Magnetic Resonance Imaging at Ultra High Field: Hardware, Methods and Applications

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Overview of Talk

- MRI Principles
- UHF MRI Hardware
- MRI Detection/Excitation Methods
- Classification RF Coils
- Virtual lab tour RF surface coils
- Double-tuned RF coils
- Travelling wave detection
- Summary
**Principles of MRI**

\[ \Delta E = h \nu_0 = \frac{\gamma h B_0}{2\pi} \]

\[ \omega_0(r) = \gamma \cdot B_0(r) \]

\[ \alpha(r) = \gamma \cdot B_1(r) \cdot t_p \]

\[ k_x(t) = \int \gamma \cdot G_x(t) \, dt \]

\[ k_y(t) = \int \gamma \cdot G_y(t) \, dt \]

**MRI Hardware**

- Human Body (spins)
- Superconductive magnet
- (Shim coils)
- Gradient coils \((x,y,z)\)
- Radio frequency coil(s)
- TX/RX electronics

\[ \frac{dB_0}{dz}, \ldots \]

\[ B_1 \]

1H, 13C, 23Na, 31P
Common Nuclei/Frequencies

<table>
<thead>
<tr>
<th>Nuclei</th>
<th>$^1H$</th>
<th>$^{13}C$</th>
<th>$^{19}F$</th>
<th>$^{23}Na$</th>
<th>$^{31}P$</th>
<th>Electron (EPR/DNP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>gamma (MHz/T)</td>
<td>42.58</td>
<td>10.71</td>
<td>40.06</td>
<td>11.26</td>
<td>17.24</td>
<td>27994</td>
</tr>
<tr>
<td>$B_0$ Field (T)</td>
<td>(MHz)</td>
<td>(MHz)</td>
<td>(MHz)</td>
<td>(MHz)</td>
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<td>(MHz)</td>
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<tr>
<td>0.001</td>
<td>0.043</td>
<td>0.011</td>
<td>0.040</td>
<td>0.011</td>
<td>0.017</td>
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<tr>
<td>1.5</td>
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<td>16.06</td>
<td>60.08</td>
<td>16.89</td>
<td>25.85</td>
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<tr>
<td>3.0</td>
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<td>120.16</td>
<td>33.79</td>
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<tr>
<td>4.0</td>
<td>170.31</td>
<td>42.82</td>
<td>160.22</td>
<td>45.05</td>
<td>68.94</td>
<td>111976</td>
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<tr>
<td>7.0</td>
<td>298.04</td>
<td>74.94</td>
<td>280.38</td>
<td>78.83</td>
<td>120.64</td>
<td>195958</td>
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<tr>
<td>9.4</td>
<td>400.22</td>
<td>100.68</td>
<td>376.52</td>
<td>105.86</td>
<td>162.01</td>
<td>263143</td>
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<tr>
<td>11.7</td>
<td>498.15</td>
<td>125.25</td>
<td>468.64</td>
<td>131.76</td>
<td>201.65</td>
<td>327530</td>
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</table>

BENEFITS OF HIGH FIELD MRI

- Higher signal to noise ratio
- Improved spatial resolution
- Shorter scan times
- Greater spectral dispersion
- Larger BOLD contrast
- Special applications
  ▲ ($^{23}Na$, $^{17}O$, etc)

\[ \nu_0 = \frac{\gamma}{2\pi} B_0 \quad \text{(proton)} \]

\[ B_0 \ (T) \quad \nu_0 \ (MHz) \]

<table>
<thead>
<tr>
<th>1.5</th>
<th>64</th>
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<tr>
<td>3</td>
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<td>7</td>
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<tr>
<td>8</td>
<td>340</td>
</tr>
<tr>
<td>9.4</td>
<td>400</td>
</tr>
</tbody>
</table>
Design Criteria for High Field RF Coils

1. Coil issues:
   - Self-resonance frequency
   - Increased radiative losses
   - Lumped vs distributed models

2. Sample issues:
   - Electric and magnetic losses
   - RF penetration effects
   - RF standing wave effects

<table>
<thead>
<tr>
<th>$B_0$ (T)</th>
<th>$v_0$ (MHz)</th>
<th>$\lambda_0/2$ (cm)</th>
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<td>8</td>
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<td>42</td>
</tr>
<tr>
<td>9.4</td>
<td>400</td>
<td>36</td>
</tr>
</tbody>
</table>

Signal-to-noise-ratio and RF coils

$$\text{SNR} \propto \frac{M_{xy} \cdot \left( \frac{B_{l,xy}}{I} \right)}{\sqrt{T_{\text{coil}} \cdot \Delta f \cdot V_{\text{coil effective}}}}$$

$$\text{SAR}_{\text{WB}} = \frac{\text{Total RF Energy Dissipated in Sample (J)}}{\text{Exposure Time (s) \cdot Sample Weight (Kg)}} = \frac{\sigma |E|^2}{2 \cdot \rho}$$

- Basic design goals:
  - minimise $B_1$ spatial variations over ROI
  - maximise $B_1$ amplitude per unit current (reciprocity)
  - minimise losses in the RF coil (cool)
  - minimise losses in the sample (volume)
  - minimise Specific Absorption Rate (SAR)
  - and many others!!!
Analytical Model Dielectric Slab

\[ B_1(x) \propto \sqrt{e^{-2\alpha x}} + \Gamma_s^2 e^{2\alpha x} + 2\Gamma_s \cos(2\beta x) \]

- \( \alpha \) = attenuation constant
- \( \beta \) = propagation constant
- \( \Gamma_s \) = reflection coefficient
- \( \omega \) = Larmor frequency
- \( \varepsilon \) = permittivity of dielectric
- \( \sigma \) = conductivity
- \( d \) = slab thickness

