Use of COMSOL Multiphysics® to Simulate RF Heating of Passive Conductive Implants in MRI Scanners

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Boston, MA
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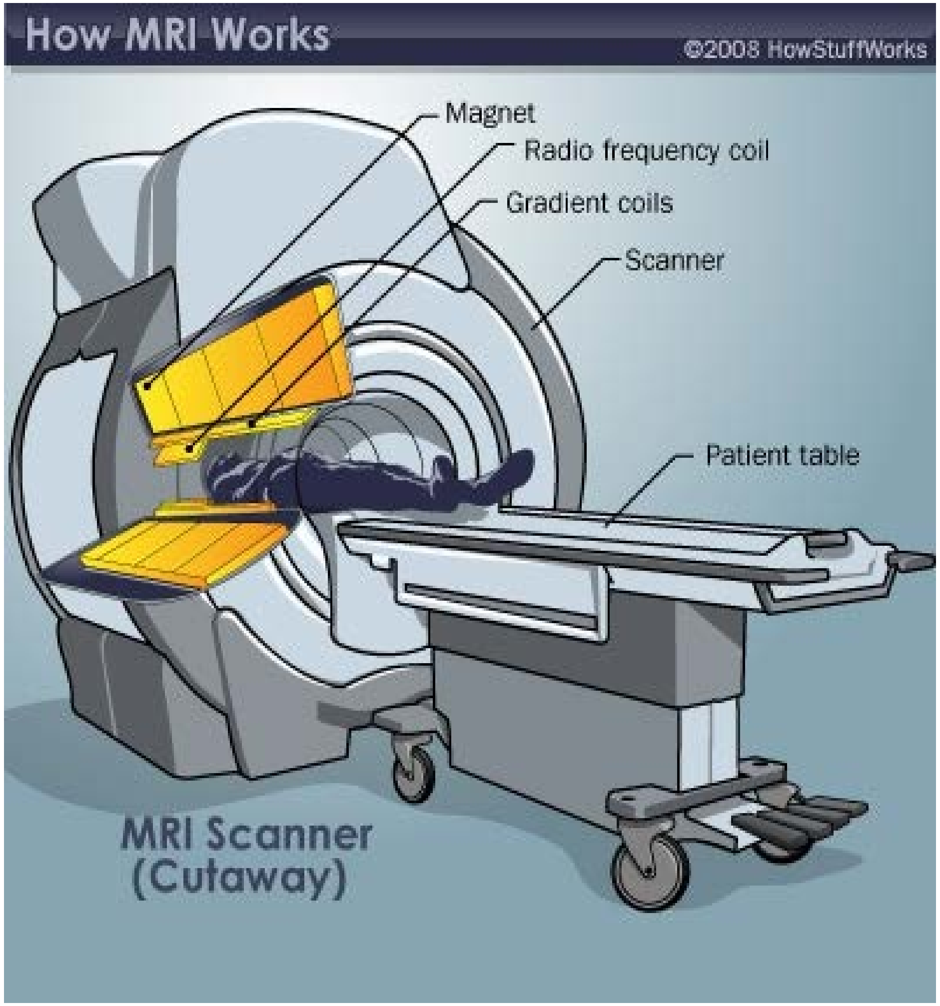
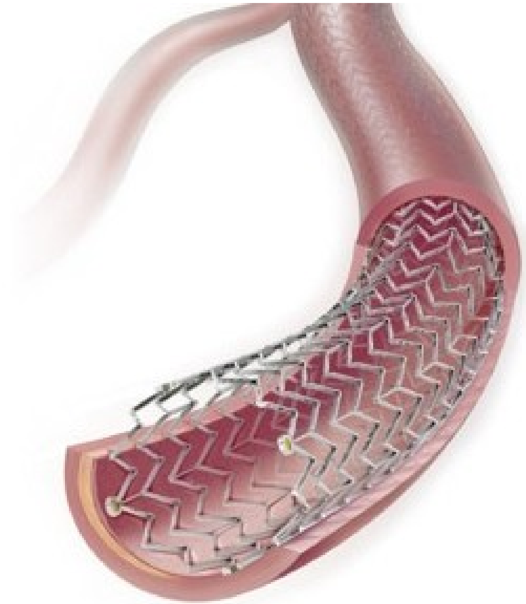
MR Safety: Heating of Passive Implants





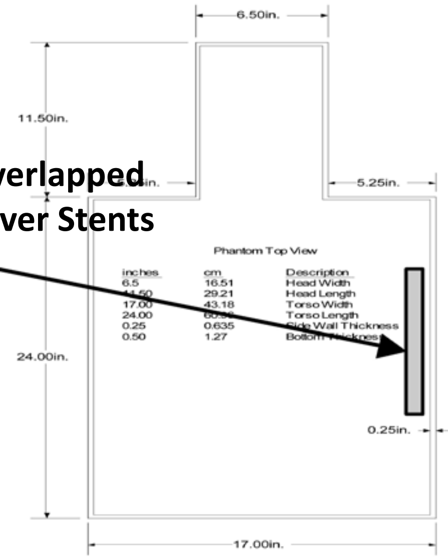
Zilver (Self-Expanding Vascular Stent)

