RF Pulse Sequence and Temperature Elevation (in MRI) (mostly)

(plus some more general MRI Safety and Bioeffects)

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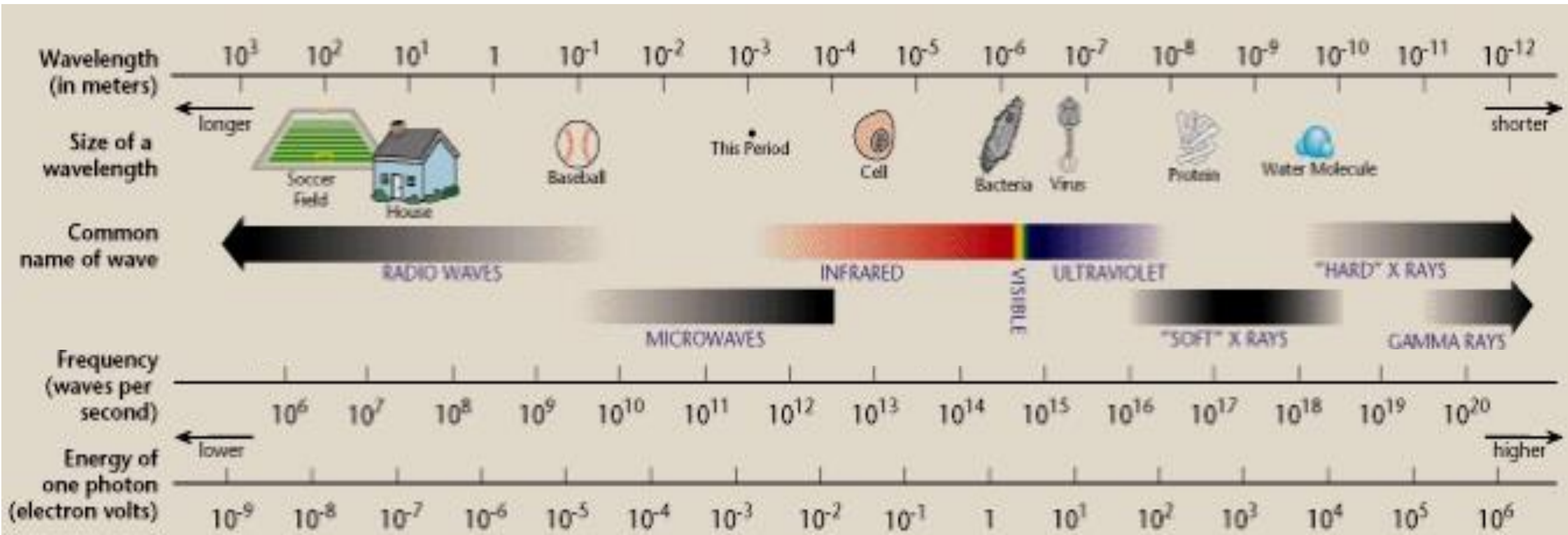
The Electromagnetic Spectrum



Lawrence Berkeley Laboratories

Nonionizing

MRI
(DC to >400MHz in humans)

In MRI we apply magnetic fields to manipulate net nuclear magnetization vector

Felix Bloch (1905-1983)

$$\frac{d\vec{M}}{dt} = \gamma\left(\vec{M}\times\vec{B}\right) - \left(\frac{M_x}{T_2}\vec{i} + \frac{M_y}{T_2}\vec{j} + \frac{M_z - M_0}{T_1}\vec{k}\right)$$

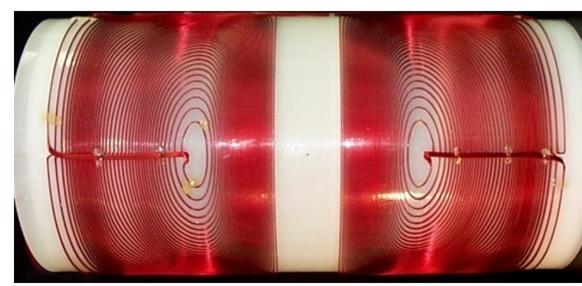
DC Magnetic Field
B_0

Causes coherent nuclear precession

Transmit RF Magnetic Field
B_1 or B_1^+

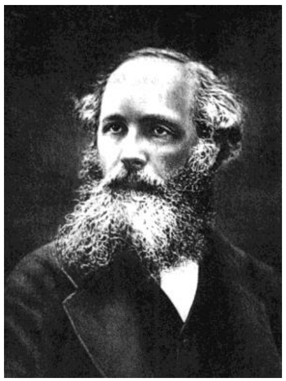
Perturb magnetization vector from equilibrium state

Switched (AF) Magnetic Fields
(G_x, G_y, G_z) or (G_s, G_f, G_ϕ)



Encode spatial information onto nuclear magnetic moments

In nature, time-varying magnetic fields induce electric fields



James C. Maxwell (1831-1879)

$$\nabla \times E = -\frac{\partial}{\partial t} B \qquad \frac{\nabla \times B}{\mu} = \sigma E + \frac{\partial}{\partial t} \varepsilon E$$

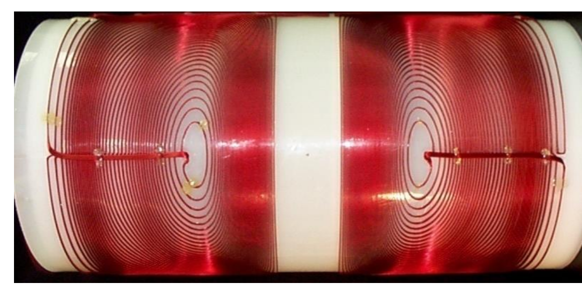
DC Magnetic Field
B_0

Induces electric currents and forces in *moving* tissues
→ Metallic taste, dizziness

Transmit RF Magnetic Field
B_1 or B_1^+

Induces electric currents and RF power deposition (SAR) in tissues → Heating

Switched Magnetic Fields
(G_x, G_y, G_z) or (G_s, G_f, G_ϕ)



Induces electric currents in tissues
→ Peripheral nerve stimulation

Some Facts & Figures Regarding MRI

- ~50,000,000 clinical MRI studies on human subjects every year
- Very wide Range of combined fields and pulsing schemes
  - 0.2 to 10.5 T DC magnetic fields in MRI of humans (earth's field is approximately 0.00005 T)
  - Switched (audiofrequency) fields with strong frequency components up to a few kHz, gradient strengths approaching 0.1 T/m and slew rates approaching 500 T/m/s
  - RF fields with frequencies up to 450 MHz and field strengths ~0.000001 T, total peak power >30 kW

Established Nonthermal EM Field/Tissue Interactions and Associated Bioeffects in MRI

- Magnetic Resonance (Nuclear Precession)
  - From combined DC + RF magnetic fields
  - Bioeffects: none (aside: MR in ^1H in Earth's field at about 2 kHz)
- Changing magnetic field induces electrical current (Faraday's Law: $\nabla \times \mathbf{E} = -\frac{\partial}{\partial t}\mathbf{B}$)
  - Bioeffects:
    - Peripheral Nerve stimulation
      - Switched (audiofrequency) fields can simulate sensory or motor neurons directly
      - Metallic taste from motion in DC magnetic field
- Motion of charges in magnetic field results in physical force ($\mathbf{F} = q\mathbf{v} \times \mathbf{B}$)
  - Bioeffects:
    - Vertigo from motion in DC magnetic field affecting fluid in inner ear
    - (Arguably a bioeffect: Change in shape of ECG)

Bioeffects vs. Safety in MRI

- A lot of MRI safety has to do with screening everything inside and outside of a patient’s body that goes into the magnet room
  - Not a direct effect of EM fields on tissue
- Acoustic noise not directly related to effects of EM fields on tissue
- Some of the well-known bioeffects in MRI have no direct “safety” consequences
  - e.g., peripheral nerve stimulation, vertigo, efffects on ECG, and metallic taste are transient and have no long term effects – though we still try to avoid them for purposes of patient comfort and (w.r.t. PNS) image quality

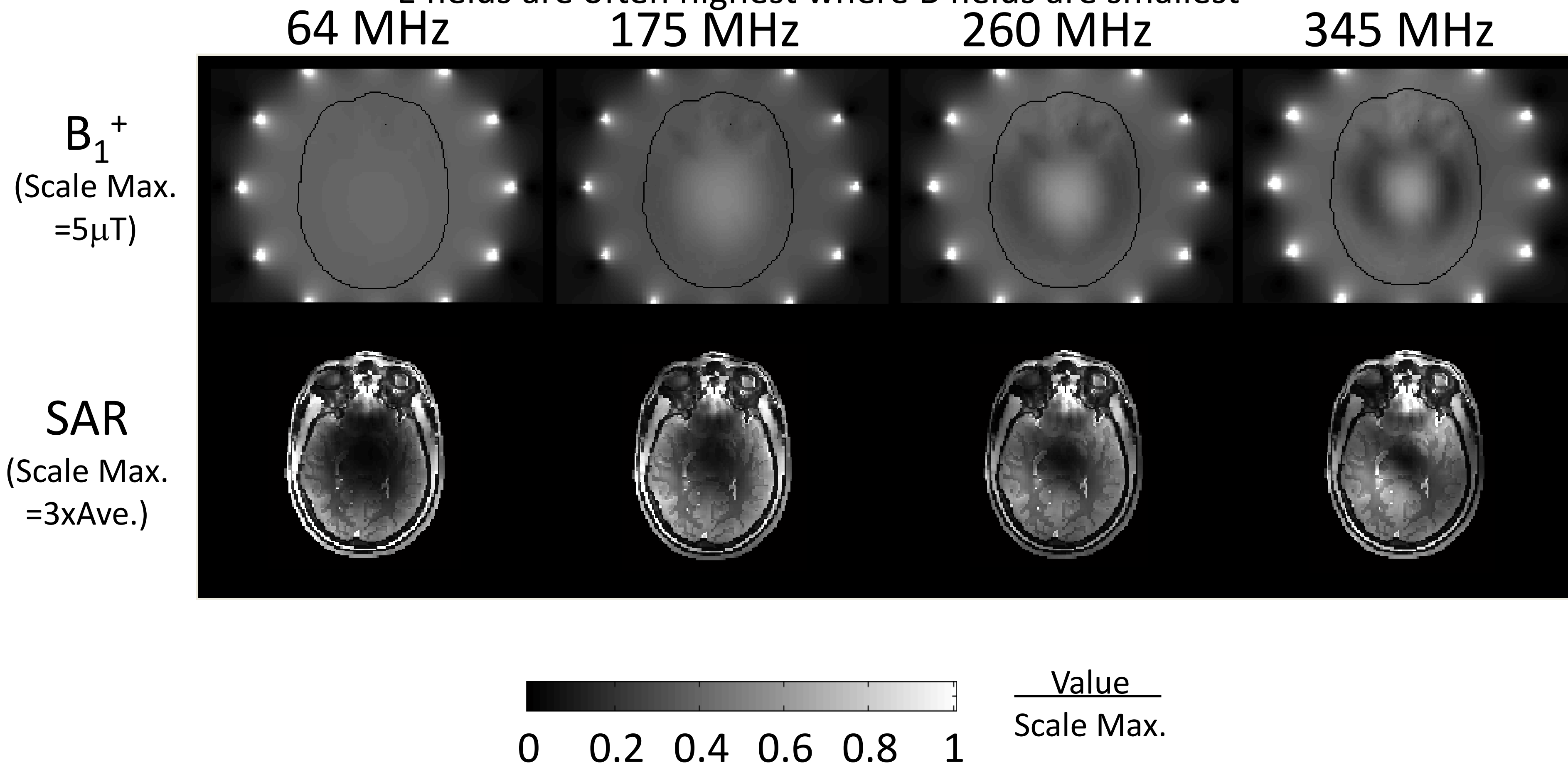
Health *Benefits* of Peripheral Nerve Stimulation!

