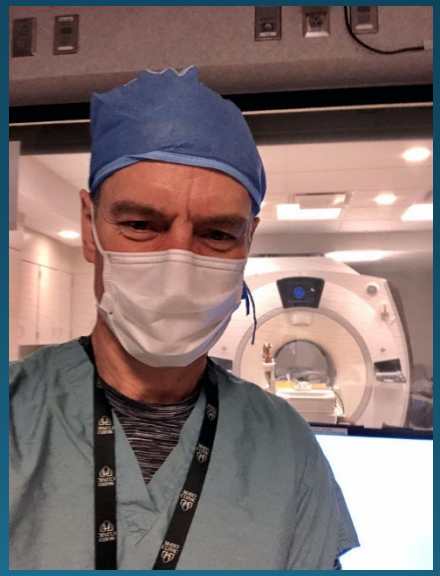
2020 Joint AAPM COMP Meeting

SAM session "Image Guided Ablation: Is it Heating Up or Cooling Down?"

MRI-guided Microwave and Cryo Ablations in the Liver



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Outline:

1. Background
   - Case for using MRI to guide and monitor thermal ablations
   - MRI-thermometry

2. MRI monitoring of clinical hepatic Microwave Ablations (MWA)
   - Challenges to real-time MRI-thermometry during MWA

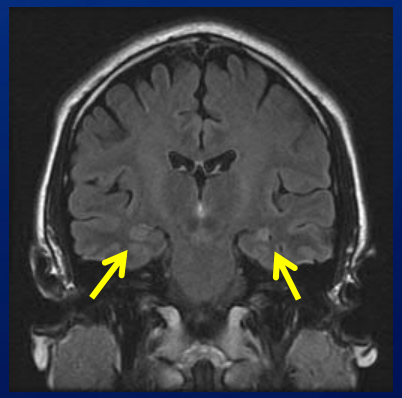
3. MRI monitoring of clinical hepatic cryoablations
   - Near-real time monitoring of tissue freezing
   - Effects of MRI monitoring

MAYO CLINIC

Why use MRI to guide ablations?

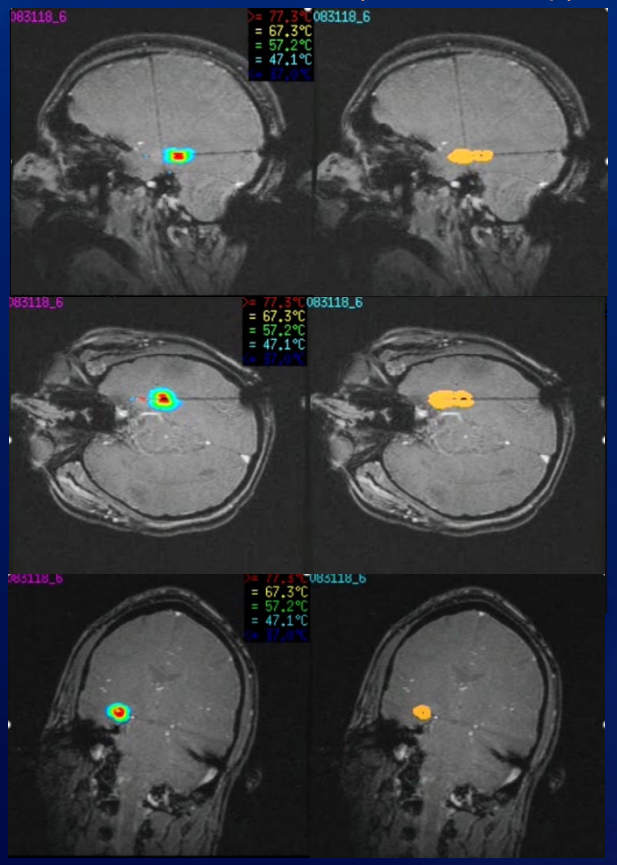
Example: MRI-guided laser treatment of refractory epilepsy

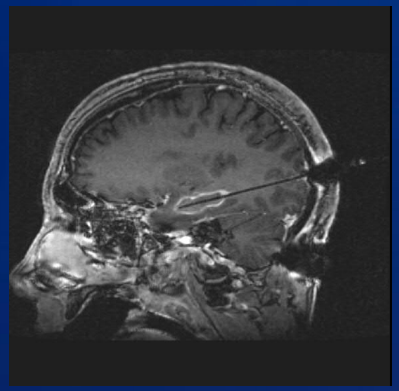
Diagnosis and **Treatment planning**



- Diagnosis made based on subtle signal intensity differences between two sites indicated by arrows
- Volumetric image sets are used for planning of trajectory for stereotactic laser applicator insertion

Temperature map | Thermal dose map (tissue kill map)





- At the end of the treatment MRI is used to evaluate extent of ablation

- MRI used to confirm accurate applicator insertion
- Ablation monitored in real-time in three orthogonal planes using MRI-thermometry

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Why use MRI to guide ablations?

- **Advantages**
  - **Great soft-tissue resolution** (great lesion conspicuity)
  - **Ease of multi-planar imaging**
  - **Real-time time MR thermometry**
  - **No radiation**

- **Disadvantages**
  - **Longer exam time (**minutes vs seconds for CT**)**
  - **Only MRI-safe or MRI-conditional equipment should be used (**MRI-safety**)**
  - **Susceptibility to metal and motion artifacts**
  - **Limited applications in patients with implanted electronic devices (**pacemakers, etc.)
  - **Cramped space inside MRI scanner**

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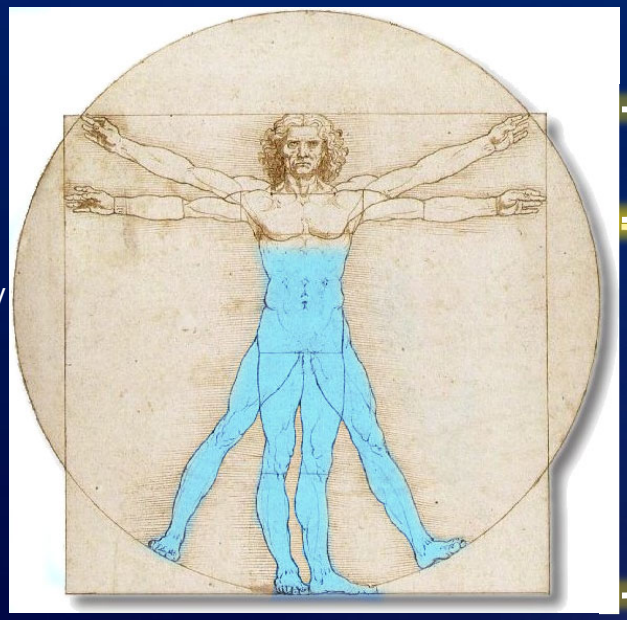
MRI - primer

- **MRI signal:** *coherent precession* of magnetic moments of hydrogen nuclei ("protons") generated by *resonant RF-pulses*
  frequency of precession is given by the *Larmor equation*

$$f_0 = \gamma \cdot B_0$$

1.5T: $f_0 \approx 64$ MHz
3.0T: $f_0 \approx 128$ MHz

Hydrogen: 67% of atoms in human body



Proteins (20%)
Lipids (12%)