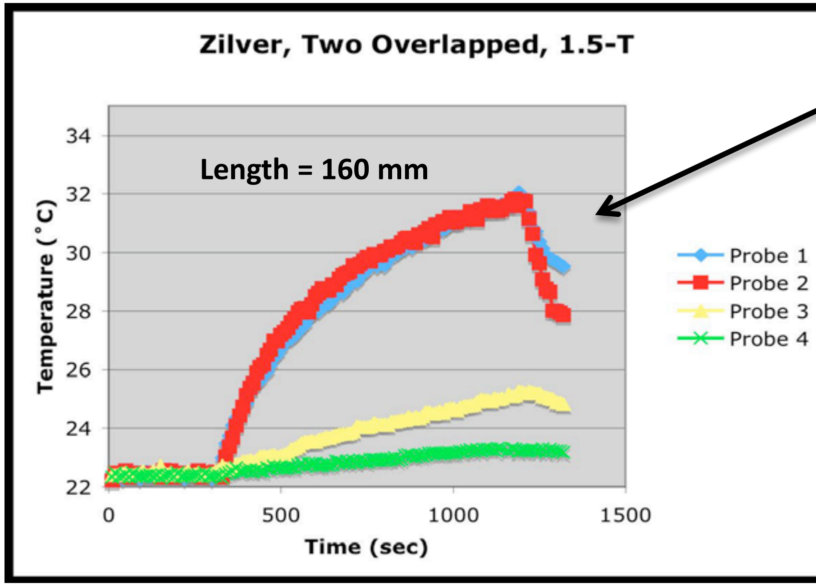
80,000,000 procedures/year

Historical Project: RF Heating of a Zilver Stent

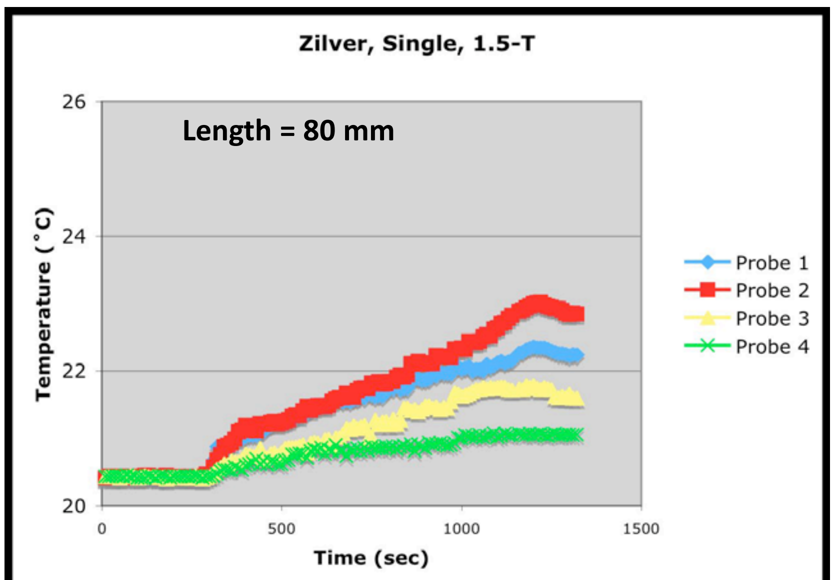
Testing Standard: ASTM F2182

Overlapped Zilver Stents





ΔT = 10°C



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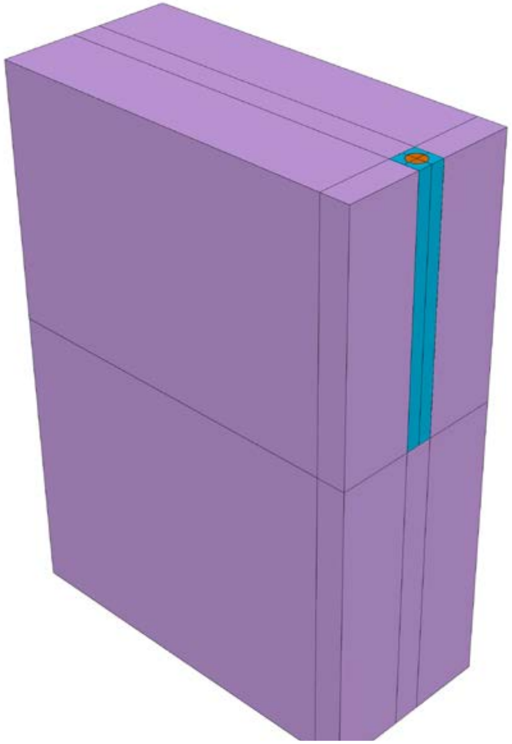
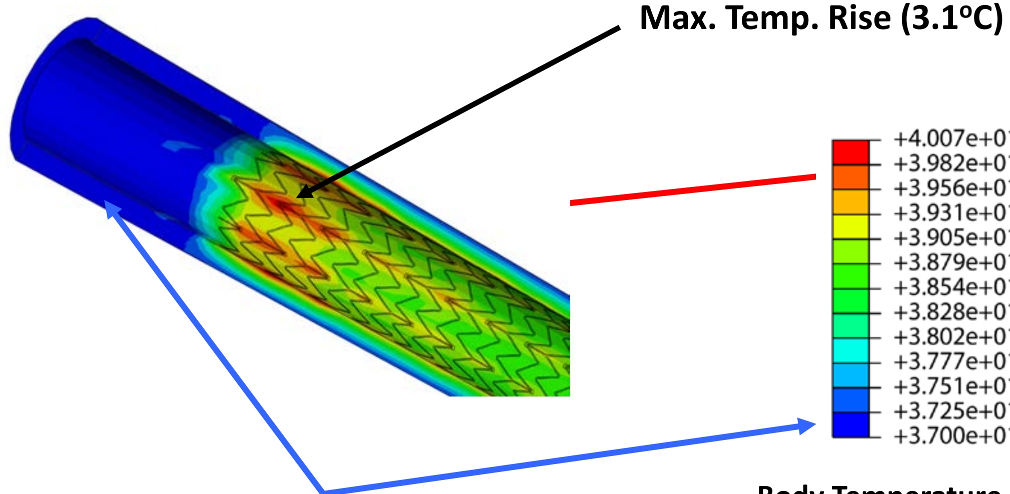
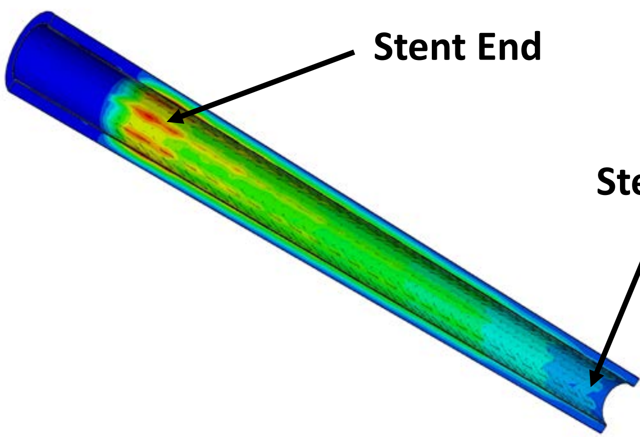
Include "Cooling" due to Vascular Blood Flow

(ABAQUS : Convective BC)



Salt-Gel Phantom





Major Idealizations

- Newtonian Convection BC
- Endothelial layer Included
- Uniform blood flow
  - Fully developed laminar *pipe* flow
  - Newtonian fluid

ASSUME LINEAR DISTRIBUTION OF JOULE HEATING TO REPLICATE MEASURED TEMPERATURES

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RF Heating Simulation: Purpose?

- Safety: Prevent excess cell death
- Determine worst case(s)
  - Many devices have multiple size(s)/length(s)
- Reduce Testing Burden
  - Historically required to test in both 1.5T & 3T scanners
  - Non-trivial device orientations & geometries
- Find Location of Maximum Heating
  - Need to know where to locate thermocouples
    - Not all devices are "one dimensional" like
      - Vena Cava Filters
- *Provide Understanding*
- Virtual Bench Testing
  - Simulation in-lieu of testing?