Back to RF Fields: No "Nonthermal Bioeffects" Established in MRI

- Only Specific energy Absorption Rate (SAR; W/kg) and temperature are considered in existing guidelines for patient safety w.r.t. RF fields
  - SAR over whole body, head, partial body, and/or 10g
  - Thermal dose concept CEM43 is a candidate for future IEC guidelines for MRI
- Nerve stimulation becomes impossible above kHz range
- "RF Hearing" is a *thermal* effect
  - Shown to be possible with RF coils used in MRI
  - Never observed during MRI

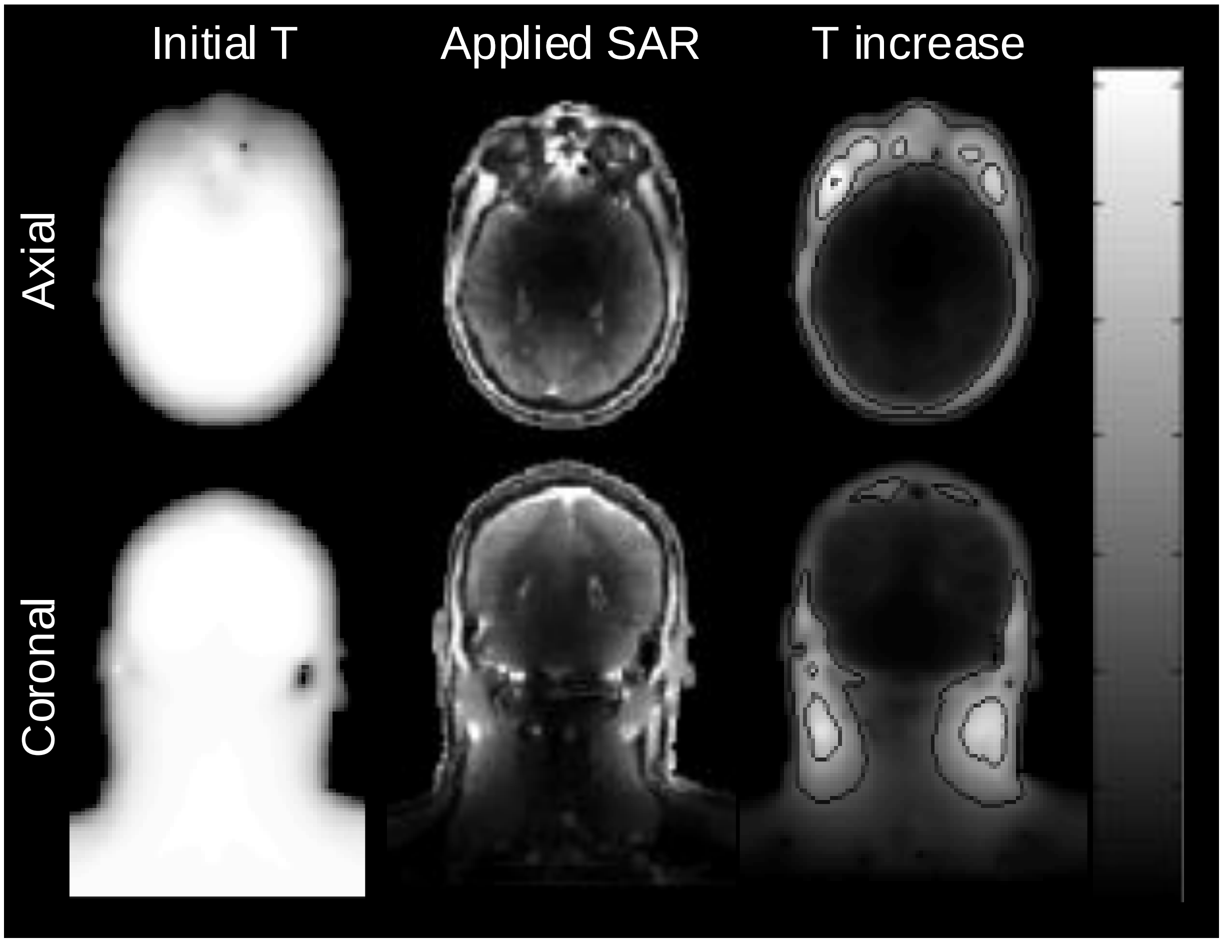
RF Heating Patterns in MRI: Head in a Birdcage Coil

Constructive Interference: In standing EM waves,
E fields are often highest where B fields are smallest



Temperature Depends on SAR, Perfusion, Conduction, …

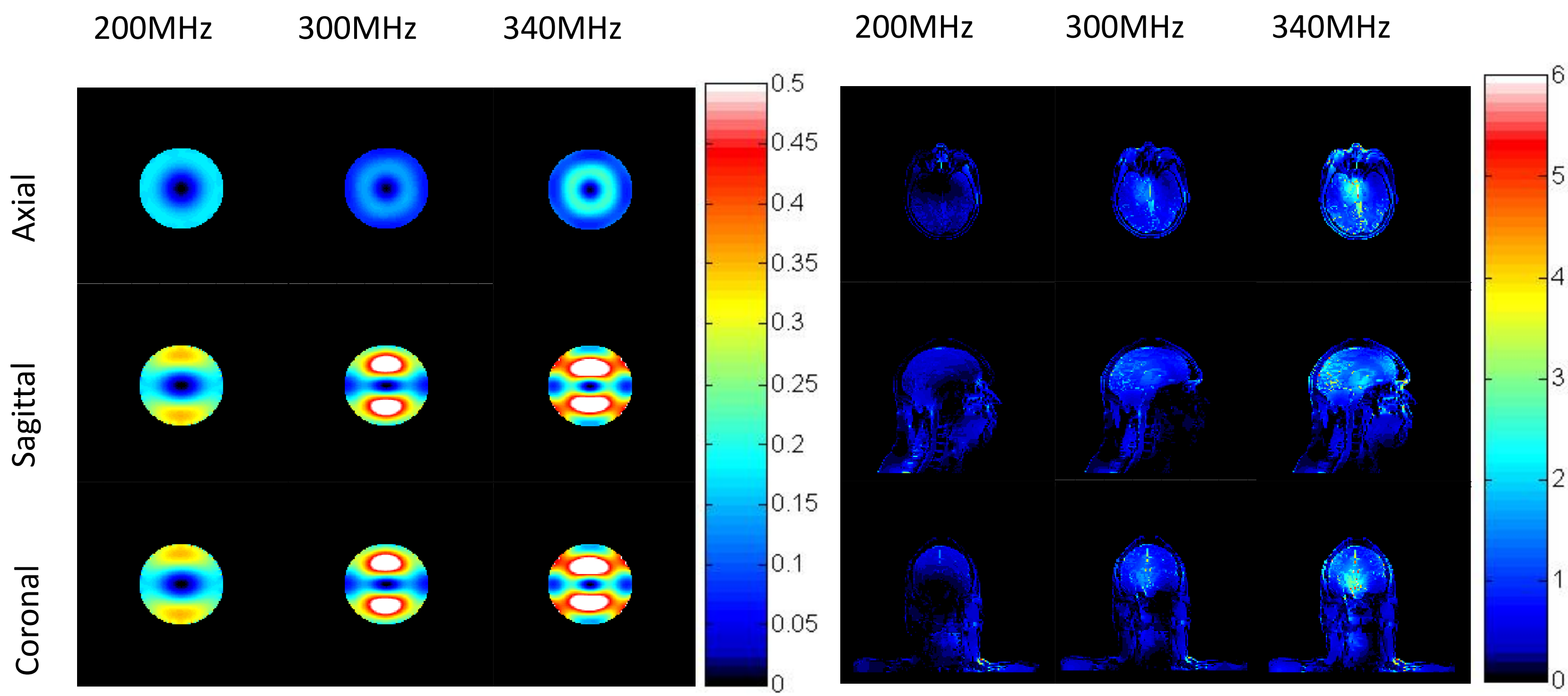
Quadrature Birdcage Coil at 64MHz
3W/kg ave. over head, ~22W input power



CM Collins *et al.*, JMRI 19:650, 2004

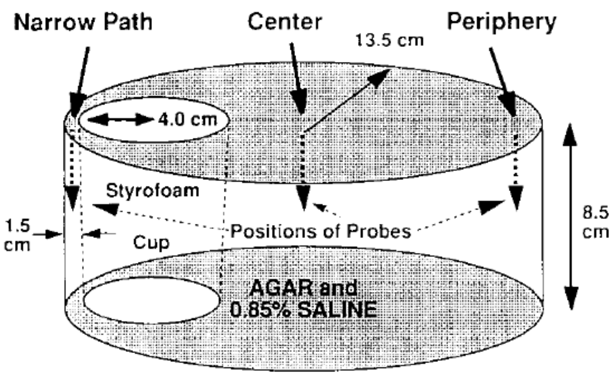
Linear grayscale from 23 (black) to 37 °C (white) for initial temperature,
0 to 10 W/kg for applied SAR, and 0 to 1.5 °C for resulting temperature increase

RF Heating Patterns in MRI: High SAR in Brain at High Frequencies?

