$ field safety concerns

Main field Safety: Torques and Force
**Magnetic Field safety: Torques and Force**

- Equipment formally designated as “MR Safe” at 1.5T may not be at 3T
- Force on a paramagnetic object at 3T can be about 5x the force at 1.5T
- Force on a ferromagnetic object can be about 2.5x the force at 1.5T

**Fringe Field Force: 1.5T versus 3.0T**

**Magnetohydrodynamic Effects**

- Electrically conductive fluid flow in magnetic field induces current and a force opposing the fluid flow
- Effects greatest when flow perpendicular to field
  - Potential across vessel \(-\mathbf{B}_0\)
  - Force resisting flow \(-\mathbf{B}_0^2\)

**Magnetohydrodynamic Effects**

- “T-wave swelling”
  - Distortions on ECG during period of highest flow through aorta during MRI exams
  - Induced potentials are on the order of 5 mV/Tesla
  - Effect will be exacerbated at high-fields
  - Will be an even greater challenge to obtain good ECG’s in a high-field MR environment

**Magnetohydrodynamic Effects**

- Increased blood pressure due to additional work needed to overcome magnetohydrodynamic force has a negligible effect on blood pressure
  - \(< 0.2%\) at 10 Tesla
- Hypothesized that field strengths of 18 Tesla are needed before a significant risk is seen in humans.

**Transient Effects**

- Phenomena reported in association with patients moving in/out of high field magnets
  - Nausea (slight)
  - Vertigo
  - Headache
  - Tingling/numbness
  - Visual disturbances (phosphenes)
  - Pain associated with tooth fillings
- All effects are transient and cease after leaving the magnet
  - Actively-shielded high-field magnets (large gradient fields)
  - Reduced or avoided by moving slowly in the main field
Radiofrequency at high-field

- $B_1$ field sensitivity increases approximately linearly with $B_0$
- RF propagation becomes increasingly inhomogeneous
  - Permittivity, conductivity and patient conformation
  - Reduced penetration
  - Increased dielectric effects
- RF phase and magnitude function of position
- Significant imaging challenge

Specific Absorption Ratio (SAR)

- Deposition of RF power in body can cause heating
  - Primary concern: whole body and localized heating
  - Significant concern at high-fields
  - Don’t forget about heating of medical devices!
- SAR = RF Power Absorbed per unit mass (W/kg)
  $$\text{SAR} = B_1^2 \cdot (\text{flip angle})^2 \cdot (\text{RF duty cycle})$$
- Another thumb rule
  - $1 \text{ W/kg} \rightarrow 1^\circ \text{C/hr} \text{ heating in an insulated tissue slab}$

SAR influenced operating modes

- Commercial scanners now must report SAR in real-time and notify users of operating thresholds
- Normal Mode
  - $\text{SAR} < 2 \text{ W/kg}, (\Delta T < 0.5^\circ \text{C})$
- First Level controlled Mode (medical supervision)
  - $\text{SAR} < 4 \text{ W/kg}, (\Delta T < 1.0^\circ \text{C})$
- Second level controlled mode (need IRB)

FDA SAR limits

<table>
<thead>
<tr>
<th>Site</th>
<th>Dose</th>
<th>Time (min)</th>
<th>SAR (W/kg)</th>
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<tr>
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<td>averaged</td>
<td>15</td>
<td>4</td>
</tr>
<tr>
<td>hand</td>
<td>averaged</td>
<td>10</td>
<td>3</td>
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<td>part grams</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>extremities</td>
<td>part grams</td>
<td>5</td>
<td>12</td>
</tr>
</tbody>
</table>


RF Sensitivity: Field Focusing

- Hyperintensity in middle of imaged volume
  - Dielectric effects become more significant as $B_0$
  - Oil filled phantoms homogeneous
  - Challenge for brain and body homogeneity

How the scanner estimate SAR

- Scanner run calibration routine
  - Determine energy needed for $90^\circ$ and $180^\circ$ flip angles
  - Sum energy of all RF pulses in sequence
  - Divide by pulse repetition time (TR) to estimate power
  - Divide by patient weight for whole body SAR
  - Peak SAR estimated as $\sim 2.5$ times whole body SAR on many scanners
SAR limits on imaging