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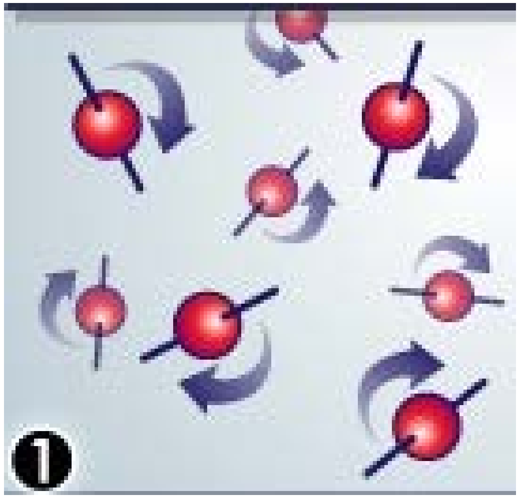
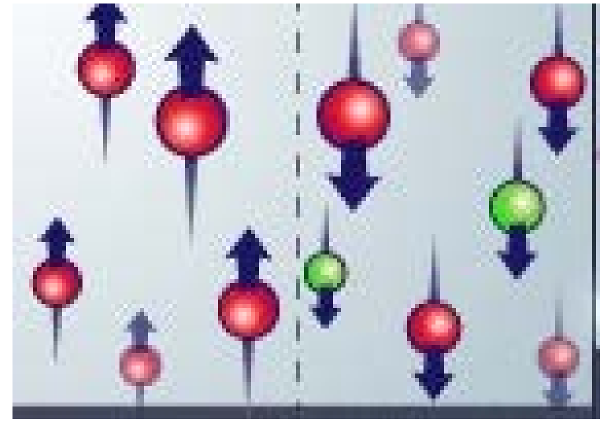
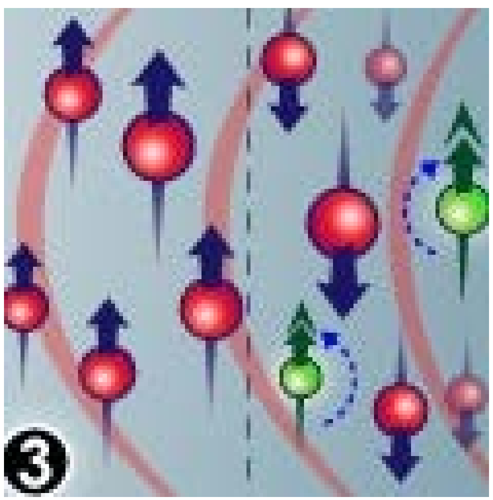
MR Physics Fundamentals



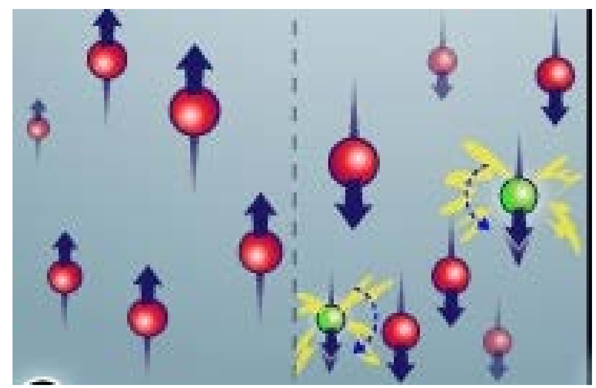
Static Bo Field





RF Energy Added
(Larmor Freq.)

Protons flipped 90°



Decay after RF Pulse

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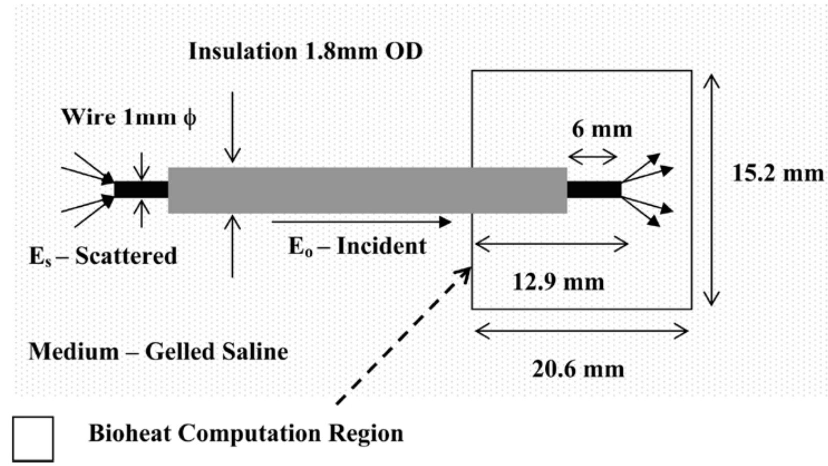
RF Heating: Passive Implant (Wire)

Name	Differential form
Gauss's law	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\nabla \cdot \mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\nabla \times \mathbf{E} = \boxed{-\frac{\partial \mathbf{B}}{\partial t}}$
Ampère's circuital law (with Maxwell's correction)	$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$



Time Varying Magnetic Field Induces Electric Field/Current

IEEE TRANSACTIONS ON MAGNETICS, VOL. 41, NO. 10, OCTOBER 2005 4197
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S. M. Park1*, Student Member, IEEE*, R. Kamondetdacha1, A. Amjad1, and J. A. Nyenhuis1*, Senior Member, IEEE*
Purdue University, West Lafayette, IN 47907-2035 USA

Coupled Heat Transfer

Pennes Bioheat Equation

Perfusion

Metabolism

RF Energy

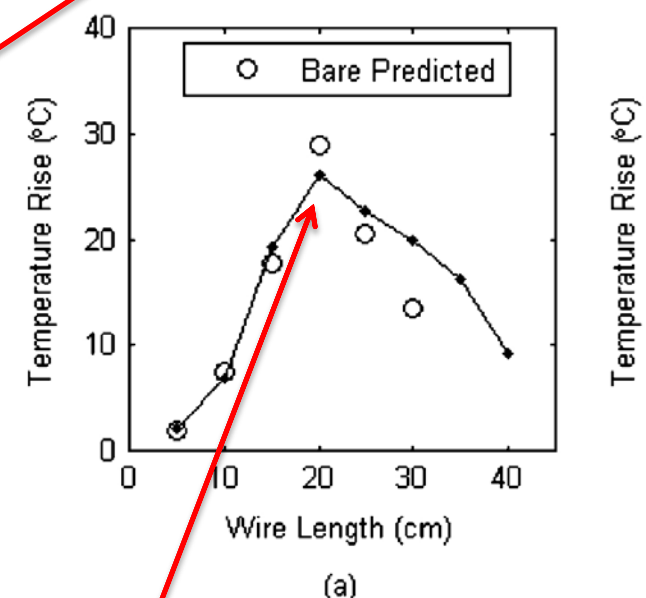
$$\rho c \frac{dT}{dt} = \nabla \bullet (K \nabla T) + \left[-\rho_{blood} w c_{blood} \left(T - T_{blood} \right) \right] + Q_m + SAR\rho$$