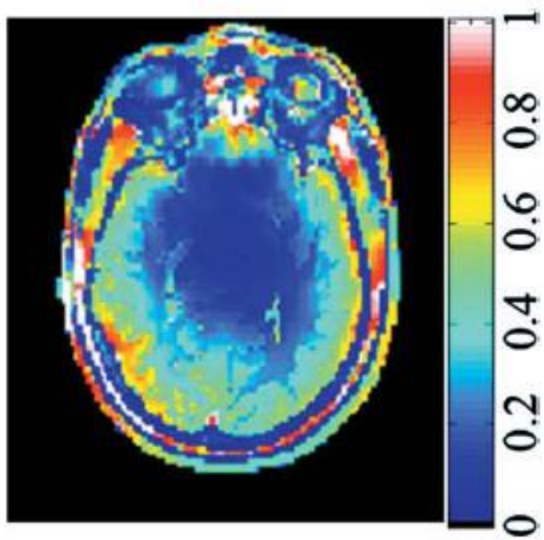


- SAR distribution depends largely on sample geometry, heterogeneity, and complexity.
- Maximum 1g SAR levels tend to be higher in models of human geometries than in homogeneous models for a given magnetic field strength (factor of 2 to 3: Collins *et al*., MRM 40:847, 1998).

Maximum Local SAR levels Higher in Heterogeneous objects

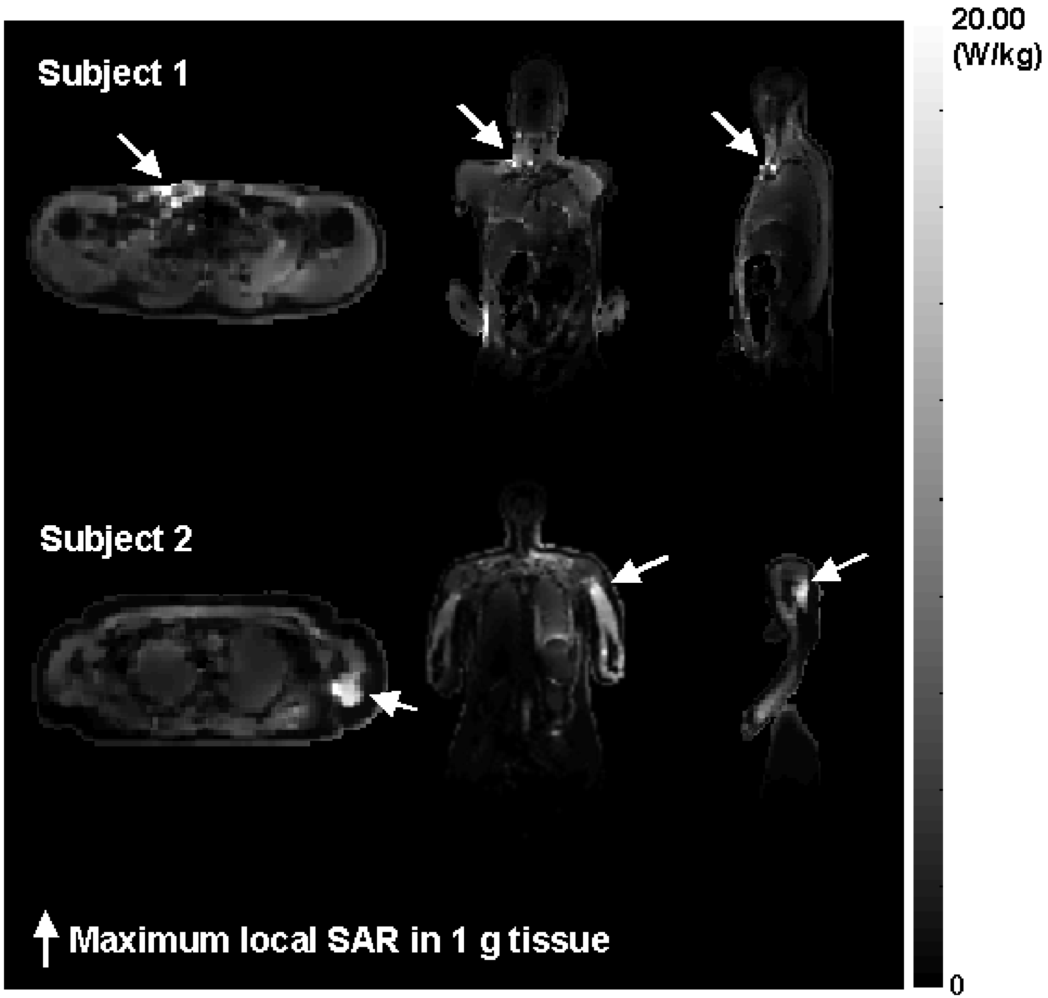


ΔT in narrow path about 4x higher when cup is present
- Davis et al., IEEE TBME 1993;40(12):1324-7



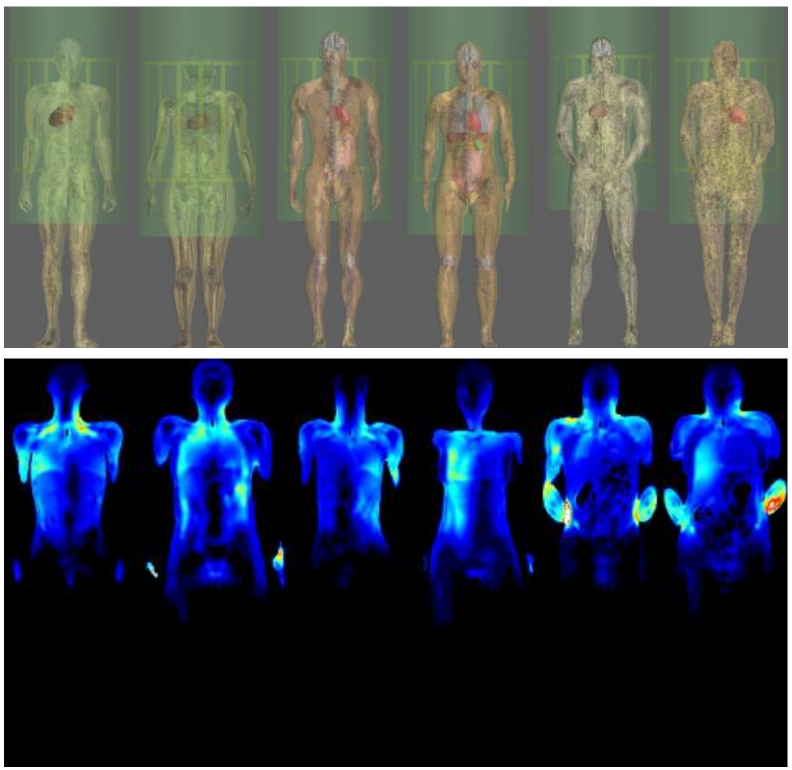
Calculated SAR distribution for head in birdcage coil
- Collins and Wang, MRM 2011;65:1470-82

Comparison of Different Subject Geometries: Location of Maximum 1g SAR

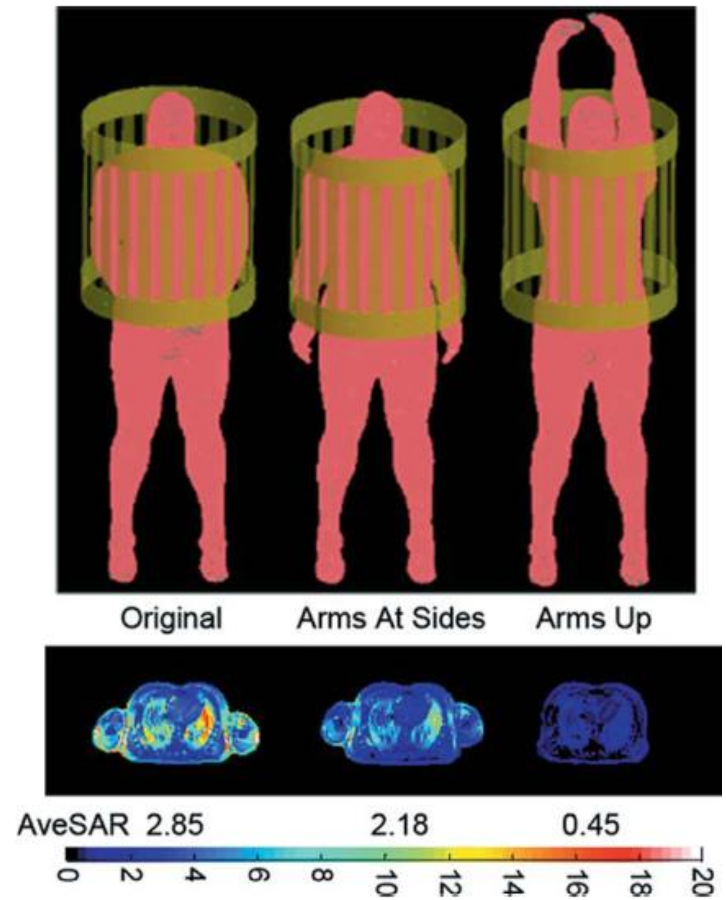


Wanzhan Liu *et al.*, Appl. Magn. Reson. 29:5-18, 2005.

