MR Acoustic Radiation Force Imaging and MR Thermometry
MR Acoustic Radiation Force Imaging
MR-ARFI

- displacement or motion encoding gradients

\[ \omega = 2\pi \gamma B \]

\[ \Delta B = G \Delta x \]

J. Chen, MRM 2010
MR Acoustic Radiation Force Imaging
Focal Spot Localization

- spin echo imaging, flexible contrast
- good image quality
- temperature effects below FDA limits

E. Kaye, ISMRM 2010
Focal Spot Localization

A. Holbrook, Med Phys 2011
Tissue Changes During Treatment

Pre-ablation

Post-ablation

Displacement

R. Bitton, JMRI 2012
MR Thermometry
Proton Resonance Frequency

\[ \omega = \gamma B_0 \]

- rotation rate is very specific
- 42.57 MHz/T
Proton Resonance Frequency

\[ \omega = \gamma B_0 \]

- rotation rate is very specific
- 42.57 MHz/T
Proton Resonance Frequency Shift Thermometry

As the temperature rises, the hydrogen bonds stretch, bend, and break.

- The protons are more shielded from the field, decreasing the resonant frequency.

$$\omega = \gamma B_0$$
Phase Difference

\[ \omega = \gamma B \]

\[ \phi = \gamma BTE \]

\[ \Delta \phi = \alpha \Delta T \gamma B_0 T E \]

\[ \Delta T = \frac{\Delta \phi}{\alpha \gamma B_0 T E} \]

\[ \alpha = -0.01 \text{ppm} / ^\circ \text{C} \]

Known values: \( \alpha, \gamma, B_0, \text{TE} \)
Nothing that is tissue type dependent here.
Linear over the temperature range of interest.
No hysteresis.
Ex Vivo Tissue-Type Independence in Proton-Resonance Frequency Shift MR Thermometry

Robert D. Peters, R. Scott Hinks, R. Mark Henkelman


\[ \alpha = -0.01 \text{ppm/°C} \]

all aqueous tissue
**Quantitative MRI-based temperature mapping based on the proton resonant frequency shift: Review of validation studies**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Tissue type tested</th>
<th>Temperature range tested (°C)</th>
<th>Temperature sensitivity (ppm/°C)</th>
<th>Heating duration</th>
<th>Heating method</th>
</tr>
</thead>
<tbody>
<tr>
<td>[80]</td>
<td>Pig brain</td>
<td>−15–2</td>
<td>Good fit to −0.0102</td>
<td>N/A</td>
<td>Hypothermia, ischemia</td>
</tr>
<tr>
<td>[81]</td>
<td>Rat muscle</td>
<td>−2–4</td>
<td>−0.0101 to −0.0146</td>
<td>120 min</td>
<td>Heated water bag</td>
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<tr>
<td>[19]</td>
<td>Canine brain</td>
<td>0–10</td>
<td>−0.00674 ± 0.0022</td>
<td>90 min</td>
<td>RF antenna</td>
</tr>
<tr>
<td></td>
<td>Canine muscle</td>
<td></td>
<td>−0.00695 ± 0.0022</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Canine tumor</td>
<td></td>
<td>−0.00652 ± 0.0022</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[82]</td>
<td>Rabbit muscle</td>
<td>0–20</td>
<td>0.007 ± 0.001</td>
<td>90 min</td>
<td>Focused ultrasound</td>
</tr>
<tr>
<td>[62]</td>
<td>Human sarcoma</td>
<td>−2–8</td>
<td>−0.0111 ± 0.0005</td>
<td>~60 min</td>
<td>RF antenna</td>
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<tr>
<td>[83]</td>
<td>Rabbit brain</td>
<td>~0–5</td>
<td>−0.0111</td>
<td>~90 min</td>
<td>Whole body hyperthermia</td>
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<tr>
<td></td>
<td>(gray matter)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(white matter)</td>
<td></td>
<td>−0.0083</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[84]</td>
<td>Rabbit muscle</td>
<td>0–50</td>
<td>−0.00876 ± 0.00069</td>
<td>10 s</td>
<td>Focused ultrasound</td>
</tr>
<tr>
<td>[84]</td>
<td>Rabbit brain</td>
<td>0–15</td>
<td>−0.008</td>
<td>5 min</td>
<td>Microwave probe</td>
</tr>
<tr>
<td>[63]</td>
<td>Human prostate carcinoma</td>
<td>~0–25</td>
<td>Reasonable agreement with −0.01</td>
<td>20–30 min</td>
<td>Microwave probe</td>
</tr>
<tr>
<td>[32]</td>
<td>Rabbit muscle</td>
<td>0–40</td>
<td>−0.00909 ± 0.00068</td>
<td>20 s</td>
<td>Focused ultrasound</td>
</tr>
<tr>
<td>[46]</td>
<td>Rabbit brain</td>
<td>0–40</td>
<td>−0.0088 ± 0.0001</td>
<td>70–120 s</td>
<td>Microwave probe</td>
</tr>
<tr>
<td>[40]</td>
<td>Rabbit brain</td>
<td>0–5</td>
<td>−0.0107 ± 0.0009</td>
<td>10 s</td>
<td>Focused ultrasound</td>
</tr>
<tr>
<td>[85]</td>
<td>Pig muscle</td>
<td>22–40</td>
<td>−0.009 ± 0.001</td>
<td>Unknown</td>
<td>RF probe</td>
</tr>
<tr>
<td>[37]</td>
<td>Rabbit brain</td>
<td>10–47</td>
<td>−0.0098 ± 0.0005</td>
<td>30–581 s</td>
<td>Laser probe</td>
</tr>
<tr>
<td>[86]</td>
<td>Rabbit muscle</td>
<td>5–35</td>
<td>−0.0104 ± 0.0002</td>
<td>30 s</td>
<td>Focused ultrasound</td>
</tr>
<tr>
<td>[87]</td>
<td>Canine brain</td>
<td>~1–33</td>
<td>−0.0079</td>
<td>10 min</td>
<td>Laser probe</td>
</tr>
</tbody>
</table>