Traditional Newtonian Heat Flow

Specific Absorption Ratio (W/kg)

$$\boxed{SAR = \frac{\sigma E^2}{\rho}}$$

E = Electric Field
σ = Electrical Conductivity
ρ = Density



Resonant Length: Function of RF Freq.

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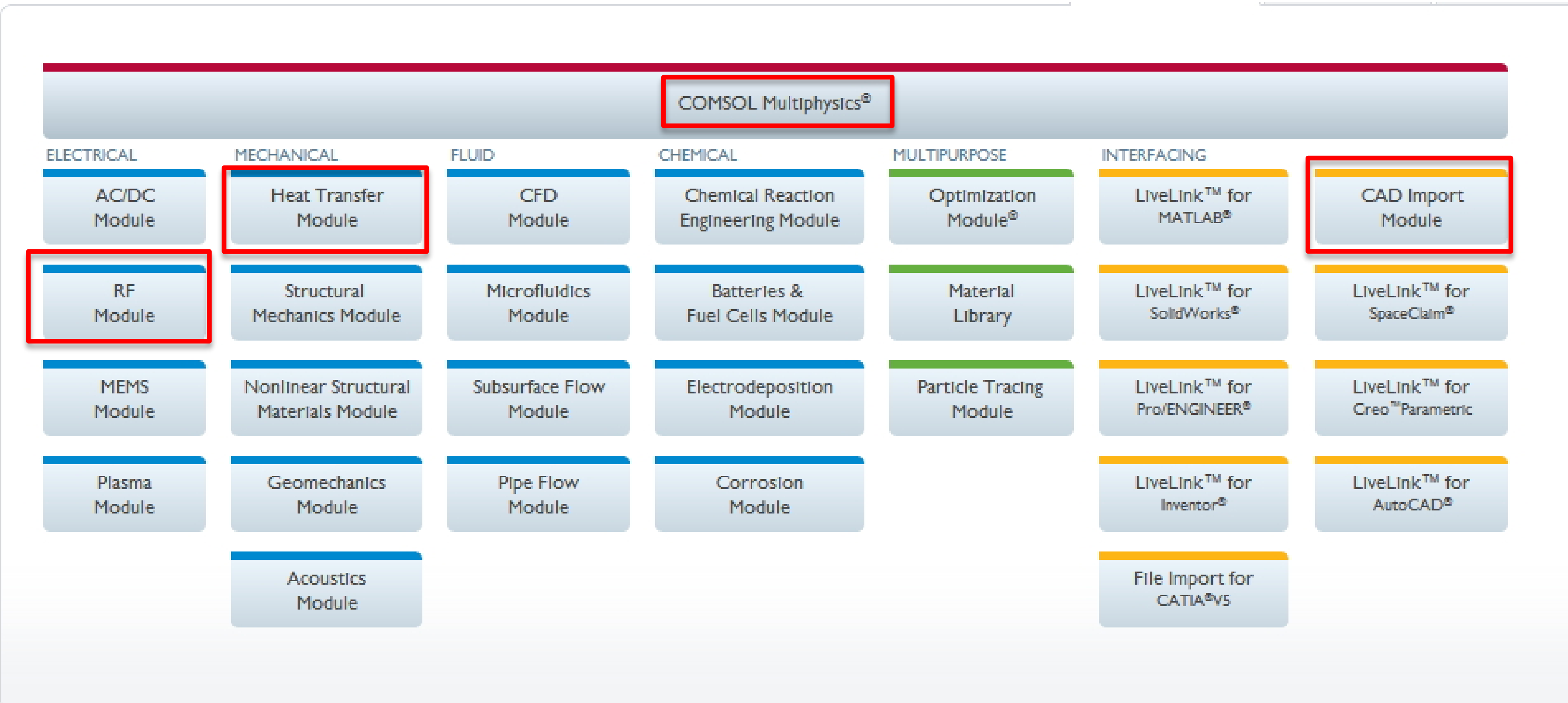
COMSOL Multiphysics©



RF Module:	Electromagnetic Open Field Solution
Heat Transfer Module:	Transient Temperature Solution (Bioheat)
COMSOL Multiphysics:	Vascular Cooling (Laminar Flow)
CAD Import:	Direct CAD Geometry Import

Leveraging Independent Experts

Identify, implement and validate the appropriate physics in COMSOL.

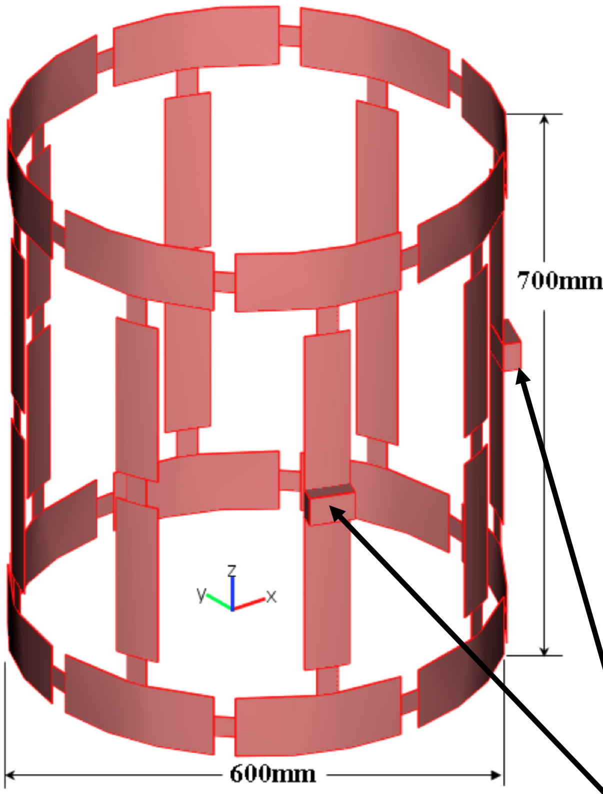
Expertise in the understanding and use of MR scanners