Local and average SAR levels and distribution depend on Subject Geometry



Calculated SAR distribution for models of different individuals
- Wang *et al*. 2010 ISMRM, p. 3880

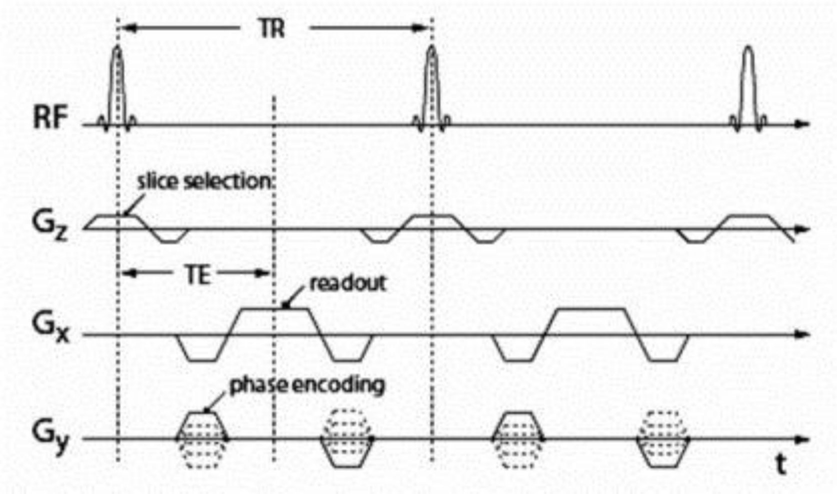


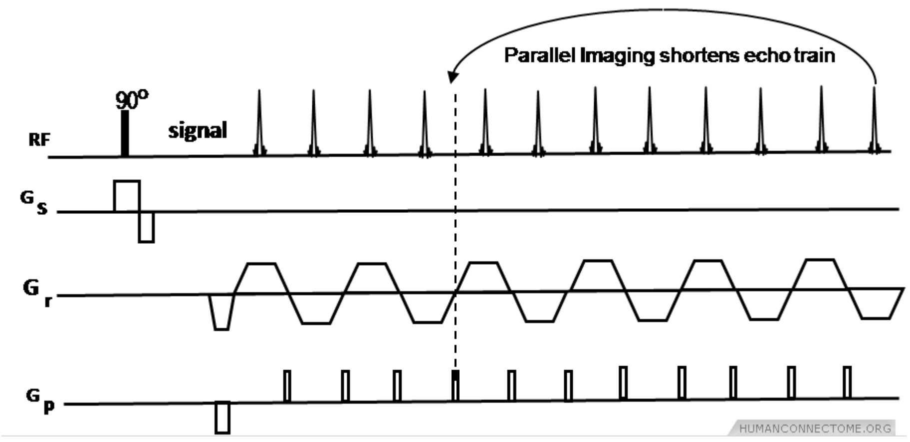
Calculated SAR distribution for body in different postures
- Collins and Wang, MRM 2011;65:1470-82

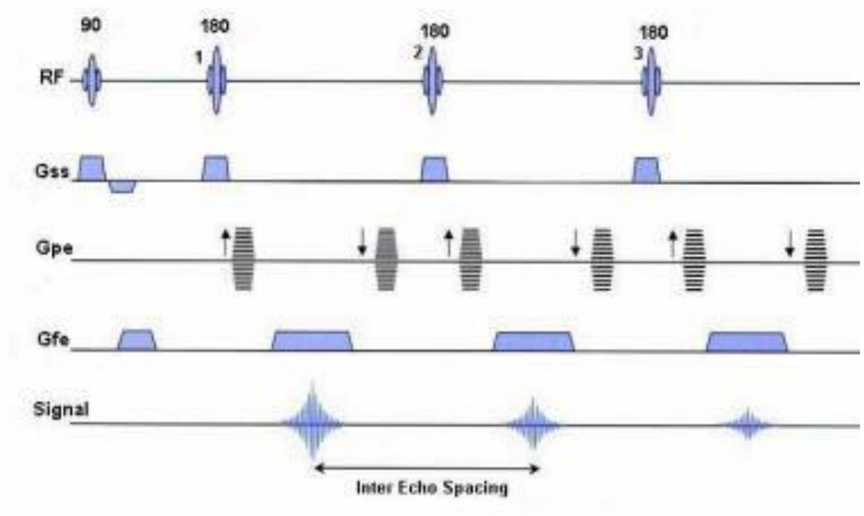
Case Study: Unusual RF Burns

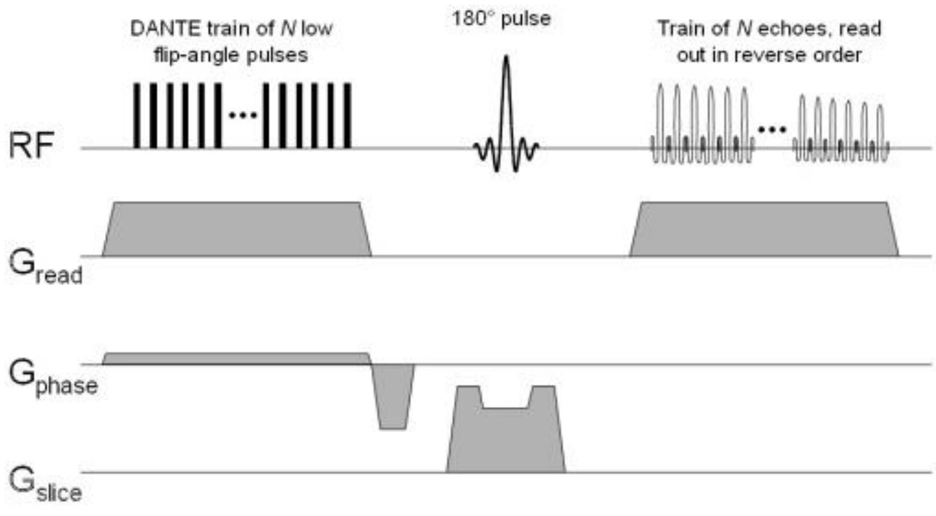
Safety requires proper patient screening and proper patient handling!

Pulse Sequences in MRI









RF Pulse Sequence and Temperature (in MRI)

- Simulation study considering Maxwell equations, Bioheat equation, and realistic MR pulse sequences

Figure 1 Coil and head model geometry on the axial, sagittal, and coronal planes passing through the coil center. Figures with greater detail have been published previously (*6*).

Wang and Collins, Concepts in Magn Reson 2010;37B:215-9

RF Pulse Sequence and Temperature (in MRI)

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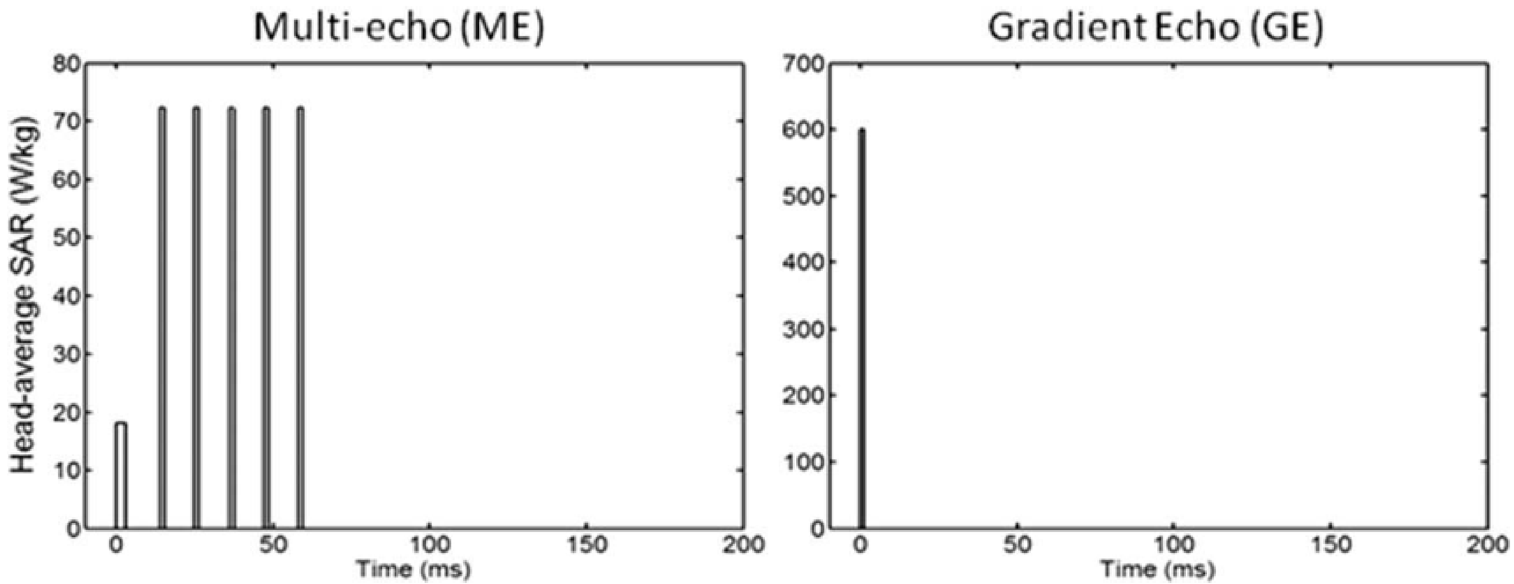

Figure 2 Head-average SAR for different sequences simulated. Left: Multiple spin echo (ME) with TR = 200 ms and TE = 11 ms; the duration of 90° and 180° pulse is 3 and 1.5 ms, respectively. Right: Gradient echo (GE) at TR = 200 ms and pulse duration of 1 ms. Also simulated (but not shown in this figure) was a continuous-wave (CW) excitation. For all sequences, the time-average SAR over the head is 3 W/kg.