H_2O (65%)

MRI - primer

- In hydrogen *atoms* electrons shield protons from B_0
- Resonance frequency is effectively reduced (this phenomenon is called "chemical shift")

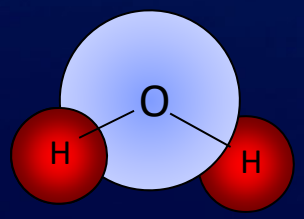
$$f = f_0 \cdot (1 - \sigma)$$

In tissues:

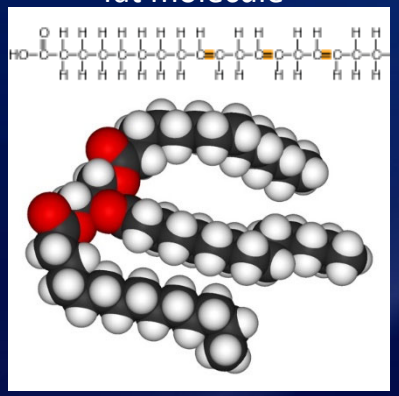
- In water molecules hydrogen neighbors oxygen, which is very chemically active.
- In fat molecules hydrogen neighbors carbon, which is not as chemically active as oxygen.

Chemical shift in fat is *stronger* than in water

water molecule



fat molecule



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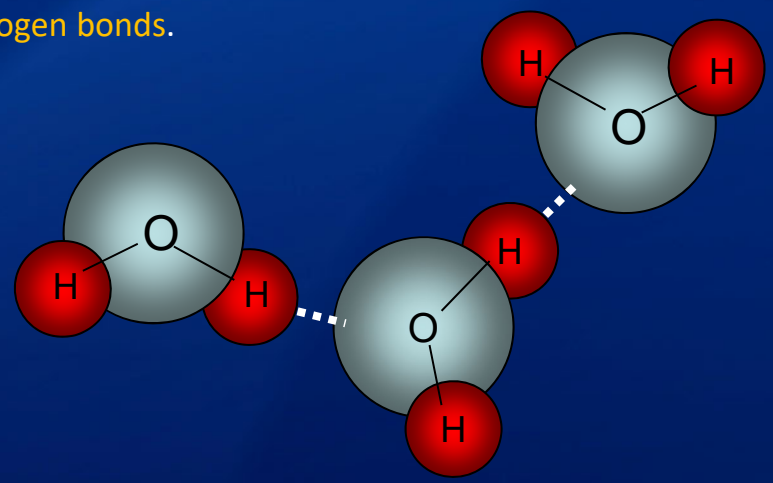
MRI - primer

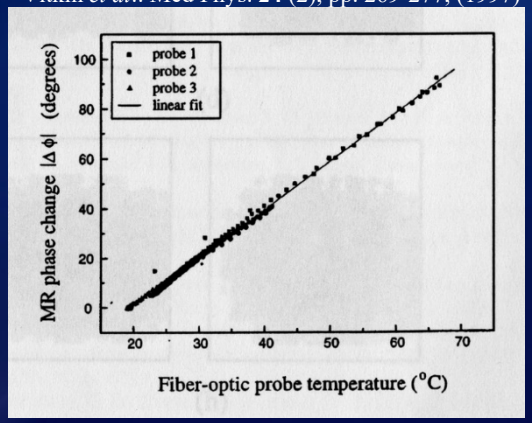
- Oxygen's chemical activity results in additional "stealing" electrons from neighboring water molecules, which results in hydrogen bonds.



- Hydrogen bonds further limit the shielding effects of protons, increasing the chemical shift.
- However, as temperature rises, increased motion of molecules breaks the bonds.
- As a result, proton precession frequency becomes temperature-dependent.

$$f = f_0 \cdot (1 - \sigma) \longrightarrow f(T) = f_0 \cdot (1 - \sigma(T))$$

Vitkin *et al.*: Med Phys. **24** (2), pp. 269-277, (1997)



Change in frequency is linear in temperature

$$\frac{\Delta f}{f_0} = \alpha \times \Delta T \qquad \alpha = -0.01\text{ppm/°C}$$

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MRI - primer

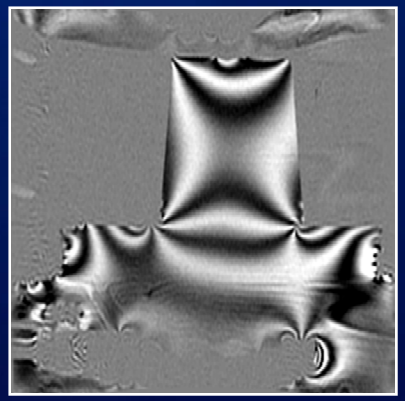
Based on review article: Rieke, Butts Pauly, "MR Thermometry" , *J Magn Reson Imaging*, 27(2):376-390 (2008)

MR thermometry – are things heating up?

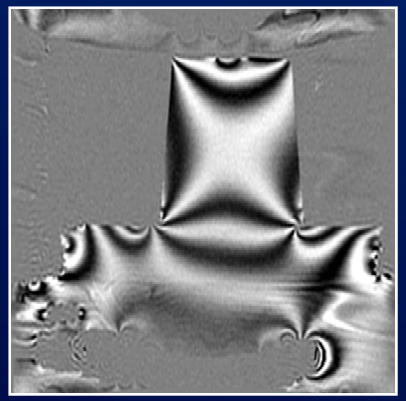
"Proton Resonance Frequency Shift" (PRFS)

- MRI acquires data along the *real* and *imaginary* channels
- These channels are conventionally used to reconstruct *magnitude images*
- They can also be used to reconstruct *phase images*

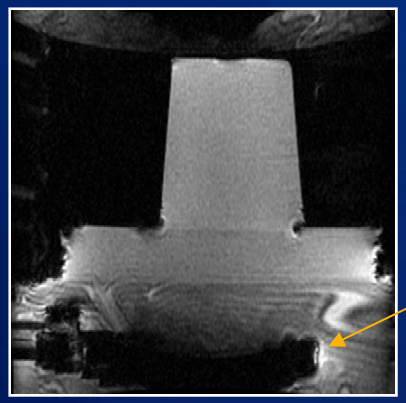
MR images of gel phantom positioned above focused ultrasound transducer



Real channel

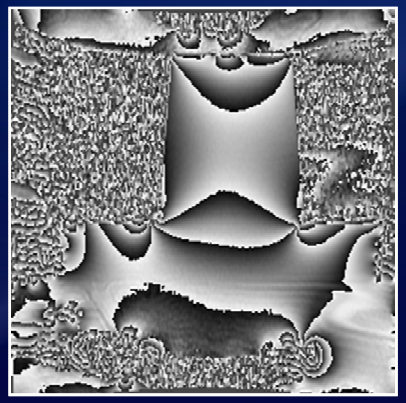


Imaginary channel



Magnitude image

transducer



Phase image

MRI - primer

Based on review article: Rieke, Butts Pauly, "MR Thermometry" , *J Magn Reson Imaging*, 27(2):376-390 (2008)

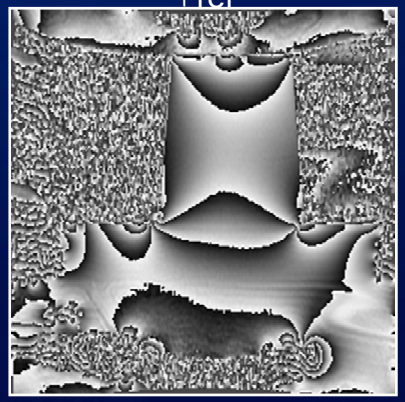
MR thermometry – are things heating up?