Provide RF Coil specifications

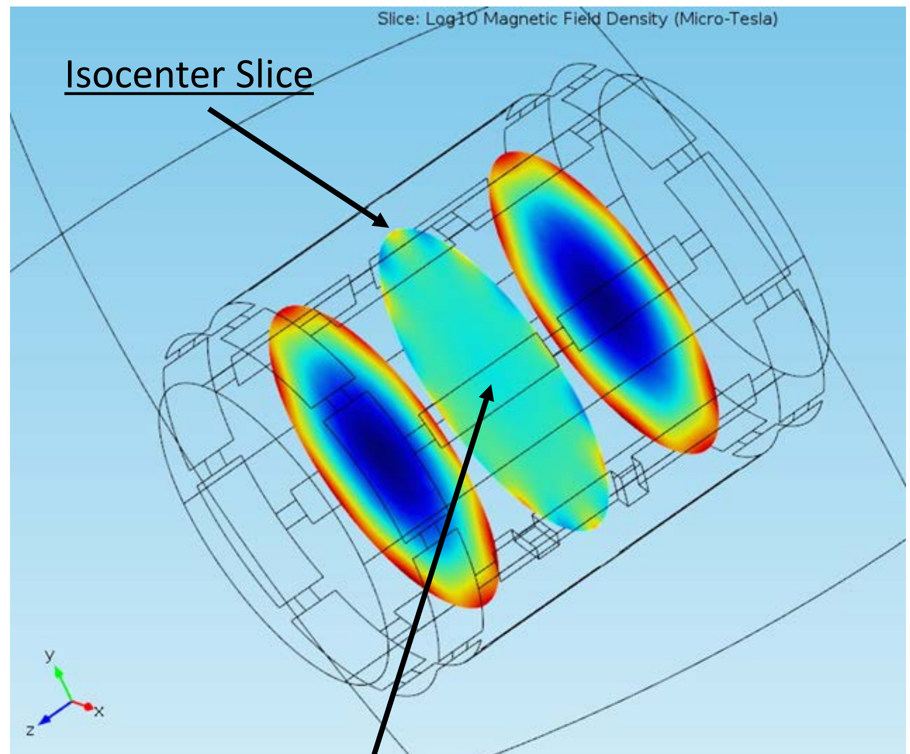
Low Bypass RF Coil

(Coil is *tuned* to 64Mhz for 1.5T Scanner)

Birdcage Coil
(Circularly Polarized)



Magnetic Field (Log_{10}(B))

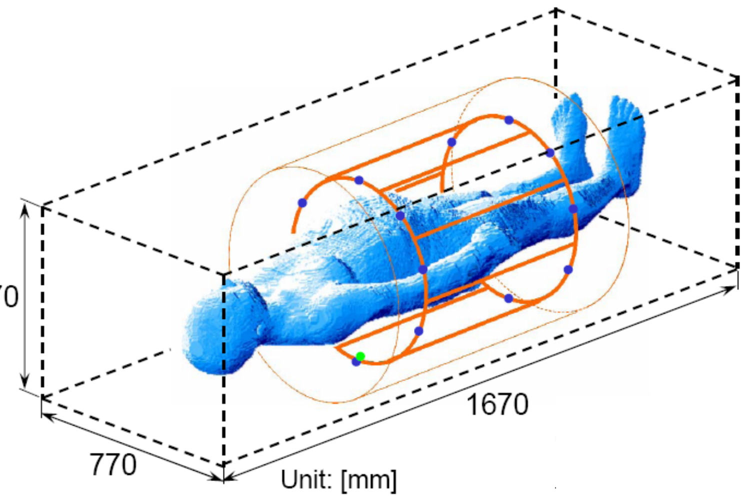


Quadrature Excitation

Uniform Magnetic Field
(2-3 ppm)

Saline Gel Phantom

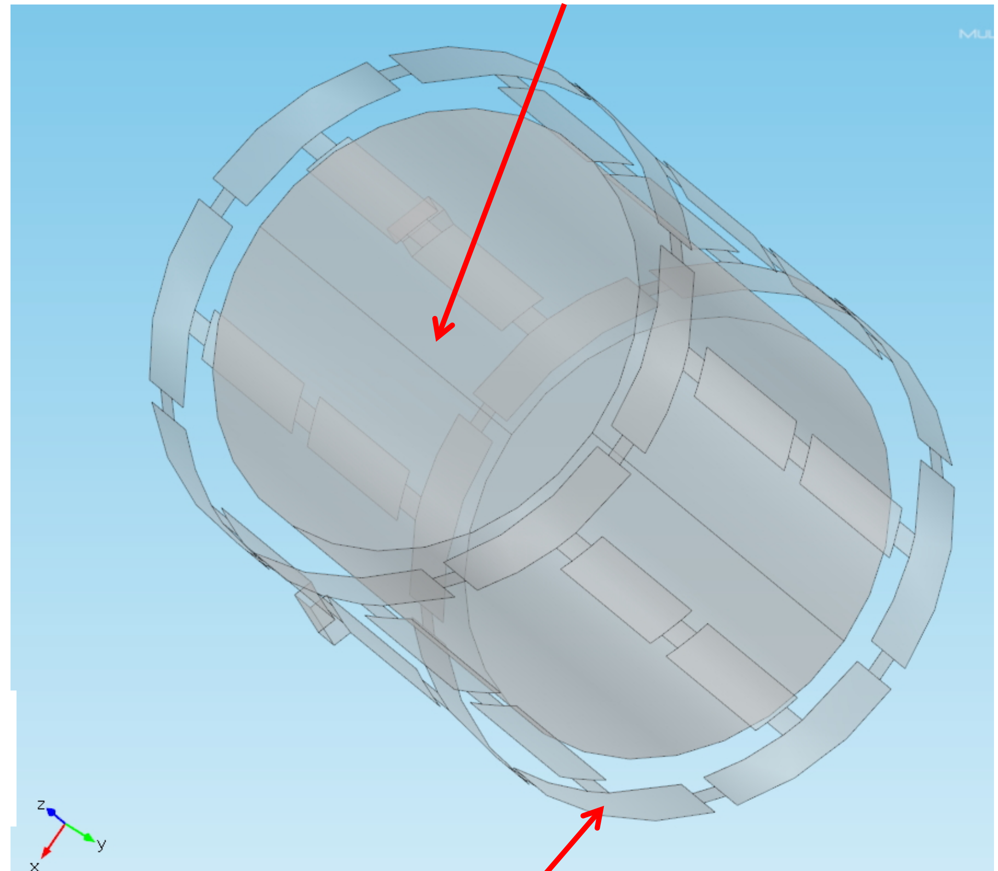
Japanese Standard



$$\mathrm{SAR} = \frac{\sigma}{\rho} E^2 \quad \text{[W/kg]}$$

E: Electric field (r.m.s.) [V/m]
σ: Conductivity of the media [S/m]
ρ: Density of the media [kg/m^3]

