High Field MRI Technology, Applications, Safety, and Limitations

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THE UNIVERSITY OF TEXAS
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Making Cancer History

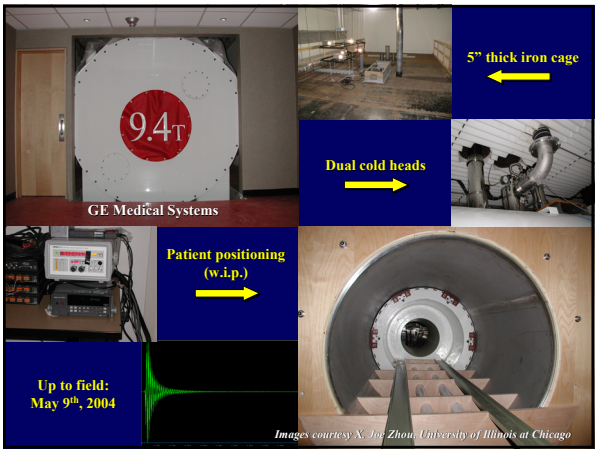
The promise of high-field MRI

- 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/altered 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



University of Minnesota CMRR

(http://www.cmrr.umn.edu)

Installed April 2004

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

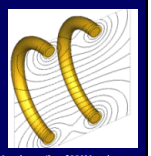
A *brief* overview of high-field MRI

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

Berry MV, Geim AK, "Of Flying Frogs and Levitrons", European Journal of Physics **18**: 307-313 (1997).

The Main Field (B_o)

- 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 (Nb^3Sn) for higher fields
    - Brittle and difficult to wind
    - Expensive to use
  - Fields above 10 T likely to interleave both



http://www.integratedsoft.com/Newsletters/June2001Newsletter.asp

Magnetic Field Homogeneity

- Often stated as the $\Delta\upsilon$ (in Hz or ppm) across a given **d**iameter of **s**pherical **v**olume (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

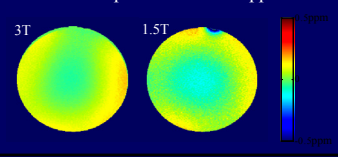
- With constant homogeneity, as field is increased
  - Magnet size increases
  - Overall weight increases
  - Cryogen volume and consumption increased
    - Energy stored in windings is increased
  - Stray field lines
- Costs and siting concerns can be significant
  - Modern 3T scanners weigh 2x as much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

High-field siting challenges

- Challenge is how to minimize these costs while maintaining field homogeneity?
- Magnet winding circuits
  - Tighter/more windings to reduce length
  - Reduced length => reduced cryogen volume/use
- Conductor formats and joining techniques
- Filament alloys
- Shimming
- Shielding

Shimming

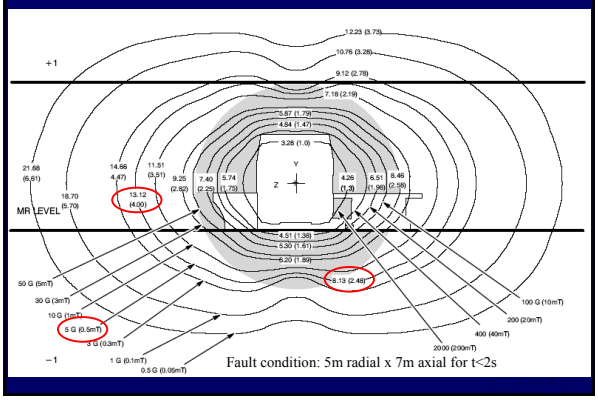
- Need higher performing, automated shims to maintain homogeneity
- Several stages
  - Magnet => δ < 125 ppm
  - Superconducting shims: δ < 1.5 ppm
  - Passive + Room Temperature: δ < 0.2 ppm



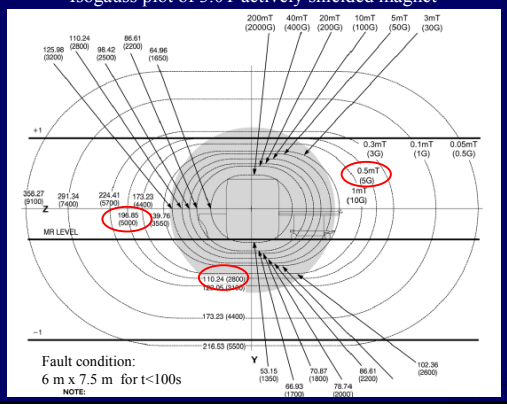
Magnet Shielding

- 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

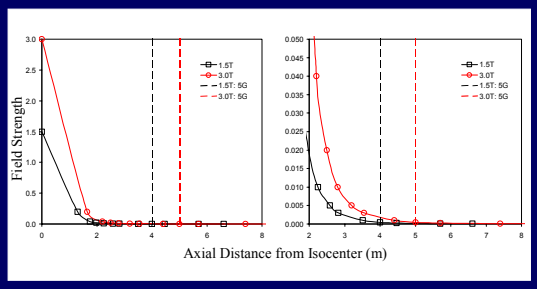
Isogauss plot of 1.5T actively shielded magnet