"Proton Resonance Frequency Shift" (PRFS)

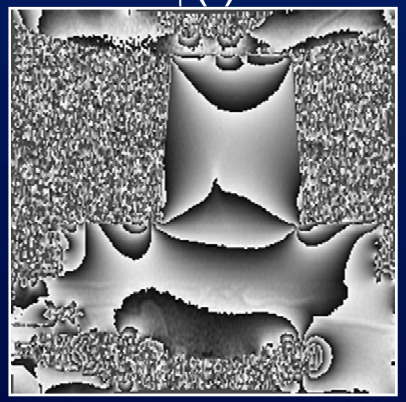
1. acquire reference phase image prior to start of ablation, ϕ_{ref}
2. during ablation acquire subsequent phase images, $\phi(t)$ - compute *phase difference* images, $\Delta\phi(t)$
3. Use linear dependence of phase difference on temperature to compute temperature difference at each voxel

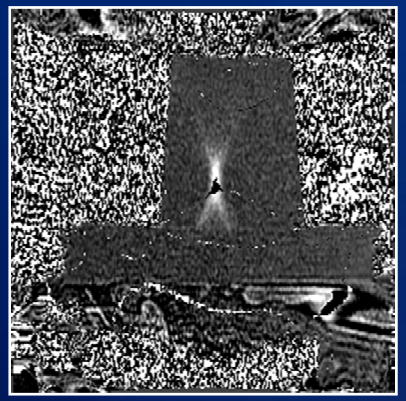
$$\Delta\phi(t) = \phi(t) - \phi_{ref}$$

ϕ_{ref}



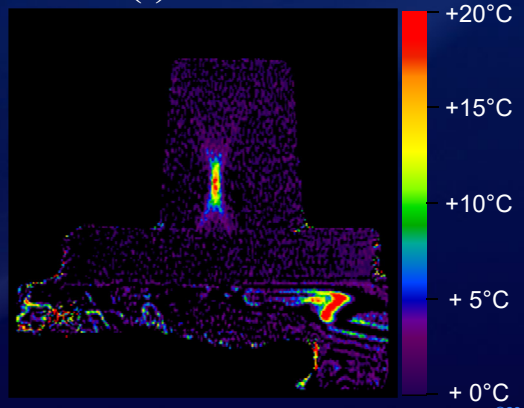
$\phi(t)$





$$\Delta T(t) \sim \Delta\Phi / \alpha$$

α = -0.01ppm/°C



MAYO CLINIC

Based on review article: Rieke, Butts Pauly, "MR Thermometry" , *J Magn Reson Imaging*, 27(2):376-390 (2008)

Limitations of PRFS thermometry

- measures only temperature change (not absolute temperature) -- relative to baseline with assumed arbitrary temperature (usually 37°C)
- thermal dose (tissue kill) is not measured directly – model-based estimate
- does not work in fat
- does not work in frozen tissues
- suffers from limitations of MR imaging
    1. motion artifacts (patient/respiratory/cardiac motion)
    2. limited around metal
    3. susceptible to effects of electronic noise or electromagnetic interference (EMI)

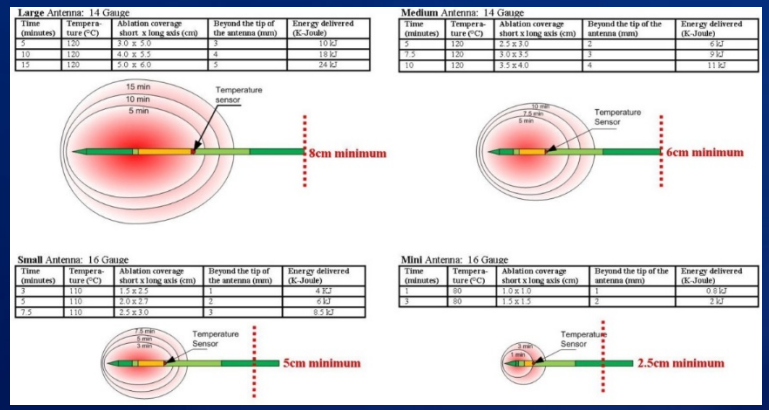
MAYO CLINIC

PRFS in clinical hepatic microwave ablations

Microwave ablations

Generator

Antennas



Large Antenna: 14 Gauge

Time (minutes)	Tempera-ture (°C)	Ablation coverage short x long axis (cm)	Beyond the tip of the antenna (mm)	Energy delivered (K-Joule)
5	120	3.0 x 5.0	3	10 kJ
10	120	4.0 x 5.5	4	18 kJ
15	120	5.0 x 6.0	5	24 kJ

Medium Antenna: 14 Gauge

Time (minutes)	Tempera-ture (°C)	Ablation coverage short x long axis (cm)	Beyond the tip of the antenna (mm)	Energy delivered (K-Joule)
5	120	2.5 x 3.0	2	6 kJ
7.5	120	3.0 x 3.5	3	9 kJ
10	120	3.5 x 4.0	4	11 kJ

Small Antenna: 16 Gauge

Time (minutes)	Tempera-ture (°C)	Ablation coverage short x long axis (cm)	Beyond the tip of the antenna (mm)	Energy delivered (K-Joule)
3	110	1.5 x 2.5	1	4 kJ
5	110	2.0 x 2.7	2	6 kJ
7.5	110	2.5 x 3.0	3	8.5 kJ

Mini Antenna: 16 Gauge

Time (minutes)	Tempera-ture (°C)	Ablation coverage short x long axis (cm)	Beyond the tip of the antenna (mm)	Energy delivered (K-Joule)
1	80	1.0 x 1.0	1	0.8 kJ
3	80	1.5 x 1.5	2	3 kJ

- Ablation frequency: 902-928MHz, 32W
- Mini, Small, Medium, Large antenna applicators with integrated temperature sensors
- Different antennas produce different ablation lesions and are selected based on tumor size
- Antennas are connected to the generator by a pair of coaxial Power and Sensor lines

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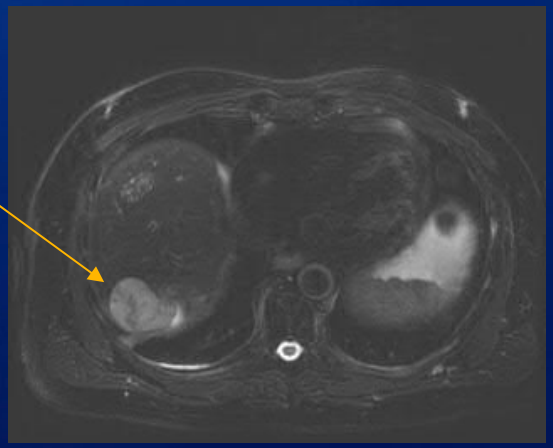
PRFS in clinical hepatic microwave ablations