Gel Phantom
(ε_r = 77; μ_r=1; S=.27 S/m)

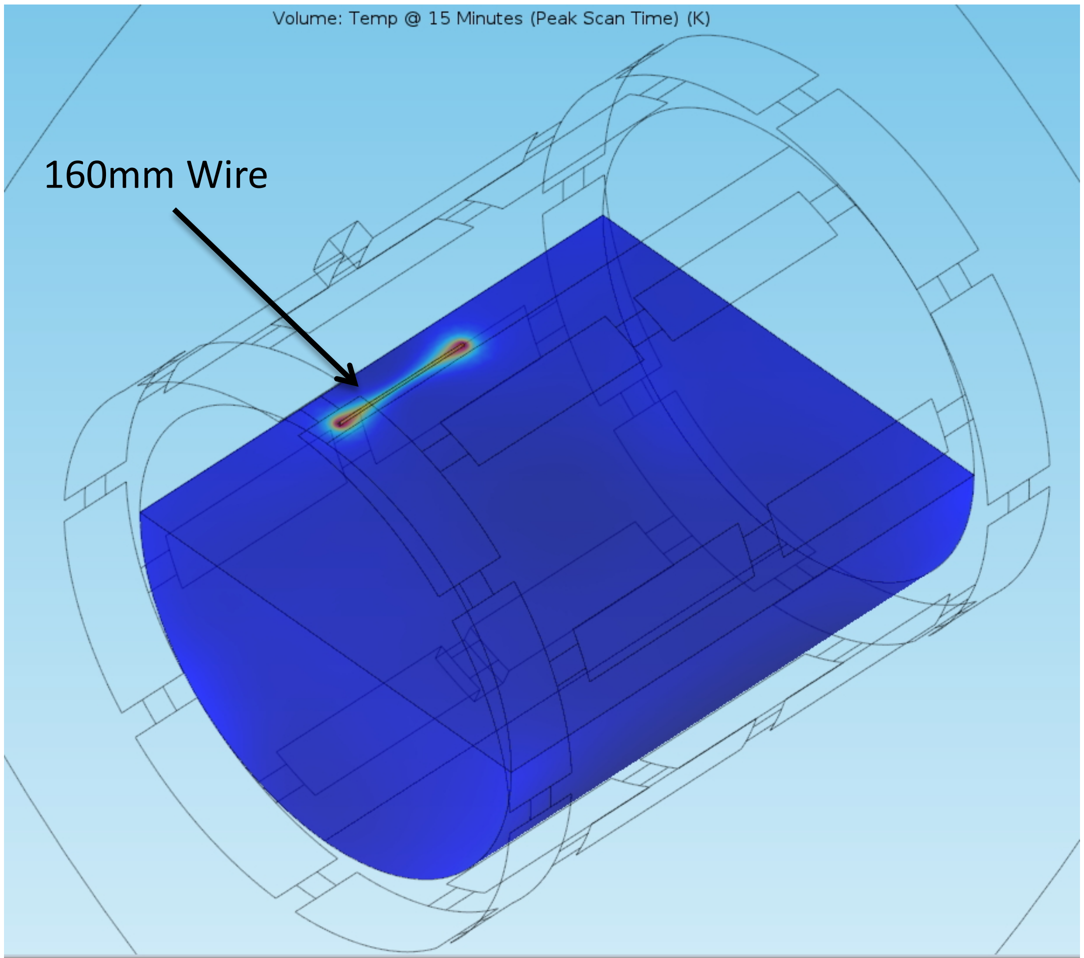


RF Coil (PEC)

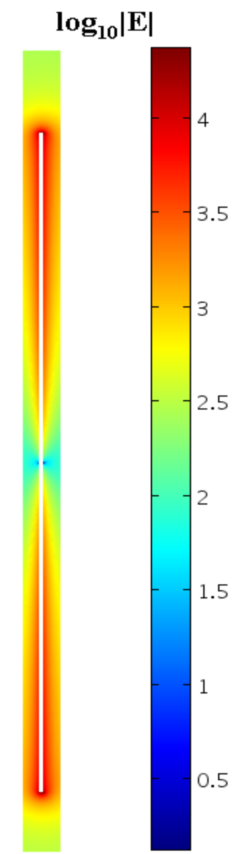
RF Heating of a Straight Wire

Wire Resonates in Magnetic Field: Drives Transient Thermal Problem

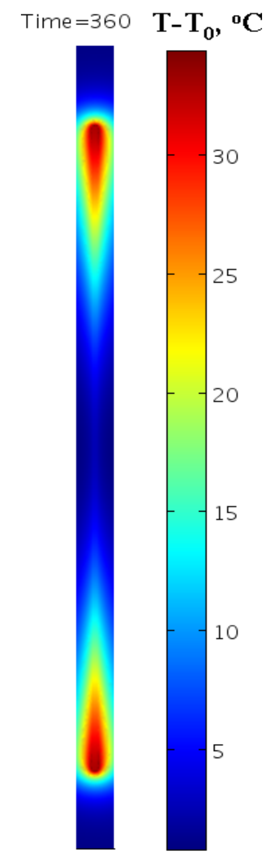
Global Temperature Field (@ Peak Scan Time)