Isogauss plot of 3.0T actively shielded magnet



Fringe Fields: 1.5T versus 3.0T



FDA B_0 Field Safety limits

Main Static Magnetic Field

Population	Main static magnetic field greater than (tesla)
adults, children, and infants aged > 1 month	8
neonates i.e., infants aged 1 month or less	4

Guidance for Industry and FDA Staff: Criteria for Significant Risk Investigations of Magnetic Resonance Diagnostic Devices, July 14th, 2003.
http://www.fda.gov/cdrh/ode/guidance/793.pdf

B_0 field safety concerns

- Ferromagnetic projectiles
- Medical devices
  - Translation
  - Torque
  - Interference
- Magnetohydrodynamic effects

Main field Safety: Torques and Force

- Torque (L) on an object in magnetic field

$$L \propto m \cdot B_0 \cdot \sin\theta \propto B_0^2 \cdot \sin\theta$$

- Translational force on object in magnetic field

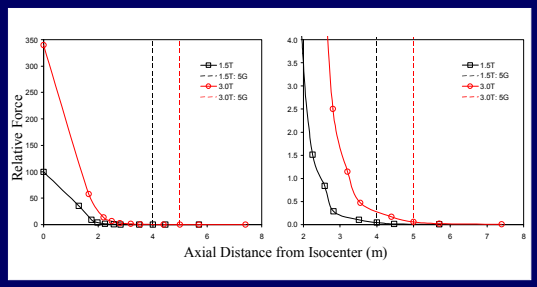
$$F \propto \nabla(\vec{m} \bullet \vec{B}_0) \propto B_0 \nabla B_0$$

- Torque and translational force also proportional to susceptibility and volume of material

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 ~ B_0
  - Force resisting flow ~ 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

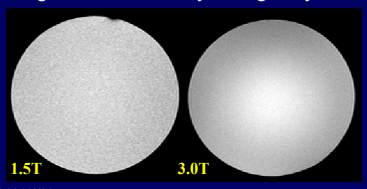
- Phenomena reported in association with patients moving in/out of high field magnets
  - Nausea (slight)
  - Vertigo
  - Headache
  - Tingling/numbness
  - Visual disturbances (phosphenes)
  - Pain associated with tooth fillings
- All effects are transient and cease after leaving the magnet
  - actively 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

RF Sensitivity: Field Focusing

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



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)

$$\text{SAR} \propto B_0^2 \cdot (\text{flip angle})^2 \cdot (\text{RF duty cycle})$$

- Another thumb rule
  - 1 W/kg => 1°C/hr heating in an insulated tissue slab

FDA SAR limits

Specific Absorption Rate (SAR)

Site	Dose	Time (min) equal to or greater than:	SAR (W/kg)
whole body	averaged over	15	4
head	averaged over	10	3
head or torso	per gram of tissue	5	8
extremities	per gram of tissue	5	12

Guidance for Industry and FDA Staff, Criteria for Significant Risk Investigations of Magnetic Resonance Diagnostic Devices, July 14th, 2003.
http://www.fda.gov/cdrh/ode/guidance/793.pdf

SAR influenced operating modes

- Commercial scanners now must report SAR in real-time and notify users of operating thresholds
- Normal Mode
  - SAR < 2 W/kg, (ΔT < 0.5 °C)
- First Level controlled Mode (medical supervision)
  - SAR < 4 W/kg , (ΔT < 1.0 °C)
- Second level controlled mode (need IRB)

How the scanner estimate SAR

- Scanner run calibration routine
  - Determine energy needed for 90° and 180° 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 ~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

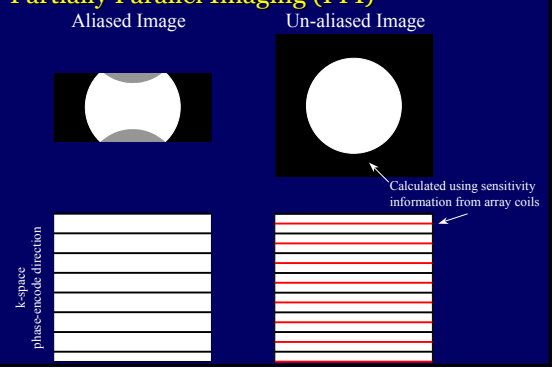
Ways to work around SAR limitations

- 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 √2
- **Less # of echoes => Less SAR**

Partially Parallel Imaging (PPI)



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
  - T1 increased
  - T2 decreases (slightly)
  - T2* 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

$$M_0 \propto \Delta N_{\uparrow\downarrow} \sim N_s \frac{h\gamma B_0}{kT}$$

- Faraday's Law: Induced e.m.f. in coil proportional to time rate of change of transverse magnetization

$$\text{Larmor Precession Frequency} = \omega_0 = \gamma B_0$$

Higher fields ... how much SNR?