- SAR can put serious restrictions on
  - Pulse repetition time
  - Number of RF pulses in a multi-echo sequence (FSE)
  - Slice efficiency in multi-slice imaging
  - Ability to use high SAR pulses
    - Fat saturation
    - Magnetization transfer pulses
    - Inversion pulses

Ways to work around SAR limitations

- RF pulse design
  - Reduced flip angle (particularly for fast spin echo)
- Use of array coils
  - Transmit-receive arrays to reduce power
  - Parallel imaging techniques (SENSE, SMASH)
- Imaging parameters
  - Rectangular field of view
  - Reduced number of phase encoding steps
  - Increased TR
  - Less slice in multi-slice imaging (lower efficiency)

Partially parallel imaging

- Standard software on new generation scanners
  - SENSE, ASSET, etc.
- Uses information encoded into receive array with apriori information of the coil sensitivities to facilitate undersampling in k-space
- This allows the user to speed up the acquisition by collecting less echoes
  - Doesn’t compromise resolution
  - SNR reduced by AT LEAST a factor of $\sqrt{2}$
- Less # of echoes => Less SAR

Partially Parallel Imaging (PPI)

Aliased Image

Un-aliased Image

Calculated using sensitivity information from array coils

Gradients at higher-fields

- High performance gradients wanted to take advantage of increased SNR for high resolution/speed
- Current systems have
  - Max amplitude ~ 20-50 mT/m
  - Max slew rates ~ 120-200 T/m/s
- Increased reactive (inductive and capacitive) coupling to bore/shims/RF coils
  - increased eddy currents and non-linearities
  - self-inductance limits maximum amplitude and slew rate
  - lower inductance designs the easiest fix

Gradient safety at higher fields

- Physiological constraints on dB/dt to prevent peripheral nerve stimulation limit gradient performance
  - One strategy for overcoming: shorten linearity volume
- Acoustic noise
  - force on the coils scales with the main field
Field Strength and Image Quality

- Increased main field
  - Signal to noise ratio increased
  - $T_1$ increased
  - $T_2$ decreases (slightly)
  - $T_2^*$ decreases
  - Spectral resolution increases

Signal as a function of field strength

- Where does the increase in signal come from?
- Sample magnetization proportional to $B_0$
  $$M_0 \propto N \Delta V_{z+} \sim N \frac{hyB_0}{kT}$$
- Faraday’s Law: Induced e.m.f. in coil proportional to time rate of change of transverse magnetization

Larmor Precession Frequency $= \omega_0 = \gamma B_0$

Higher fields ... how much SNR?

- Signal versus field strength
  $$\text{Signal} \propto \alpha_0 M_0 \propto B_0^2$$
- Noise versus field strength
  $$\text{Noise} \propto \sqrt{\sigma_{\text{coil+ system}}^2 + \sigma_{\text{sample}}^2} \propto \sqrt{aB_0^2 + bB_0^2}$$

High-field signal-to-noise ratio

$$\text{SNR} \propto \frac{B_0^2}{\sqrt{aB_0^2 + bB_0^2}} \propto \frac{B_0^{3/4}}{B_1}$$
- At high-field, $B_1(B_0)$ is no longer easily quantifiable
- SNR is still “nearly” linear with $B_0$ in this regime

T1 relaxation as a function of $B_0$

- Spin lattice relaxation both lengthens and converges for most tissues with increased field strength
  - Increases of ~30%
- Consequences
  - Contrast and SNR reduction
  - Need longer TR and/or preparatory pulses
  - Longer inversion times needed
  - STIR and FLAIR
  - Tissue and blood more easily saturated
  - Reduced Ernst angles in gradient echo imaging

T1-weighted imaging

- Can use SNR boost for higher resolution
  - Keep similar scan time
- Spin-echo T1-W imaging will be SAR limited
  - Number of slices
  - Fat saturation
- Solutions
  - Use an array head coil
  - Reduce number of slices
  - Rectangular field of view
  - Longer TR
  - Multiple acquisitions