Electric Field

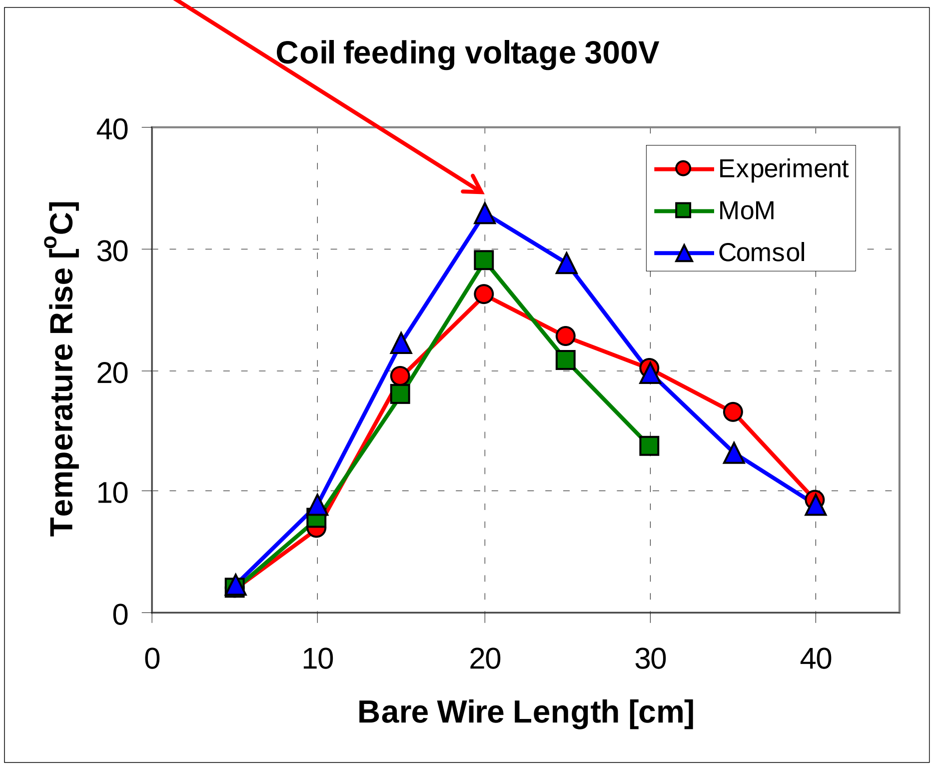


Temperature



Validation (1.5T – 64 MHz)

Resonant Length



Journal Publication

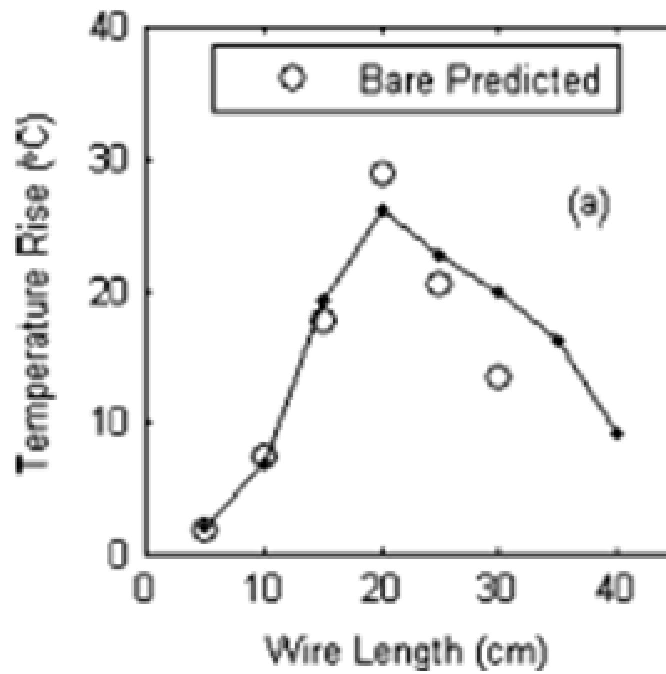


Fig. 5. Measured and predicted temperature rises versus different lengths of the subject wires at the tip. (a) Bare wire.

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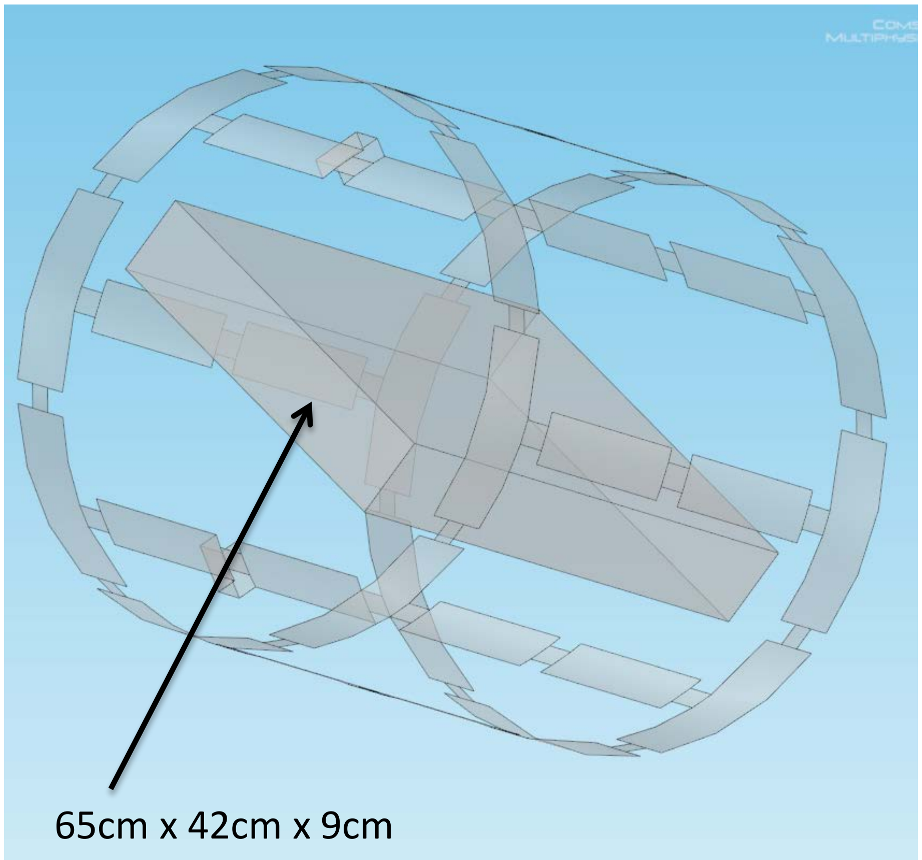
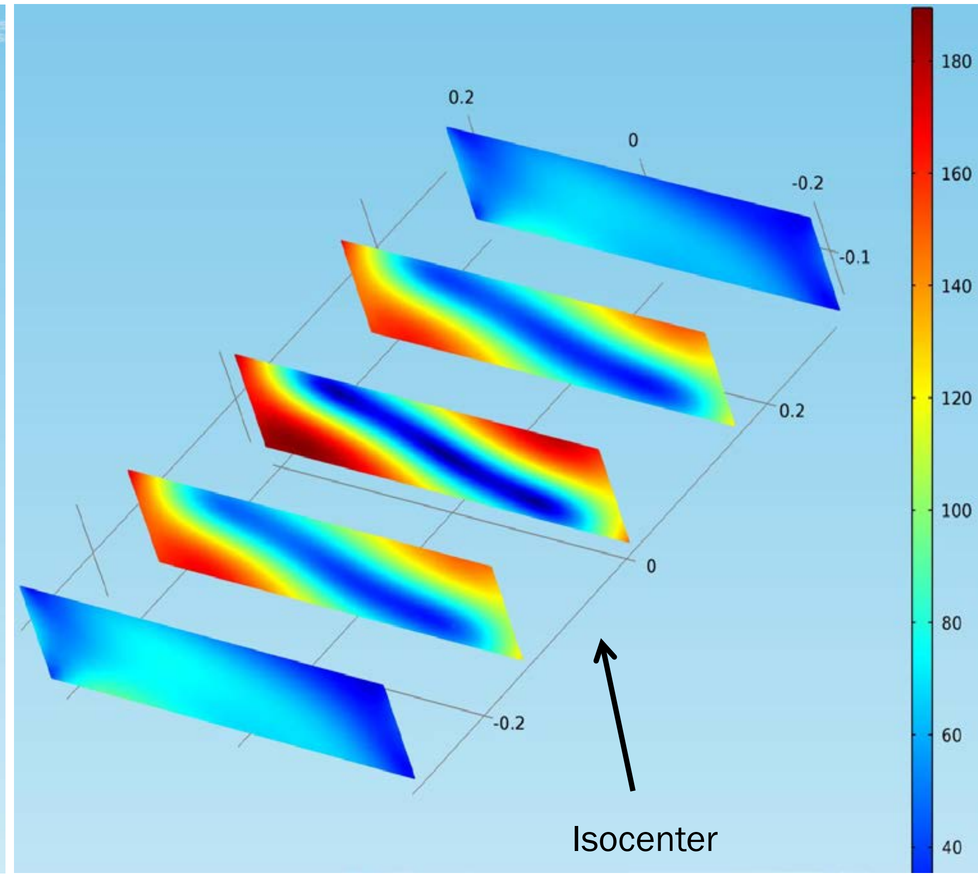
OSU Medical School: Experimental Validation