Wang and Collins, Concepts in Magn Reson 2010;37B:215-9

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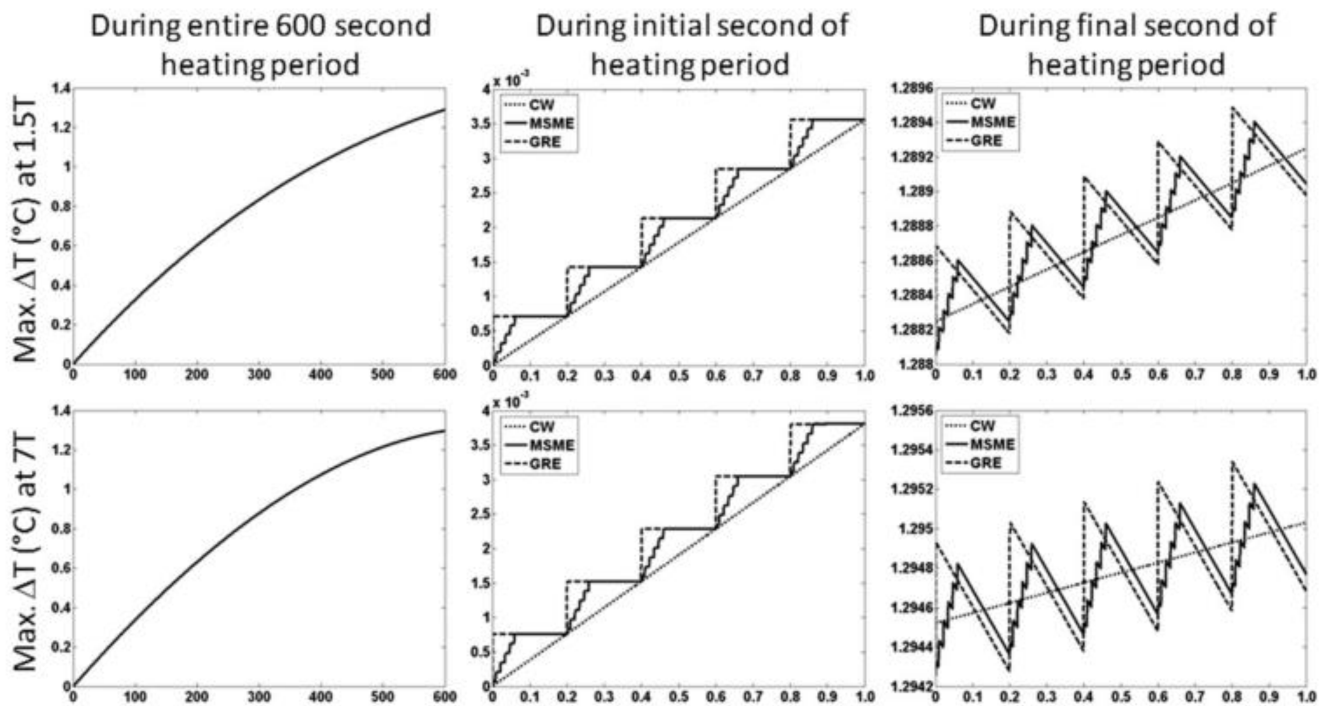


Figure 3 The temperature rise above baseline at the location of maximum temperature change during the entire time course (left), during the first 1 s (center), and during the last 1 s (right) of a 10-min exposure to 3.0 W/kg head-average SAR at 64 (top) and 300 MHz (bottom).

Wang and Collins, Concepts in Magn Reson 2010;37B:215-9

RF Pulse Sequence and Temperature (in MRI)

- Simulation study considering Maxwell equations, Bioheat equation, and realistic MR pulse sequences

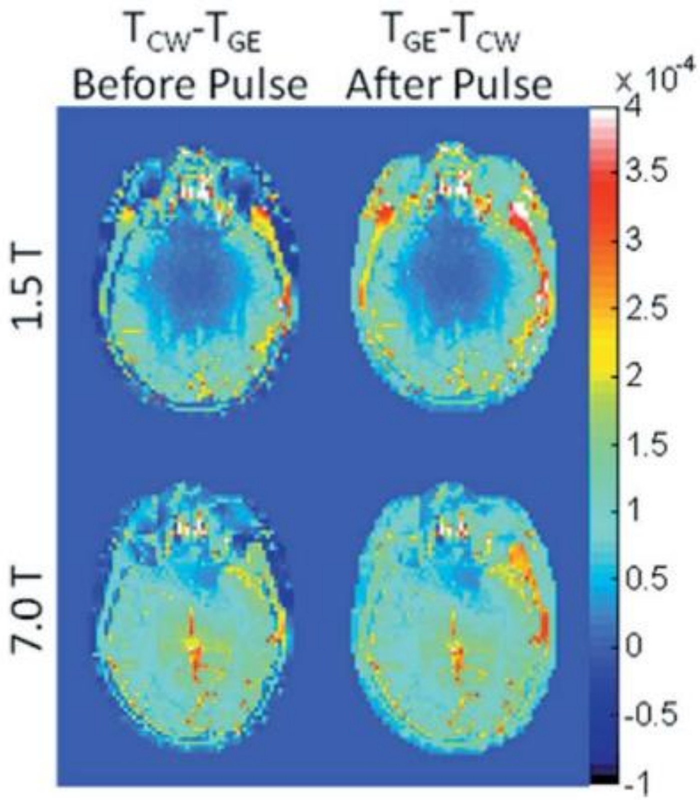


Figure 4 Temperature difference between CW and ME sequences on an axial plane passing through the eyes immediately before (left) and immediately after (right) a single RF pulse of the GE sequence applied near the end of the 10-min period of heating at both 64 (top) and 300 MHz (bottom). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Wang and Collins, Concepts in Magn Reson 2010;37B:215-9

RF Pulse Sequence and Temperature (in MRI)

- Analytically-determined maximum difference between CW and GRE sequence with TR at 10W/kg local SAR in muscle

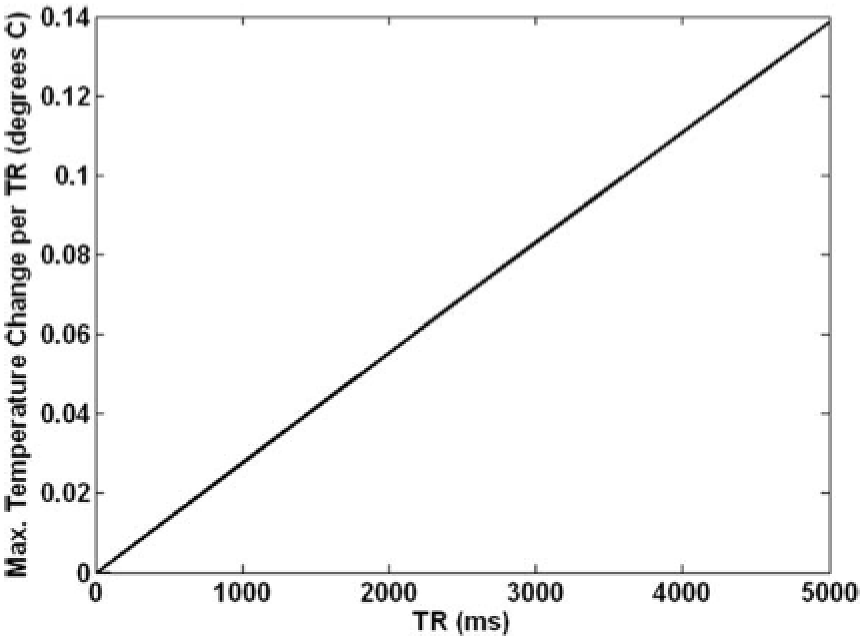


Figure 5 Maximum change in temperature during any single repetition for a 2-h gradient-echo sequence with a pulse duration of 1 ms and a value of TR varying from 1 (CW) to 5,000 ms in muscle tissue with time-average SAR of 10 W/kg as calculated with conservative semianalytical methods allowing for no thermal conduction.

Wang and Collins, Concepts in Magn Reson 2010;37B:215-9

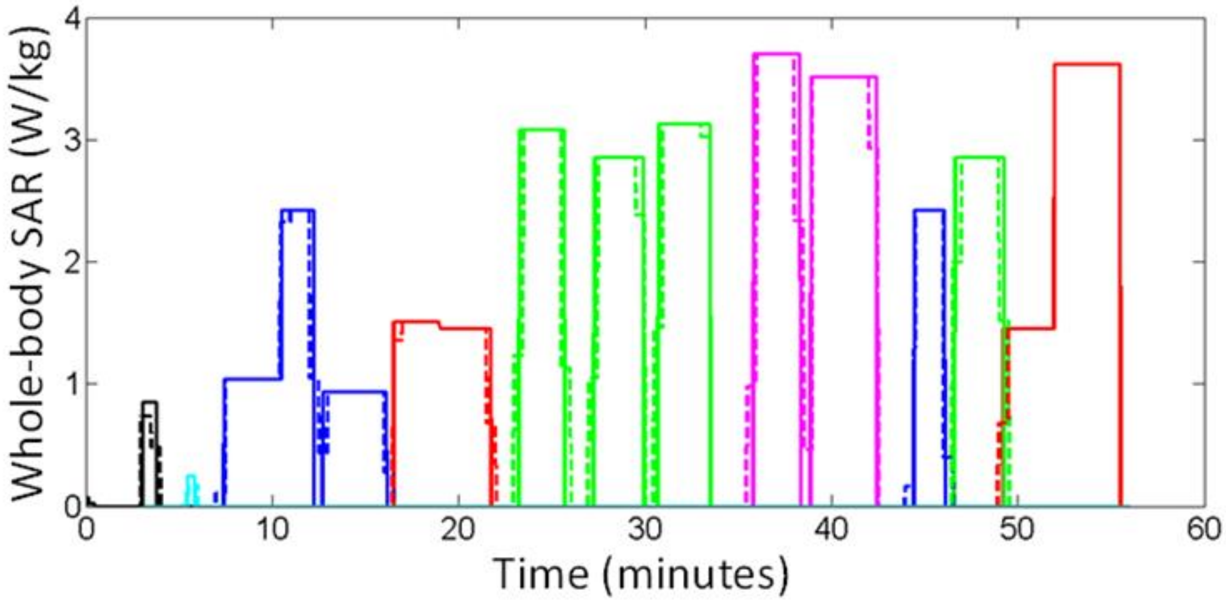
RF Pulse Sequence and Temperature (in MRI)

- <u>Conclusion:</u> no need to consider variations in SAR down to the level of milliseconds for determination of relevant temperature response in MRI
  – time averaging on the order of several seconds, or an entire MRI pulse sequence (with the same pulses repeated regularly) is OK.