Microwave ablations

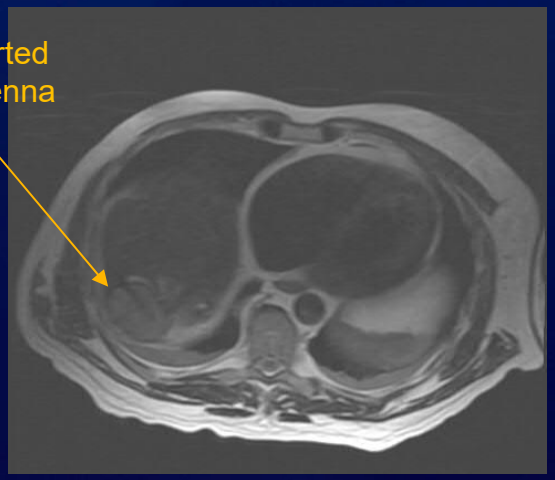
Initial experience

Patient with a prostate cancer met to the liver

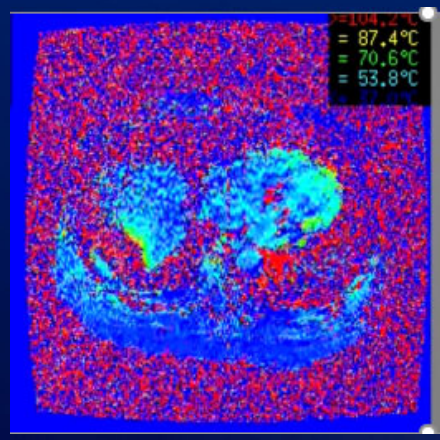
tumor



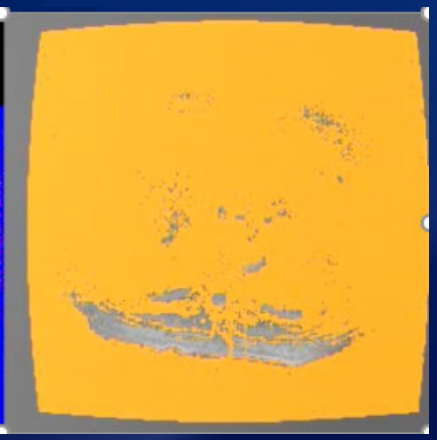
tumor with inserted microwave antenna



Temperature map



Thermal dose map
(tissue kill)



Clinically unusable thermometry

- Significant image noise
- Electromagnetic interference
- Respiratory motion artifact

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PRFS in clinical hepatic microwave ablations

Microwave ablations

Improve MR thermometry

equipment modifications

scan protocol adjustments

Reduce image noise
Reduce EMI
Reduce respiratory artifact

Clinical constraints to equipment modifications and scan protocols

1. Equipment modifications must be non-invasive (patient-safety, FDA-approval)
   cannot use in-line notch filters (only passive ferrite chokes used)

2. Generator must stay outside scanner room (MR-Safety, workflow)
   potential additional increases in RF noise and EMI
   coaxial lines fed inside scanner room via waveguides
   grounding of the coax lines to the waveguides accomplished using copper wool

3. Temporal resolution of MR-Thermometry must be less than 10 seconds (patient-safety)
   Precludes any significant signal averaging to improve SNR

4. MR-thermometry protocol should not require pausing of ablation (Efficacy of ablation)
   Have to reduce noise using other means

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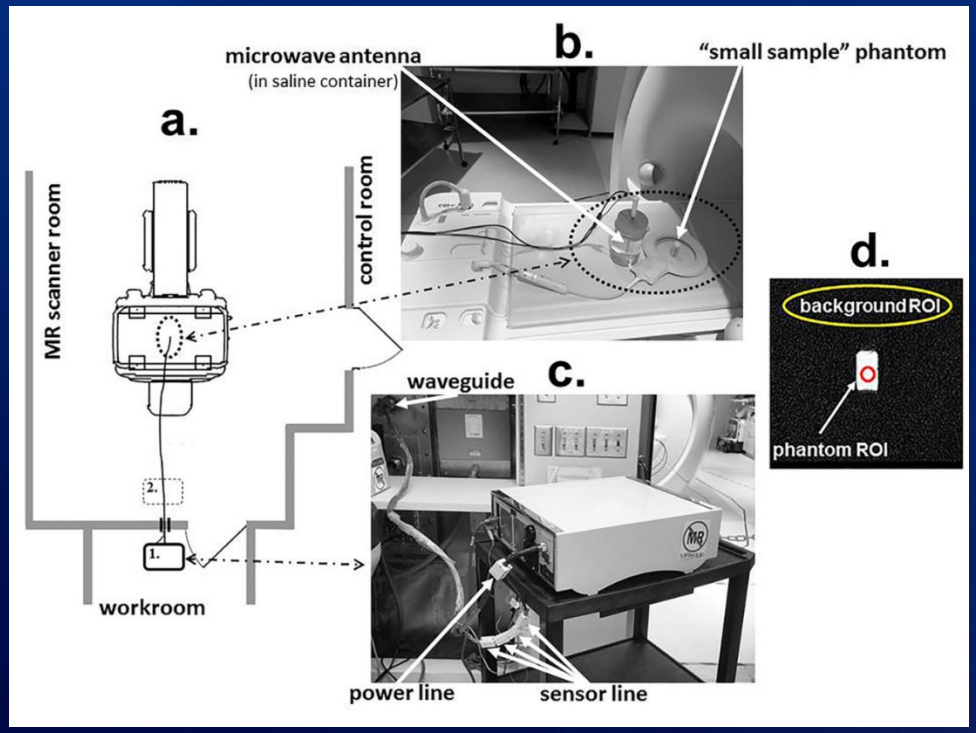
1. Gorny *et al.* Phys Med 67:91-99 (2019)
2. Lu *et al.* Phys Med 71:100-107 (2020)

PRFS in clinical hepatic microwave ablations

Microwave ablations

Experimental setup: all equipment modifications assessed in terms of SNR relative to “baseline” (without microwave equipment)



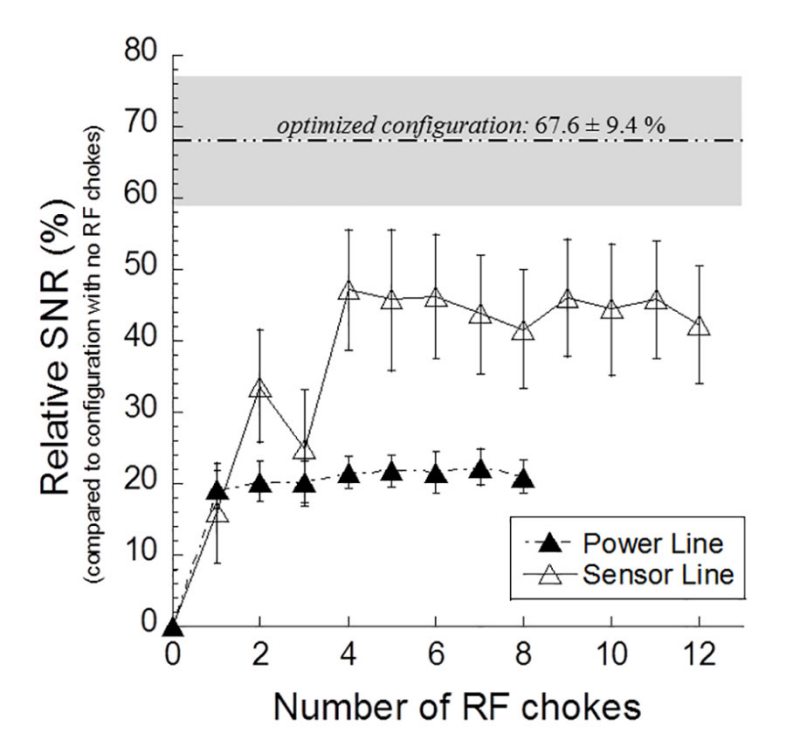
SNR measured inside a small vial of fluid positioned next to saline container with inserted microwave antenna