T2 and T2* relaxation as a function of B₀

- T2 can decrease slightly at fields > 3T
- T2* decreases significantly at higher fields
  - Changes vary strongly with tissue environment
  - Effects
    - Increased T2* contrast from contrast agents or blood
    - Decreased signal on gradient echo images due to susceptibility effects
      - Use of shorter TE
    - T2* filtering of echo trains in EPI
      - Use of shorter echo trains (multi-shot or PPI)

T2-weighted imaging

- Benefits from higher SNR
  - Can use longer echo-trains with higher bandwidths
  - Higher resolution in similar time
- Requires longer TR to compensate for T1 lengthening

T2-weighted and FLAIR imaging

Spectral resolution at higher fields

- Larger spectral separation between different chemical species
  - MR spectroscopy applications will obviously benefit from this and SNR increase
- Chemical shift between fat/water increases
  - 220 Hz @ 1.5T → 440 Hz @ 3T
  - Faster accrual of phase between water/fat for a given TE
  - Exasperates chemical shift artifacts
    - Use higher bandwidths
**Imaging applications**

- Briefly, let’s review some of the major applications that will receive the highest boost from higher field imaging

**Spectroscopy**

- Increased spectral resolution and SNR
  - Higher resolution studies, multi-nuclear, body apps

**Spectroscopy**

![Spectroscopy Chart]

**BOLD imaging**

- In general, Blood-Oxygen Level Dependent (BOLD) contrast increases with field strength
  - CNR increases by factor of 1.8-2.2 from 1.5T to 3.0T
  - Overall effects, and reasons for them, are complicated
- BOLD facilitates neuronal activation measurements without using exogenous contrast agents
- During activation oxygenated blood increases while deoxygenated blood (paramagnetic) decreases
  - T2* is lengthened ⇒ signal increase on T2* weighted images
  - BOLD contrast increases due to T2* contrast enhancement
- SNR increases sensitivity of technique as well

**Gradient-echo BOLD fMRI: 1.5T vs 3.0T**

![Gradient-echo BOLD fMRI Chart]

**Diffusion Weighted Imaging**

- SNR is crucial
  - Thinner slices
  - Reduce partial volume artifacts
  - Higher b-values
- Diffusion Tensor Imaging (DTI)
  - Same benefits
  - Can perform faster to minimize motion
- Shortened T2*
  - Limits benefits

**Perfusion imaging**

- Arterial Spin Labeling (ASL)
  - Uses and inversion pulse to “tag” blood
  - Images acquired as tagged blood perfuses into tissue
  - Long T1 results in better tagging
- Dynamic Susceptibility Contrast (DSC)
  - Bolus of paramagnetic agent
    - T2* contrast
    - T2* effect increased by field

**Perfusion imaging**

![Perfusion imaging Chart]
**Contrast Enhanced imaging**

- Higher SNR
- Longer tissue T1 versus little change in contrast agent T1
  - Better contrast
  - Use less contrast

![Dynamic contrast enhanced imaging](image)

**Angiography**

- Time of flight (TOF)
  - Relies on saturated normal tissue and bright inflow
  - Longer T1 time => better background tissue saturation
  - Magnetization Transfer Contrast can further suppress
    - Must be careful of SAR limits
  - Higher-field => increased inflow signal

![3D TOF](image)

**Cardiac Imaging**

- Speed is king in cardiac imaging
  - Trade-in SNR for speed
- Black blood imaging
  - Increased T1 of blood by 30% means a longer inversion time is needed (decrease in efficiency)
  - Larger SNR and slow T1 relaxation
  - Chances to increase the limited slice efficiency of the method
- Cine imaging
  - Bad news: SSFP (trueFISP, FIESTA) sequences will need to reduce flip angles due to SAR limitations
    - T2 weighting and SNR loss
  - Good news: SAR reduced as FA²

![Cardiac Imaging](image)