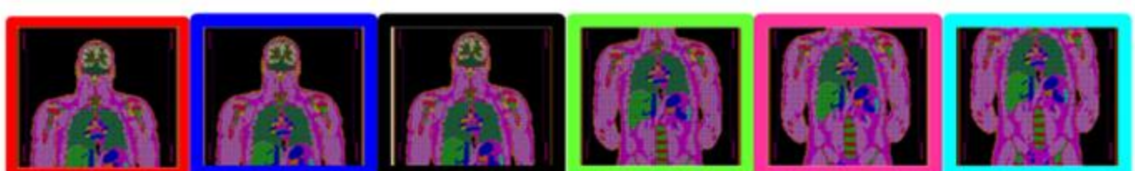
Wang and Collins, Concepts in Magn Reson 2010;37B:215-9

Series of Pulse Sequence and Temperature (in realistic MRI exam)

- SAR levels and SAR distribution can change on the order of minutes through an MRI exam



Portion of body in MRI Coil



Carluccio and Collins, Magn Reson Med, *in press*

Series of Pulse Sequence and Temperature (in realistic MRI exam)

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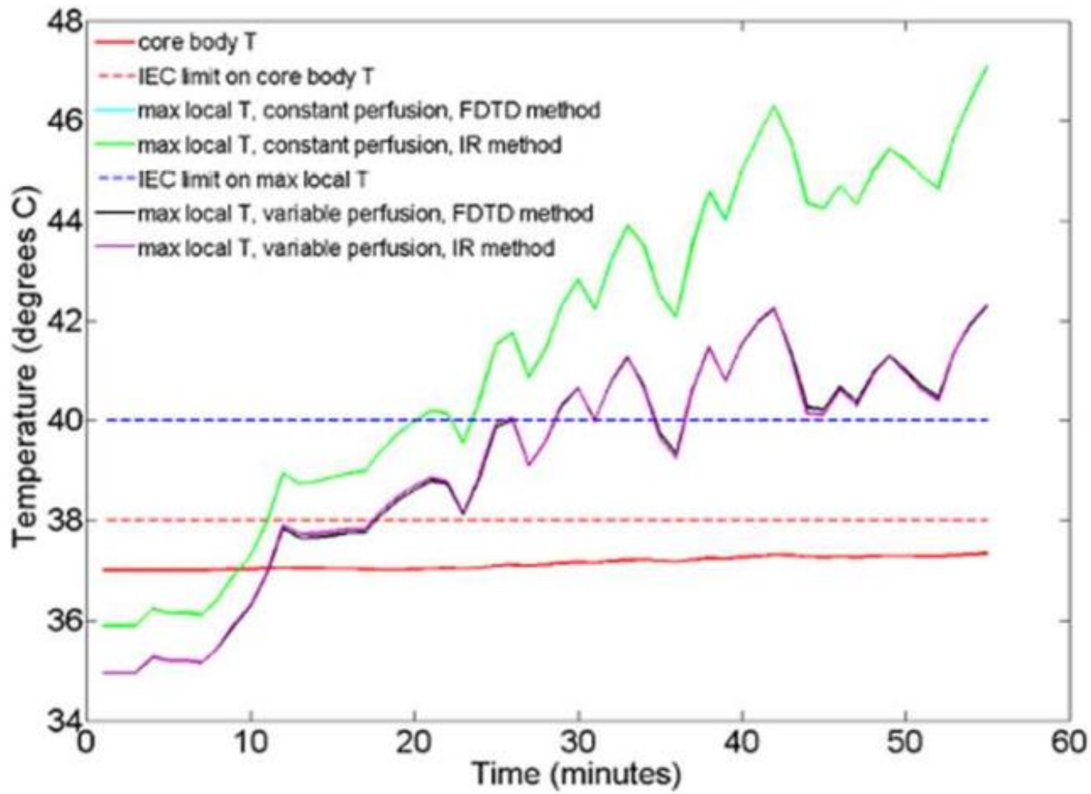
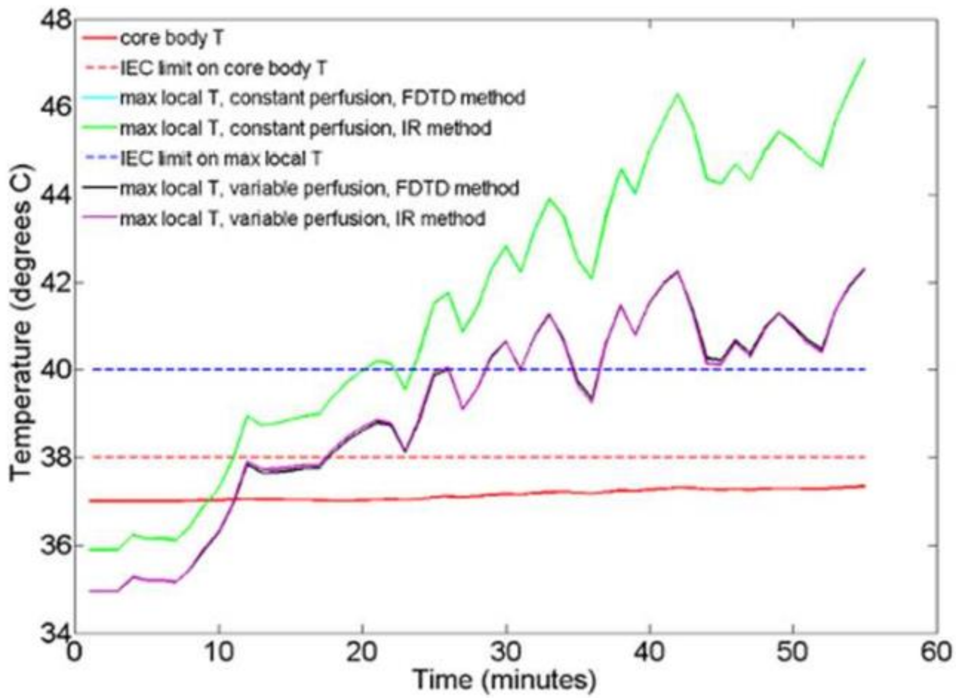


Carluccio and Collins, Magn Reson Med, *in press*

Series of Pulse Sequence and Temperature (in realistic MRI exam)

- Conclusion: It *is* necessary to consider variations in SAR levels and distributions over longer time scale through an MR Exam



Carluccio and Collins, Magn Reson Med, *in press*

Local Perfusion Increases With Local Temperature Even in Deep Tissues

- Consistent with observations in hyperthermia and ablation
- May be >10-fold increase from baseline rate in muscle tissue
- Perfusion response in numerical models of temperature

Most Relevant Averaging Time?

- Limits on SAR often have a 6 minute averaging time written into them (originated from Ken Foster's "0.1 hour")
- There is no inherent "averaging time" w.r.t. recommended limits in calculating temperature or thermal dose
- In numerical calculations of temperature for MRI, use step sizes smaller than 0.1 h, much longer than 1ms

Carluccio and Collins, Magn Reson Med, *in press*

RF Pulse Sequence and Temperature in mmWave Exposure (Just for You!)

Exposures of Humans to mmWaves

Airport mmWave scanners

- 24-30 GHz, <.006 W/m^2, seconds
- Millions of exposures
- No known biological effects

Active Denial System

- 95 GHz, >10kW/m^2, seconds
- >11,000 exposures (2009)
- Rapid heating, intense pain, reflexive reaction
- 2^{nd} degree burns (blisters) in 8 cases
- No non-thermal effects

Analytically-based Simulations of Temperature with mmWave Exposure: One-dimensional models of tissue in far field

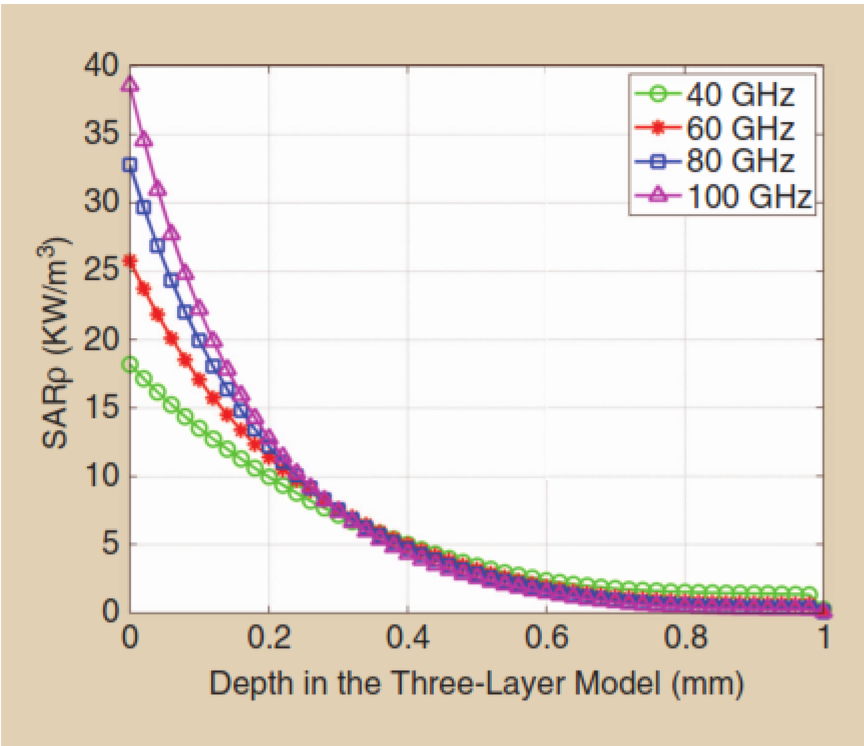


Figure 9. *The SARρ distribution due to 10 W/m² mmWave radiation at 40, 60, 80, and 100 GHz.*