1. Gorny *et al.* Phys Med 67:91-99 (2019)
2. Lu *et al.* Phys Med 71:100-107 (2020)

PRFS in clinical hepatic microwave ablations

Microwave ablations

- Ferrite clamp-on RF chokes were added to coaxial lines suppressing range of stray frequencies around 64MHz
- SNR measurements were used to select the optimal configuration of chokes on the Power and Sensor lines



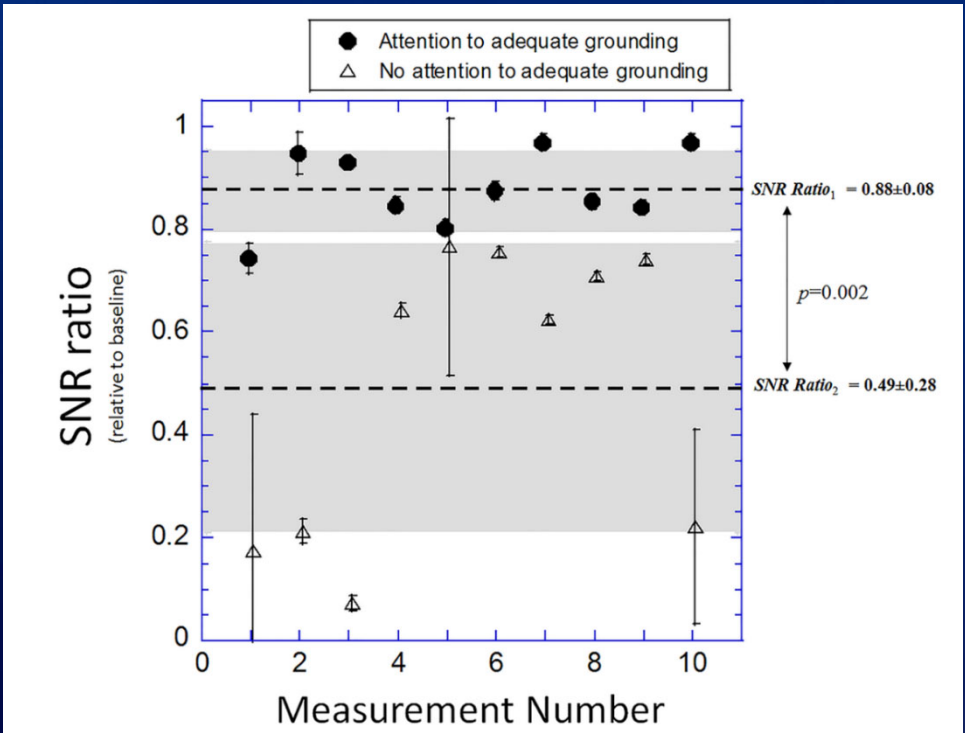
Optimal configuration: 1 choke on Power Line
4 chokes on Sensor Line

1. Gorny *et al.* Phys Med 67:91-99 (2019)
2. Lu *et al.* Phys Med 71:100-107 (2020)

PRFS in clinical hepatic microwave ablations

Microwave ablations

- Quality of grounding of coaxial lines to the waveguide with copper wool was found to be unpredictable
  poor grounding resulted in as much as 50% SNR reduction
- "SNR ratio" (relative to baseline) became the basis of our Quality Assurance testing prior to procedures



Pay attention to coax grounding! QA essential.

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1. Gorny *et al.* Phys Med 67:91-99 (2019)
2. Lu *et al.* Phys Med 71:100-107 (2020)

PRFS in clinical hepatic microwave ablations

Microwave ablations

Reducing respiratory artifact: manual respiratory gating

- Anesthesia slowed down patient breath cycle to ~ 8 breaths/minute
- ~6 second expirations
- PRFS images (6 sec) manually initiated at the beginning of each expiration
  - Expiratory phase identified by watching respiratory bellows on anesthesia machine

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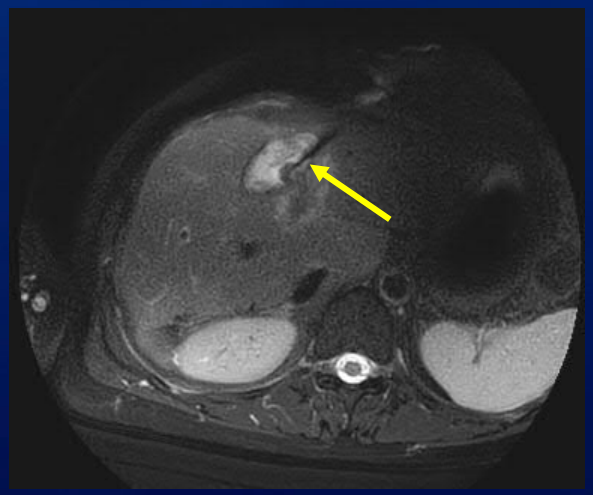
1. Gorny *et al.* Phys Med 67:91-99 (2019)
2. Lu *et al.* Phys Med 71:100-107 (2020)

PRFS in clinical hepatic microwave ablations

Microwave ablations

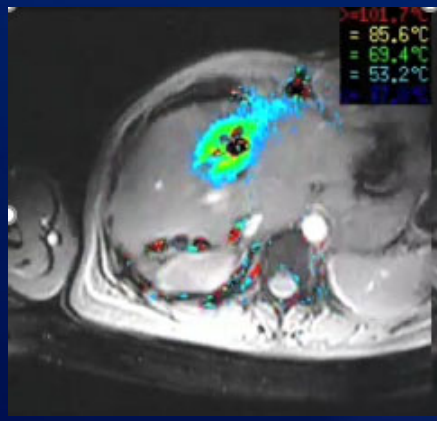
Current state

Patient with a recurrent HCC lesion

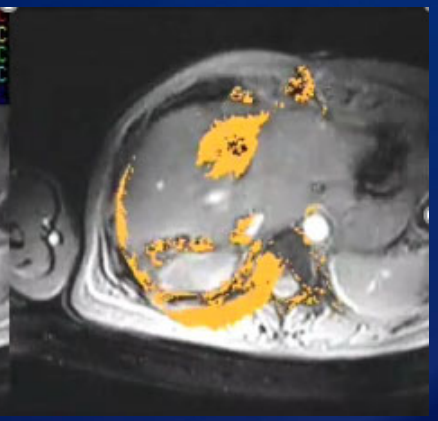


Treatment (8-min ablation)

Temperature map



Thermal dose map



Clinically usable thermometry

- image noise and EMI significantly reduced
  EMI still occasionally present
- Respiratory motion artifact reduced

1. Gorny *et al.* Phys Med 67:91-99 (2019)
2. Lu *et al.* Phys Med 71:100-107 (2020)

Can MRI tell us if tissues are freezing ?