InSightec $\alpha = -0.00909$ ppm/°C  
Phillips $\alpha = -0.0094$ ppm/°C
Image Phase

Reasons for phase:
• poor field homogeneity (poor shim)
• poor field homogeneity (perturbations from the body)
• temperature
• velocity
• other stuff

Need to extract the temperature dependent part
PRF Shift Thermometry

Phase image during heating

Temperature rise we want to extract

Background phase we need to separate out
PRF Shift Thermometry

Phase image during heating

Pre-heat image “Baseline Image”

Phase Difference
PRF Shift Thermometry

\[ \Delta \omega = \alpha \Delta T \gamma B_0 \]
PRF Shift Thermometry

\[ \Delta \phi = \alpha \Delta T \gamma B_0 TE \]

Phase image during heating

Pre-heat image "Baseline Image"

Phase Difference
PRF Shift Thermometry

\[ \Delta T = \frac{\Delta \phi}{\alpha \gamma B_0 TE} \]

Phase image during heating

Pre-heat image “Baseline Image”

T, Thermal Dose
Prostate Ablation

• central heat fixed area
• surrounded by coagulative necrosis
Temperature Mapping

Temperature maps appear every 3 seconds.

40°C  
45°C  
50°C  

V. Rieke, JMRI 2013
PRF Thermometry Limitation: Fat

- no changes in water hydrogen bonding
- no PRF shift thermometry in fat
Phase Difference

\[ f_0 = \gamma B_0 \]

\[ \Delta T = \frac{\Delta \phi}{\alpha \gamma B_0 T E} \]

Motion Corrupts!

Image during heating

Pre-heat image

=
Magnetic Susceptibility of the Lung Changes the Magnetic Field

- Long Range Effect
- Temporally Varying
Magnetic Susceptibility of the Lung Changes the Magnetic Field

- Long Range Effect
- Temporally Varying

$$\Delta \omega = \alpha \Delta T \gamma B_0$$
Magnetic Susceptibility of the Lung Changes the Magnetic Field

- Long Range Effect
- Temporally Varying

$$\Delta \omega = \alpha \Delta T \gamma \Delta B_0$$
Magnetic Susceptibility of the Lung Changes the Magnetic Field

- Long Range Effect
- Temporally Varying

$$\Delta \omega = \alpha \Delta T \gamma \Delta B_0$$

Problem for abdomen, pelvis, brain
Image Registration is not sufficient

- Temperature images were shifted and registered to the baseline
- Different lung fillings during acquisition creates large errors.

The effect is huge.
1 mm shift in acquisition looks like a 20°C rise
MR-ARFI Displacement and MR Temperature Increase with Power

Figure 3.10: (a) Cropped temperature rise and displacement phase maps obtained using the modified dual-echo MR-ARFI pulse sequence for a range of acoustic power levels. Mean displacement phase (b) and mean temperature rise (c) at the focal spot are plotted as a function of acoustic power. Linear fits to the data are also shown.