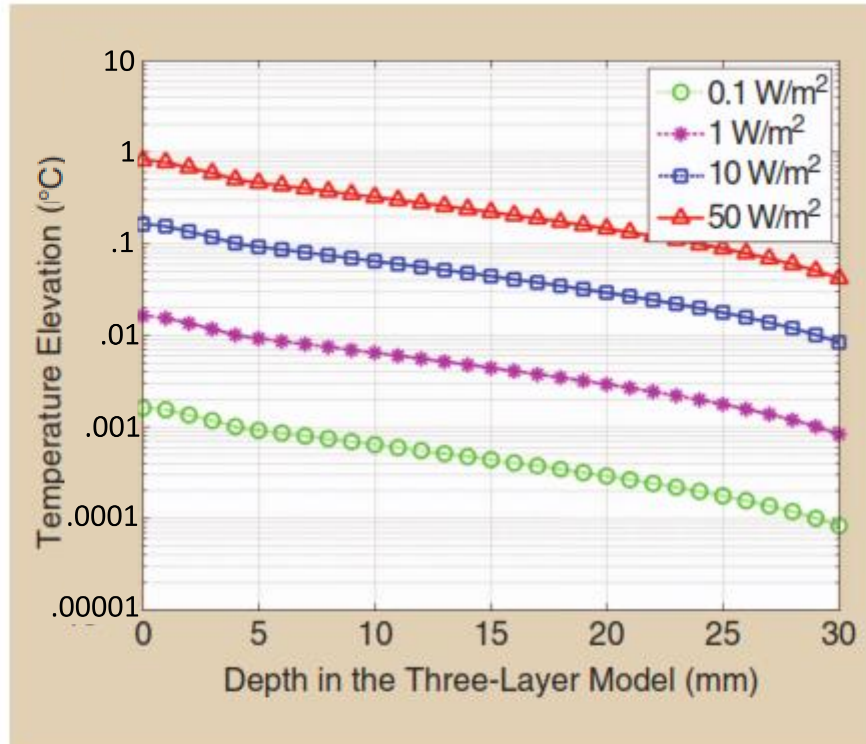
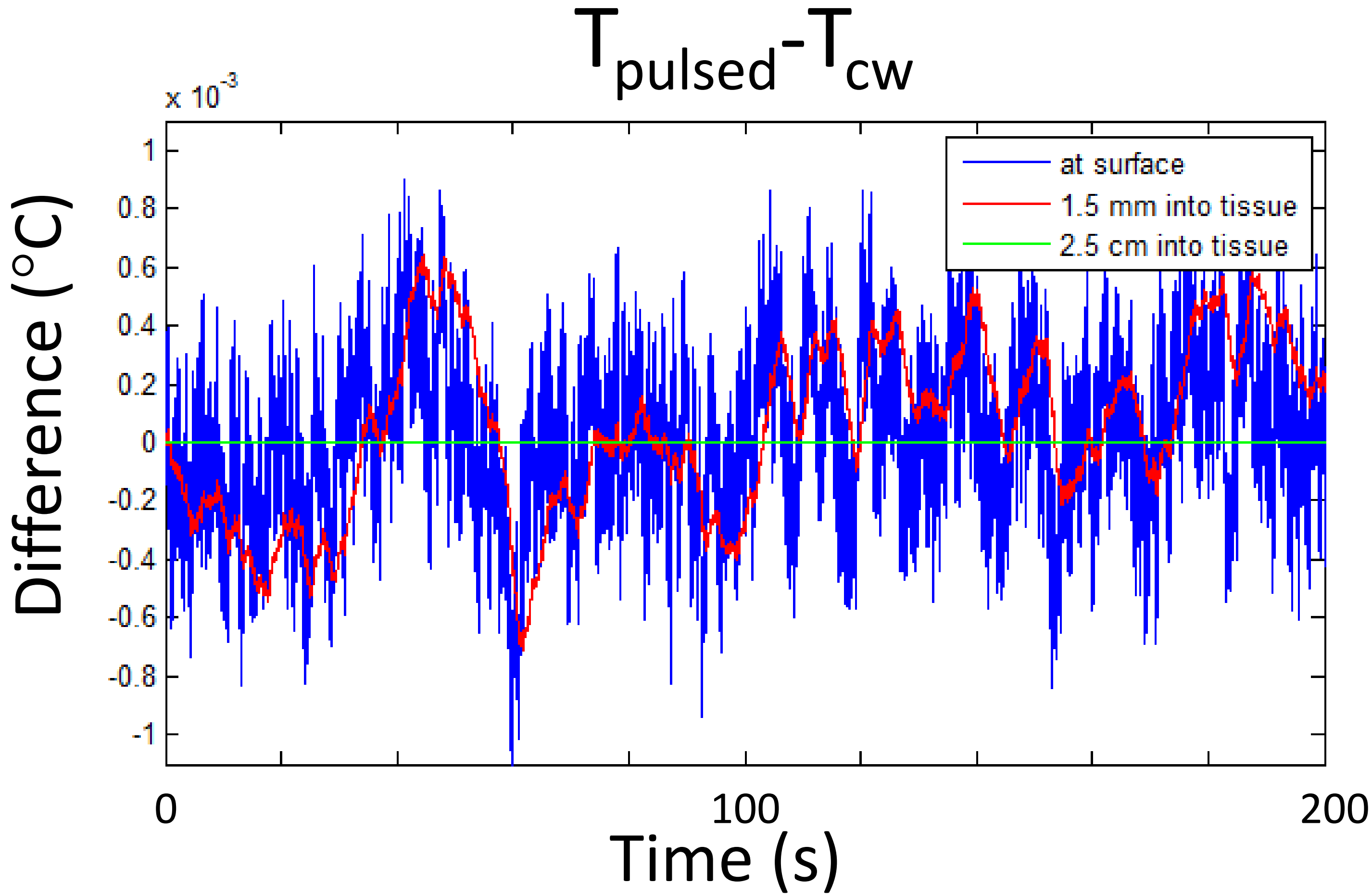


Figure 10. *The steady-state temperature elevation in the three-layer human tissue model at 60 GHz with different incident power densities.*

Wu, Rappaport, & Collins, IEEE Magazine, March 2015

RF Pulse Sequence and Temperature (in mmWave)



For random on-off pulses of 20ms duration

Conclusion: No need to consider individual pulses in Communications

What Quantity to Regulate?

- Specific energy Absorption Rate (SAR; W/kg) averaged over some portion of the subject used most often at RF frequencies up to single GHz
  - Temperature depends also on perfusion, etc.
- Power density (PD; W/m^2) used in high GHz range
  - Measured in air: no consideration of % absorbed or of distribution in body
  - Temperature depends also on perfusion, etc.
- In current IEC Guidelines for MRI, temperature can be used to assure safety
- For local heating, it is well known that it is not temperature alone, but temperature through time that is related to safety
  - Future IEC guidelines may contain "thermal dose" concepts

Using MRI to Measure Temperature Increase

PRF shift thermometry: $\Delta\phi(x,y,t) = \alpha \cdot \gamma \cdot B_0 \cdot TE \cdot \Delta T(x,y,t)$

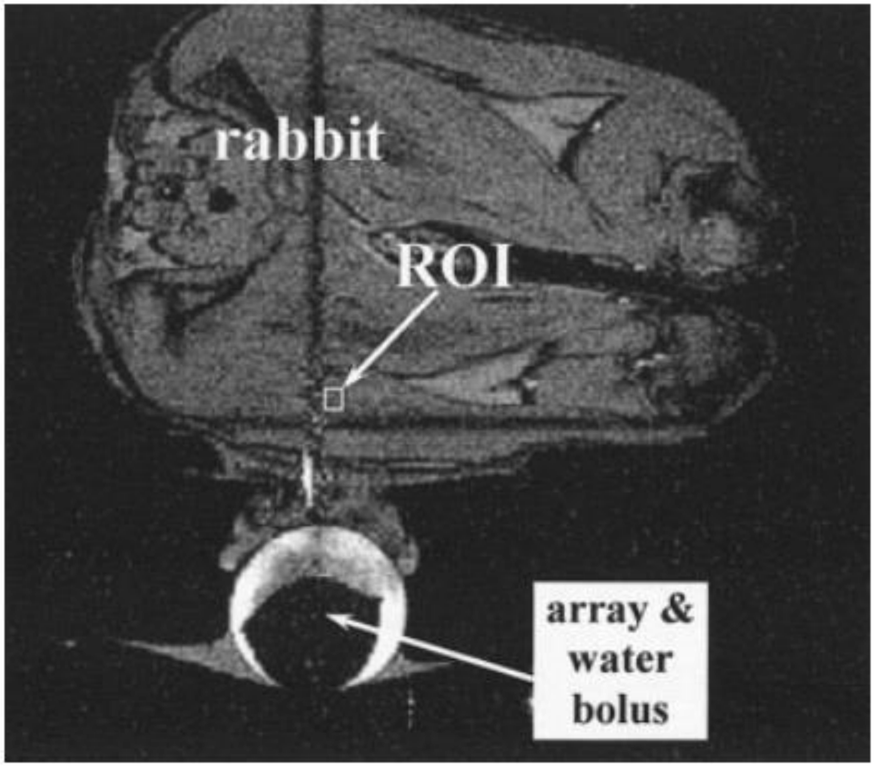


Figure 7 MR image showing the axial view of the rabbit thigh, displaying the location of the array and water bolus with respect to the ROI.