MR-guided Cryoablations

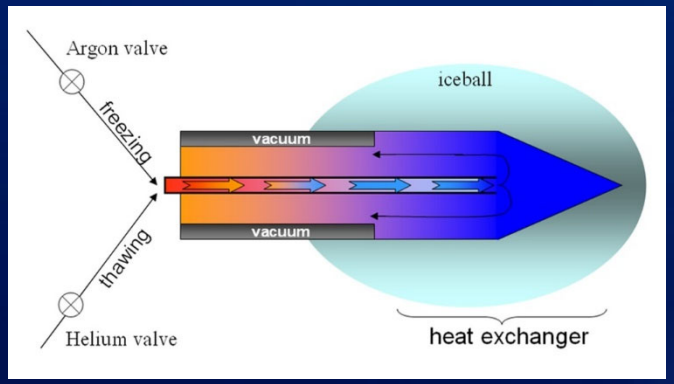
- Cryoablation: cancer tissues ablated by rapid freezing (< -20ºC)

- Joule-Thomson effect

  change of gas temperature accompanying rapid expansion at room temperature

  Argon *cools* to -186ºC

  Helium *warms* to +33ºC



- Cryoneedles are inserted into cancer tissue

  Argon used for *cooling*

  Helium used for *thawing*

  Each lesion submitted to 3 freeze-thaw cycles

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Can MRI tell us if tissues are freezing ?

MR-guided Cryoablations

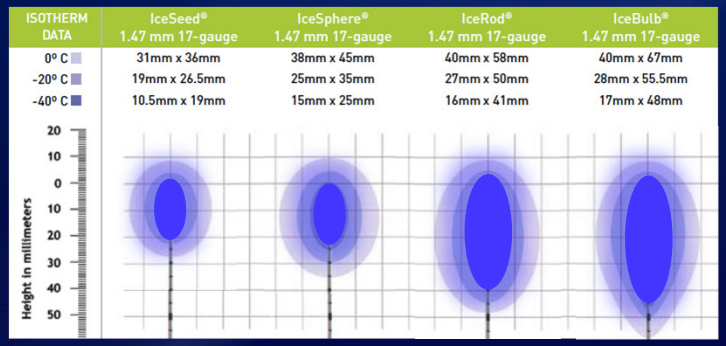
- Due to very short T2 times frozen tissues show as signal void in conventional MRI sequences

Sample T2 values (time-scale for coherent MRI signal)

Tissue	T2 (msec)
Water/CSF	2000
Muscle	90
Fat	70
Tendon	5
Frozen tissue	**0.001**

Advantage: good visualization of ice in all MRI sequences (no need for image subtraction)
Disadvantage: MRI delineates only leading edge of ice (0°C)
Exact temperature within ice is not known

We have to rely on Vendor-provided isotherms



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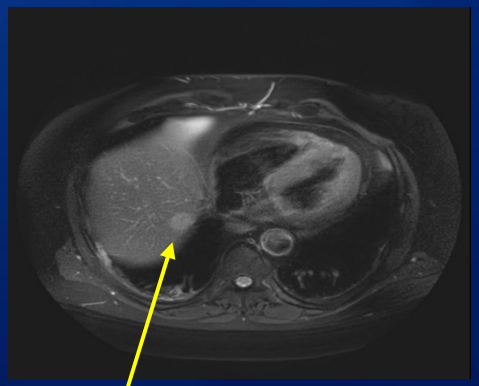
Can MRI tell us if tissues are freezing ?

MR-guided Cryoablations

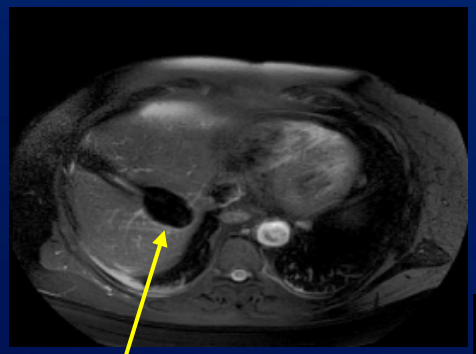
Case 1: Ablation of hepatocellular carcinoma

Pre-treatment T2



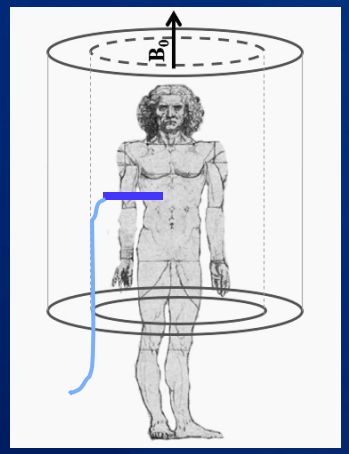
Tumor

Treatment

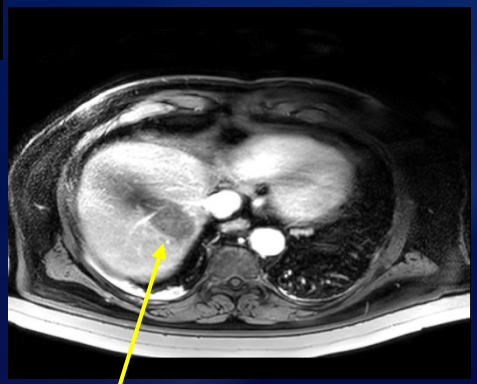


Ice ball

Cryoneedle inserted from the side roughly perpendicular to B0 field



Post-treatment T1



Post ablation defect

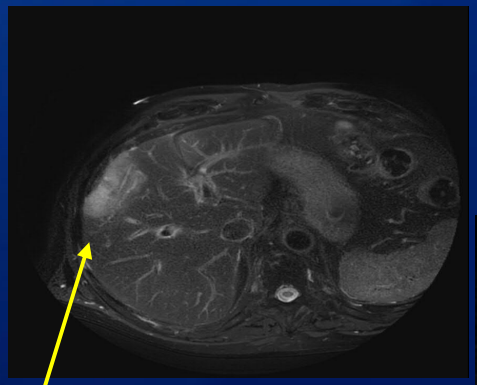
MAYO CLINIC

Can MRI tell us if tissues are freezing ?