Stratton, EM Theory, McGraw-Hill, 1941
Balanis, Advanced EM, Wiley, 1989

Analytical Model Dielectric Slab

B1 distribution is a combination of RF standing wave and RF penetration effects

- \( d=16 \text{ cm} \)
- @ 3 Tesla (128 MHz)
- \( \lambda/2=117 \text{ cm in air} \)
- \( \lambda/2=68 \text{ cm in oil} \)
- \( \lambda/2=14 \text{ cm in water} \)

Alecci et al, MRM 46:379 (2001)
3T Radial $B_1$: Phantoms

Good agreement FD-TD calculation and experiment

$B_1$ distribution is sample dependent

- $\Delta B_1$ oil $\approx$ 10%
- $\Delta B_1$ water $\approx$ 50%
- $\Delta B_1$ saline $\approx$ 30%

Alecci et al MRM 46:379 (2001)

1H UHF MRI in Humans

UHF (>4T) allows SNR improvement

human brain

ALECCI, Sapienza 2012
**1H UHF MRS in Humans**

UHF (>4T) allows spectral resolution improvement

- EMCL -CH=CH-
- IMCL -(CH2)-
- EMCL -CH3
- IMCL -(CH2)-
- Carnosine
- Carnitine
- Creatine
- Creatine
- Taurine

**UHF fMRI BENEFITS**

Functional MRI in visual cortex

- Visual stimulation
- 5mm slice
- Same ROI
- TE=40ms (1.5T)
- TE=25ms (4T)

*Turner et al., MRM, 29, (1993)*
Basic RF coils

Crossed- RF Coils NMR Detection

Traditional RF coils form standing radio-frequency waves in the sample.

The magnetic component B1, in TX mode causes nutation of the magnetization M and in RX mode governs the probe’s receive sensitivity.
MRI Signal Detection/Excitation Methods

- **Standard MRI signal detection** is based on Faraday induction via the use of one (or more) RF coil (tuned circuit) positioned in close proximity of the sample under investigation.

- **Alternative Principles:**
  - Superconducting Quantum Interference Devices (Day, PRL 1972)
  - Dielectric resonators (Balaban et al, JMR 1990)
  - Hall Probes (Boero et al, Appl Phys Lett 2001)
  - Structured Materials Flux Guides (Wiltshire et al, Science 2001)
  - Atomic Magnetometers (Savucov et al, PRL 2005)
  - Magnetoresistive Elements (Vermillat et al, PNAS 2008)

**COMMON FEATURE:**
they rely on close coupling between the detector and sample

- **Novel Principles:**
  - Parallel Receive (pRX) (Pruessmann et al, MRM 1999, Sodickson et al, MRM 1997)
  - Parallel Transmit (pTX) (Sotgiu et al, MRI 1988, Katscher et al, MRM 2003)
  - Traveling Wave Detection (Brunner et al, Nature 2009)

**Function of RF coil**

TX: high efficiency in transmission, i.e. shortest 90° RF pulse with available input peak RF power

RX: high efficiency in signal reception, i.e. highest signal-to-noise ratio

**Principle of reciprocity**

Maximize the measured voltage for a given precessing magnetization & minimize the noise from the coil, the sample and the environment

A resonant RLC circuit offers the maximum output at the resonance frequency and a reduced output at lower/higher frequencies (band pass).
Classification RF Coils (1)

- **Operating field**
  - Ultra Low Field (1µT-0.1T), Low Field (0.1T-1.5T), High Field (3T-4.0T), Ultra High Field (4.7T-11.7T)

- **Modality**
  - Single Tuned (1H), Double Tuned (1H & 23Na), Triple Tuned (1H&13C&31P)

- **Geometrical Design**
  - Surface, Volume, Phased-Array, RX-Parallel-Imaging elements (RX-PI), TX-Parallel-Imaging elements (TX-PI), Combined TX/RX-PI

- **Practical features**
  - Materials, TX/RX mode, TX-only, RX-only, Linear/Circular Polarization, Shielded/Unshielded, Quality Factor, Self-Resonance Limit, Eddy Currents, Radiation Losses, SAR

Classification RF Coils (2)

- **Applications**
  - Research, Pre-clinical, Clinical

- **Organ/Tissue Districts**
  - Whole Body, Brain, Neck, Cardiac, Shoulder, Wrist, Knee, Calf, Fingers, Endorectal, etc.

- **Structural/Functional Use**
  - Anatomy, Functional, Spectroscopy, Perfusion, DNP

- **Quality Control/Safety Aspects**
  - RF Artifacts, Periodic Check /Calibration, Positioning of coil(s), Calibration based on individuals (male, female, child, obese), SAR requirements, MR Thermometry
Double-Tuned UHF RF Coils

4T Double-Tuned Microstrip RF Coil Prototype

Vitacolonna et al, Proc. ISMRM 2009

- **1H channel**: one microstrip; width=10 mm; CL=11 pF
- **23Na channel**: two microstrips, width=5 mm; separation=20 mm; CL=68 pF
- **Air/Plastic gap**=35 mm
- **Copper ground**: 100 mm x 190 mm

\[ f_{1H} = 168.3 \text{ MHz} \quad \lambda_{1H} = 1.8 \text{ m} \]
\[ f_{23Na} = 44.5 \text{ MHz} \quad \lambda_{23Na} = 6.7 \text{ m} \]

S11(dB)
4T Double-Tuned MRI

Vitacolonna et al, Proc. ISMRM 2009

- FOV=192*230 mm^2
- Resolution=128*153
- Slice thickness=1.5 mm
- NEX=1
- TA=5 min

- FOV=192*192 mm^2
- Resolution=128*65
- Slice thickness=3 mm
- NEX=32
- TA=7 min

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References