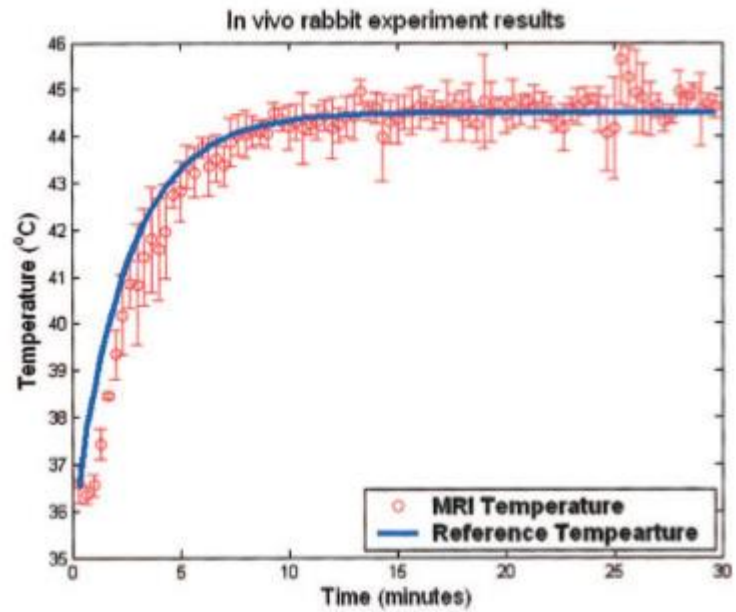


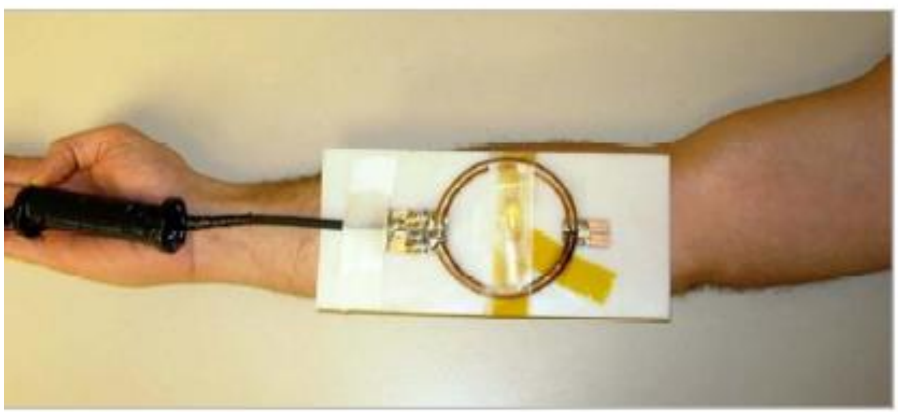
Figure 8 MRAC adaptive feedback temperature elevation from the average of the in vivo rabbit thigh muscle hyperthermia using the control variables as $4\tau = 8$ min, adaptation gain = 0.005, and optimized initial value. MR measurement (circles) and reference (line) are plotted versus the time. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

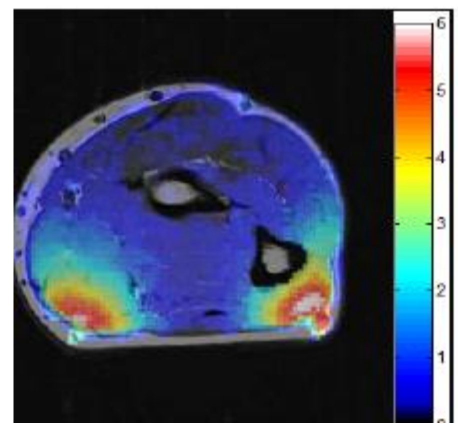
Sun, Collins, *et al.*, Concepts in Magn Reson B 2005;27:51-63

Using MRI to Measure Temperature Increase from RF Fields

PRF shift thermometry:

$$\Delta\phi(x,y,t) = \alpha \cdot \gamma \cdot B_0 \cdot TE \cdot \Delta T(x,y,t)$$





Oh *et al.*, Magn Reson Med 2014;71:1923

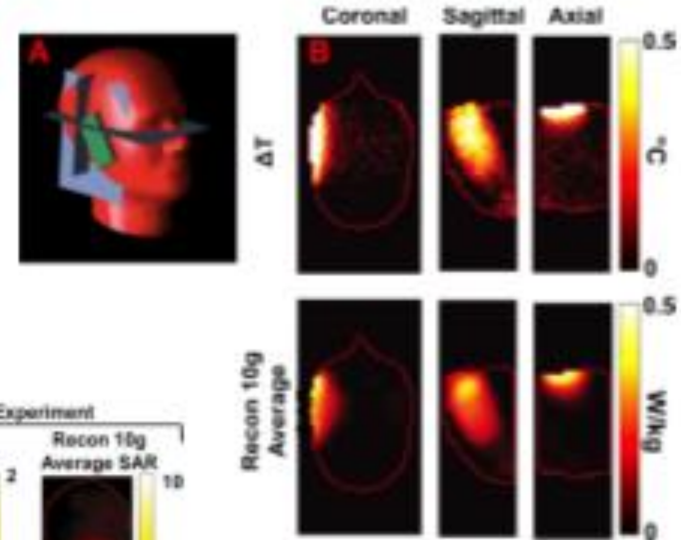
MR Thermal mapping for Safety Assessment of RF/Microwave-Emitting Devices

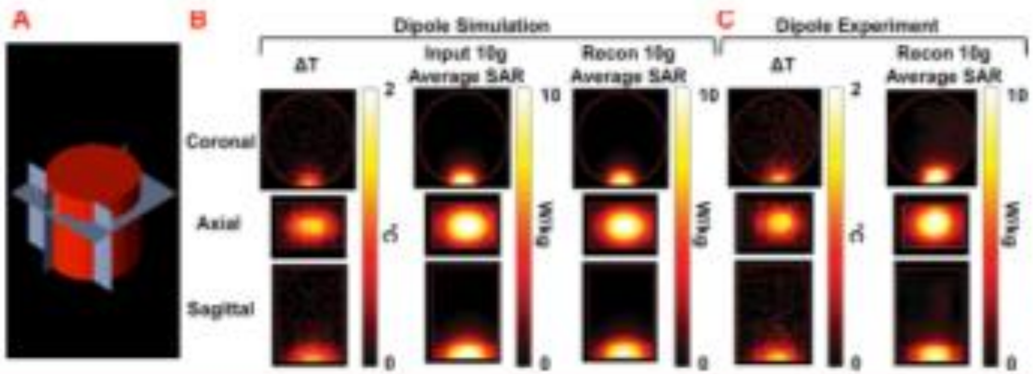
FULL PAPER

Magnetic Resonance in Medicine 00:00–00 (2014)

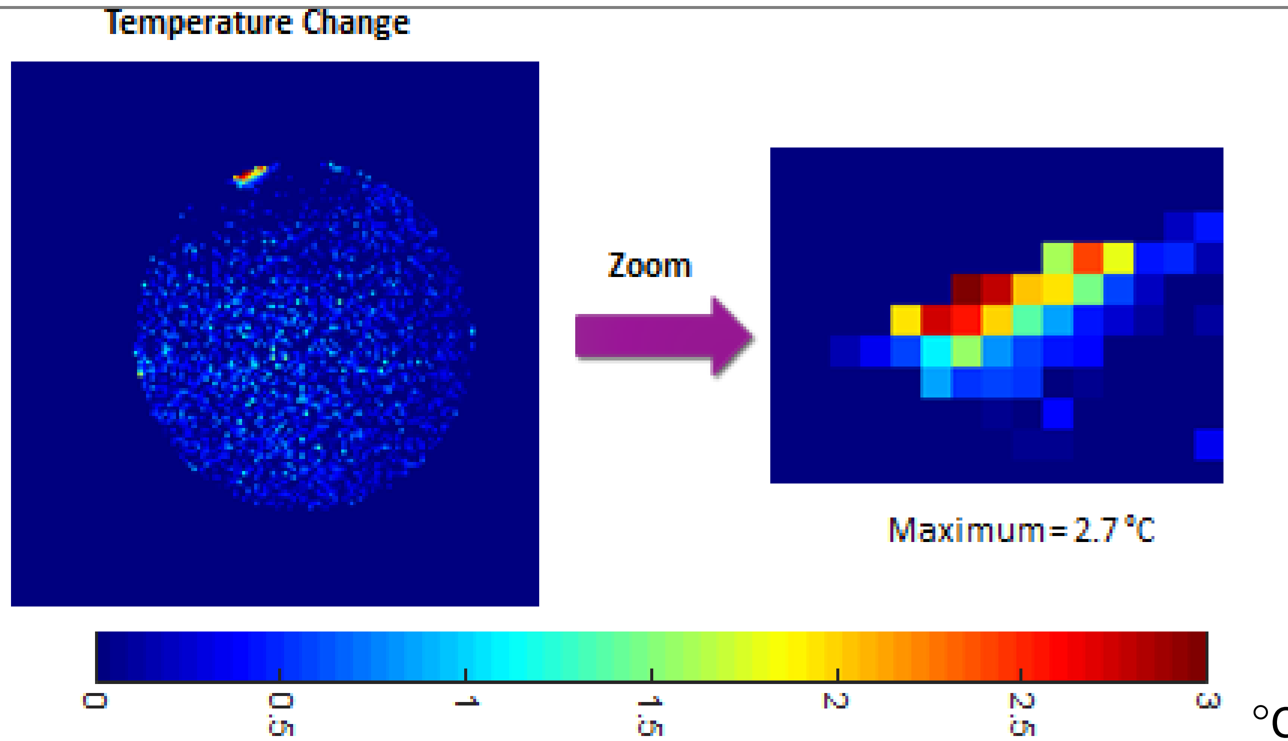
A Method for Safety Testing of Radiofrequency/ Microwave-Emitting Devices Using MRI

Leeor Alon,[1,2,3,4*] Gene Y. Cho,[1,2,4] Xing Yang, Daniel K. Sodickson,[1,2,3] and Cem M. Deniz[1,2,3,4]





Phantom results, 5 minutes exposure



24.245GHz
400 W/m^2

Conclusions(?)

- Temperature depends on RF heating distribution as well as rate of perfusion by blood, etc.
  - It is difficult to heat brain compared to most other tissues
- Limits of temperature and thermal dose can alleviate dependence on time average necessary for SAR limits and need for averaging mass for (10g) local SAR limits, as well as improve relevance of what we regulate
- For pulse sequences relevant to MRI and communications, there is no need to consider SAR timecourse down to the level of milliseconds
- Heating timecourse on the order of minutes (series of MRI pulse sequences in an exam, positioning and use – or not – of cell phone through time) can result in temperature changes on the order of 1 °C

Thanks!