MR-guided Cryoablations

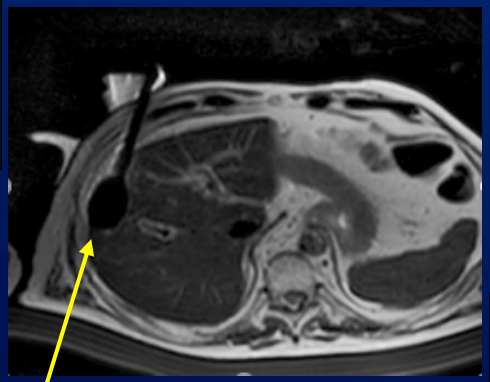
Case 2: Ablation prostate cancer metastasis

Pre-treatment T2



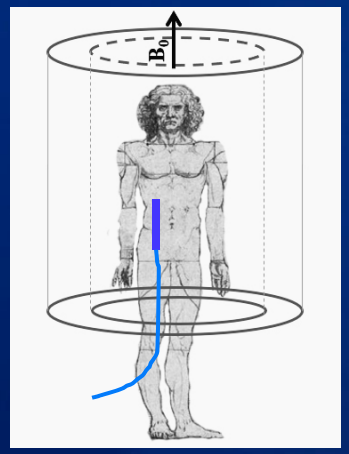
Tumor

Treatment

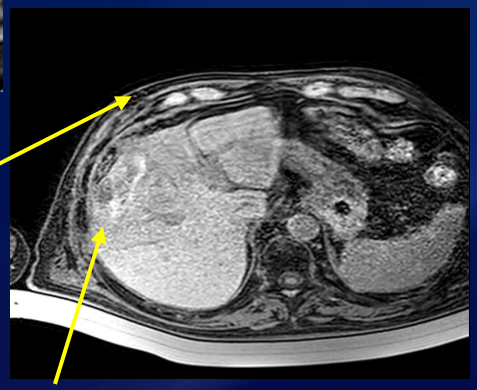


Ice ball

Cryoneedle inserted at an angle to table plane roughly parallel to B0 field



Post-treatment T1



Skin burn

Post ablation defect

<u>are we only cooling??</u>

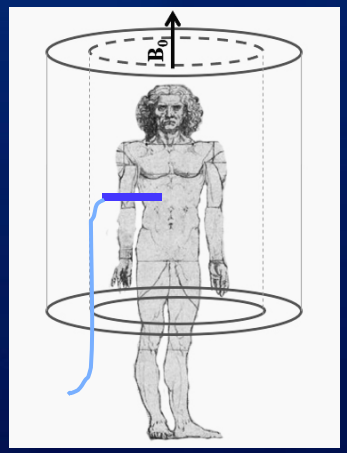
MAYO CLINIC

Can MRI tell us if tissues are freezing ?

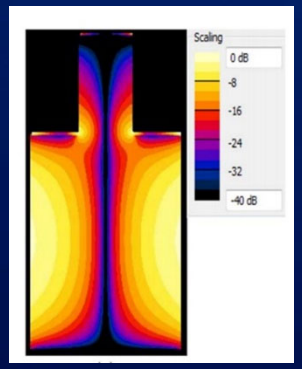
MR-guided Cryoablations

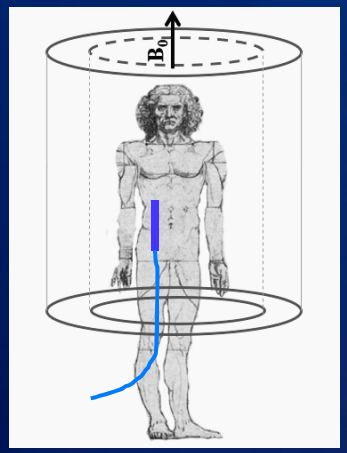
- Cases differed by orientations of cryoablation needle relative to $\mathbf{B_0}$ (z-axis)
  - Metallic leads are heated by tangential components of RF-induced electric fields, E_T
  - Dominant component of electric fields generated during MRI points along z-axis, E_Z
  - E_Z also *increases* with distance from scanner center (iso-line)
  - For "parallel" orientation $E_T \approx E_Z$

$$\Delta T_{Tip} = \left| \int_L S(l) \cdot E_T(l)\, dl \right|^2$$



"perpendicular" orientation





"parallel" orientation

1. Park *et al*. JMRI. 2007; 26:1278-1285
2. Mattei E *et al*. Biomed Eng Online. 2008; 7:11
3. Feng *et al*. IEEE Trans Microw Theory Tech. 2015; 63,1: 305-313

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Can MRI tell us if tissues are freezing ?

MR-guided Cryoablations

Experimental assessment of effects of MRI on cryoneedle heating

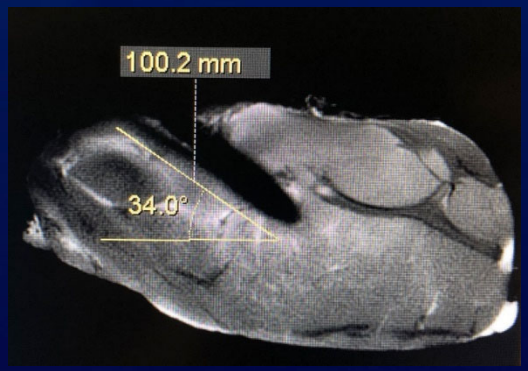
Fiber-optic thermometers placed along cryoneedle

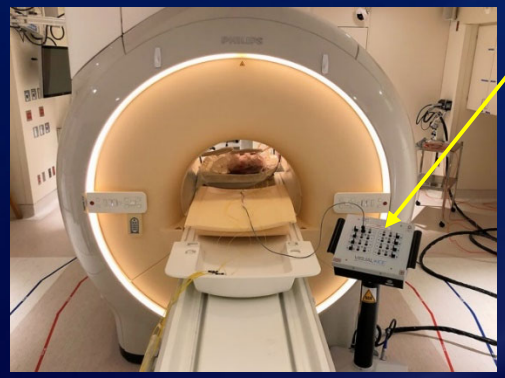
"Tip" "2cm from tip" "5cm from tip"

Additional thermometer placed at "skin" (10cm away from tip)

Porcine meat phantoms (~9kg) in "liver treatment" configurations

- cryoneedles inserted into phantom in "perpendicular" or "parallel" orientations
- RF-heating measured corresponding to execution of clinical sequences used to monitor ablations
  - Sequences executed at two SAR levels: **1.9W/kg** and at **0.7W/kg**





Mobile Connection Panel (MCP)