- Signal versus field strength

$$Signal \propto \omega_0 M_0 \propto B_0^2$$

- Noise versus field strength

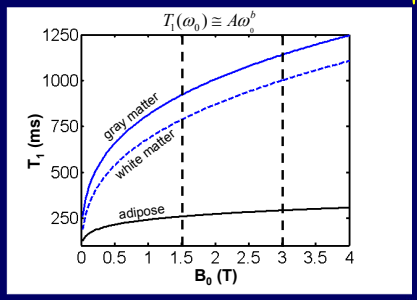
$$Noise \propto \sqrt{\sigma_{coil+system}^2 + \sigma_{sample}^2} \propto \sqrt{aB_0^{1/2} + bB_0^2}$$

High-field signal-to-noise ratio

$$SNR \propto \frac{B_0^2}{\sqrt{aB_0^{1/2} + bB_0^2}} \propto \begin{cases} B_0^{7/4} & \text{(low field limit)} \\ B_0 & \text{(mid-field regime)} \end{cases}$$

- 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



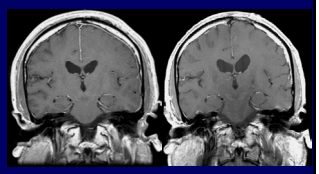
Bottomley PA, et al, **Med Phys** (1987)

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 prepatory 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

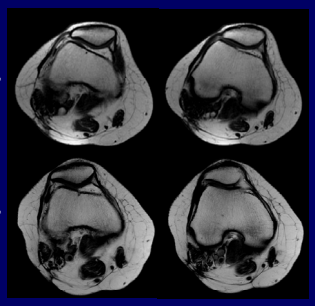


1.5T 3.0T

T1-weighted imaging: MSK Knee

1.5T

3.0T

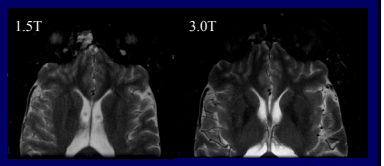


T2 and T2* relaxation as a function of B_0

- 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

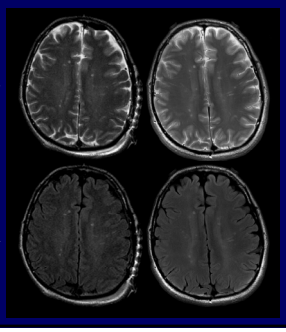


T2-weighted and FLAIR imaging

1.5T 3.0T

T2-W

FLAIR



Spectral resolution at higher fields

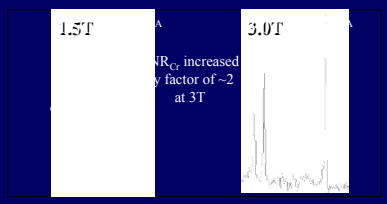
- Larger spectral separation between different chemical species
  - MR spectroscopy applications will obviously benefit from this and SNR increase
- Chemical shift between fat/water increases
  - 220 Hz @ 1.5T => 440 Hz @ 3T
  - faster accrual of phase between water/fat for a given TE
  - exasperates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

Imaging applications

- Briefly, lets 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

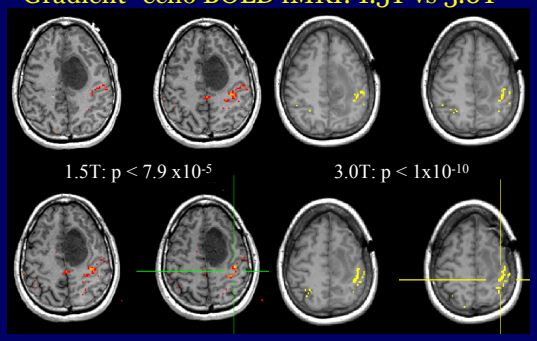


BOLD imaging

- 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

Krasnow, B, et al, **NeruoImage** (2003)

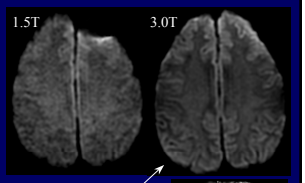
Gradient- echo BOLD fMRI: 1.5T vs 3.0T

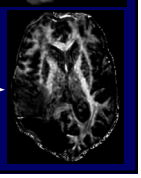


Right Hand Sensorimotor Task

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

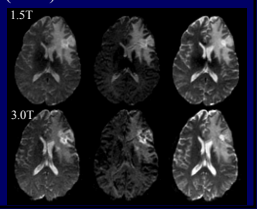




3.0T Diffusion and Diffusion Tensor Imaging

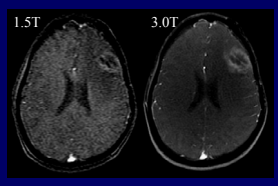
Perfusion imaging

- 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



Contrast Enhanced imaging

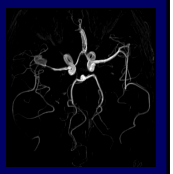
- Higher SNR
- Longer tissue T1 versus little change in contrast agent T1
  - Better contrast
  - Use less contrast



Dynamic contrast enhanced imaging

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
(www.medical.philips.com)

Gibbs, GF, et al, **AJNR** (2004)

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 FA^2

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