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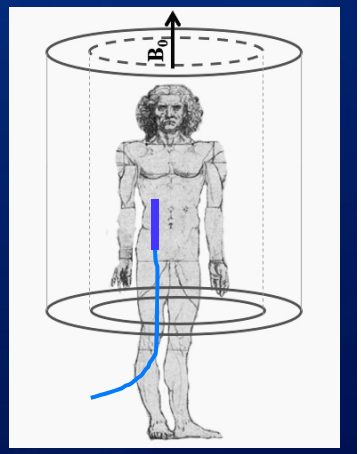
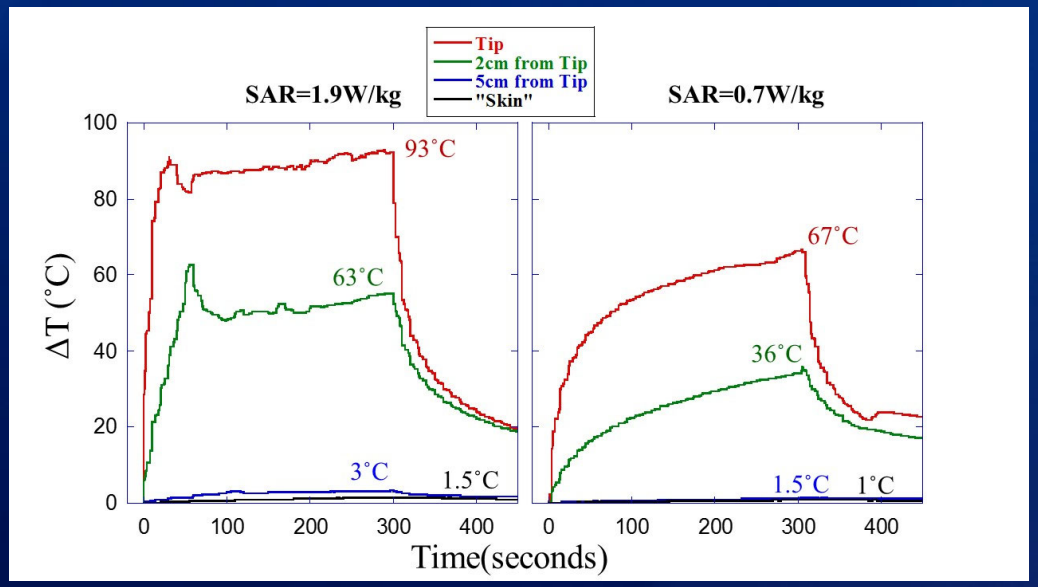


"parallel" orientation



- In "parallel" orientation MRI resulted in ***very high*** temperature elevations along the cryoneedle (clinically unacceptable) – regardless of the SAR level
- Disconnecting cryoneedle from MCP for scanning resulted in minimizing temperature elevations ($\Delta T \sim 1\text{-}3^{\circ}C$)

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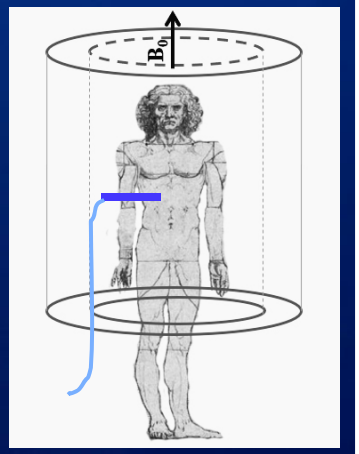
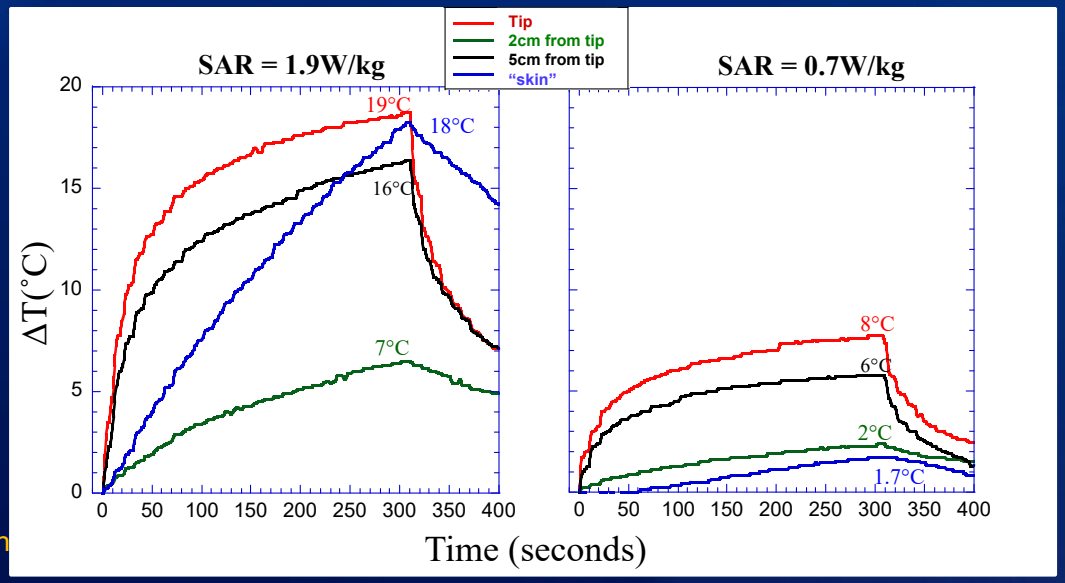


"perpendicular" orientation



- In "perpendicular" orientation MRI resulted in notable temperature elevations along the cryoneedle
- Lowering SAR further reduced RF heating
- Disconnecting cryoneedle from MCP for scanning resulted in minimizing temperature elevations (ΔT~1-3˚C)

Sfold reduction relative to "parallel" orientation

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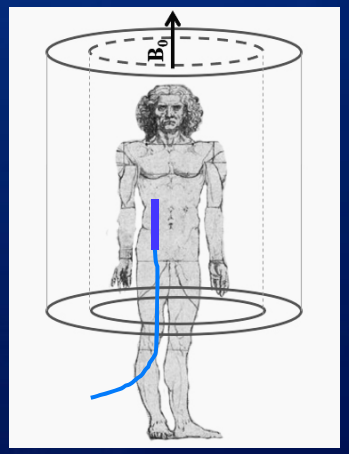
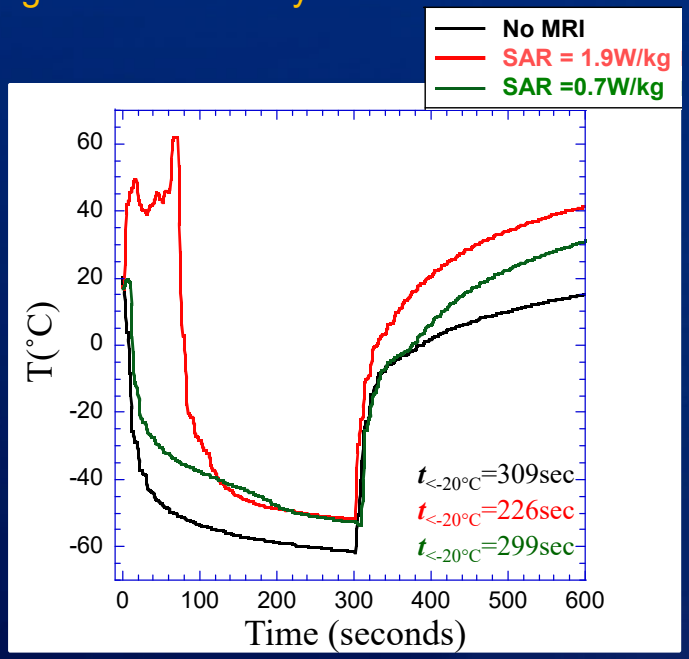
MRI during Freeze-Thaw cycle



"parallel" orientation



- Continuous MRI had **observable effect** on temperatures during freezing and thawing cycles
  - Times below -20°C were reduced
  - Minimal temperatures were elevated by ~10°C
- Temperatures at the end of the thaw cycle were significantly increased as a result of MRI scanning

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Clinical recommendations

- Use low-SAR sequences (< 1W/kg)
- When possible disconnect gas lines from MCP for MRI scanning
- For monitoring Freeze cycle delay scanning until the cycle is ~1min under way
- Monitor patient skin at insertion sites frequently during procedure

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Thank you

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