1.5T & 3T Siemens Scanners



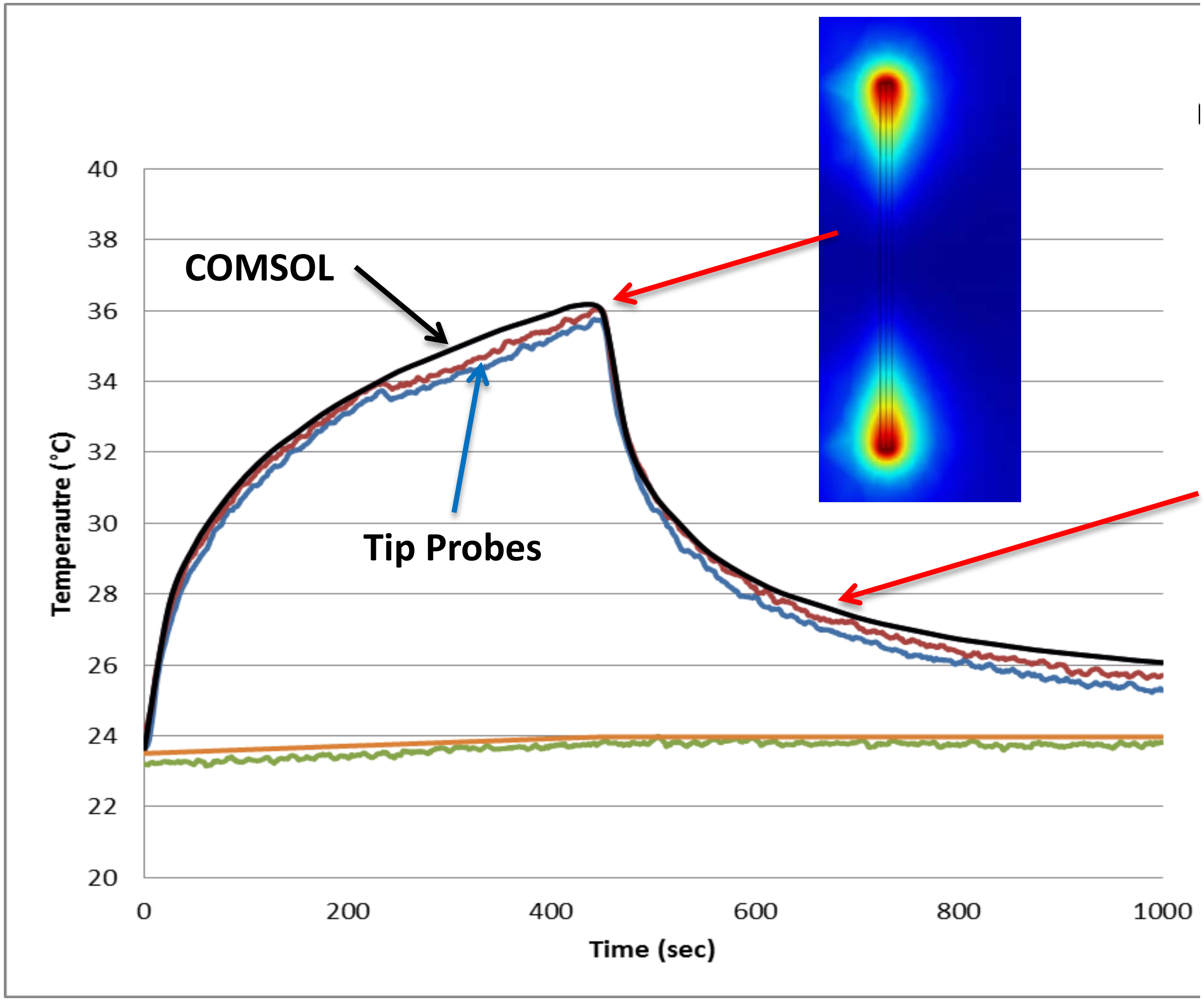
ASTM F2182 Rectangular Gel Phantom

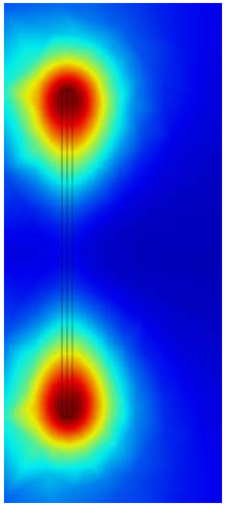
Electric Field Norm [3.0T]: ASTM Phantom



Ti Rod (Dia=1/8” L=10cm)

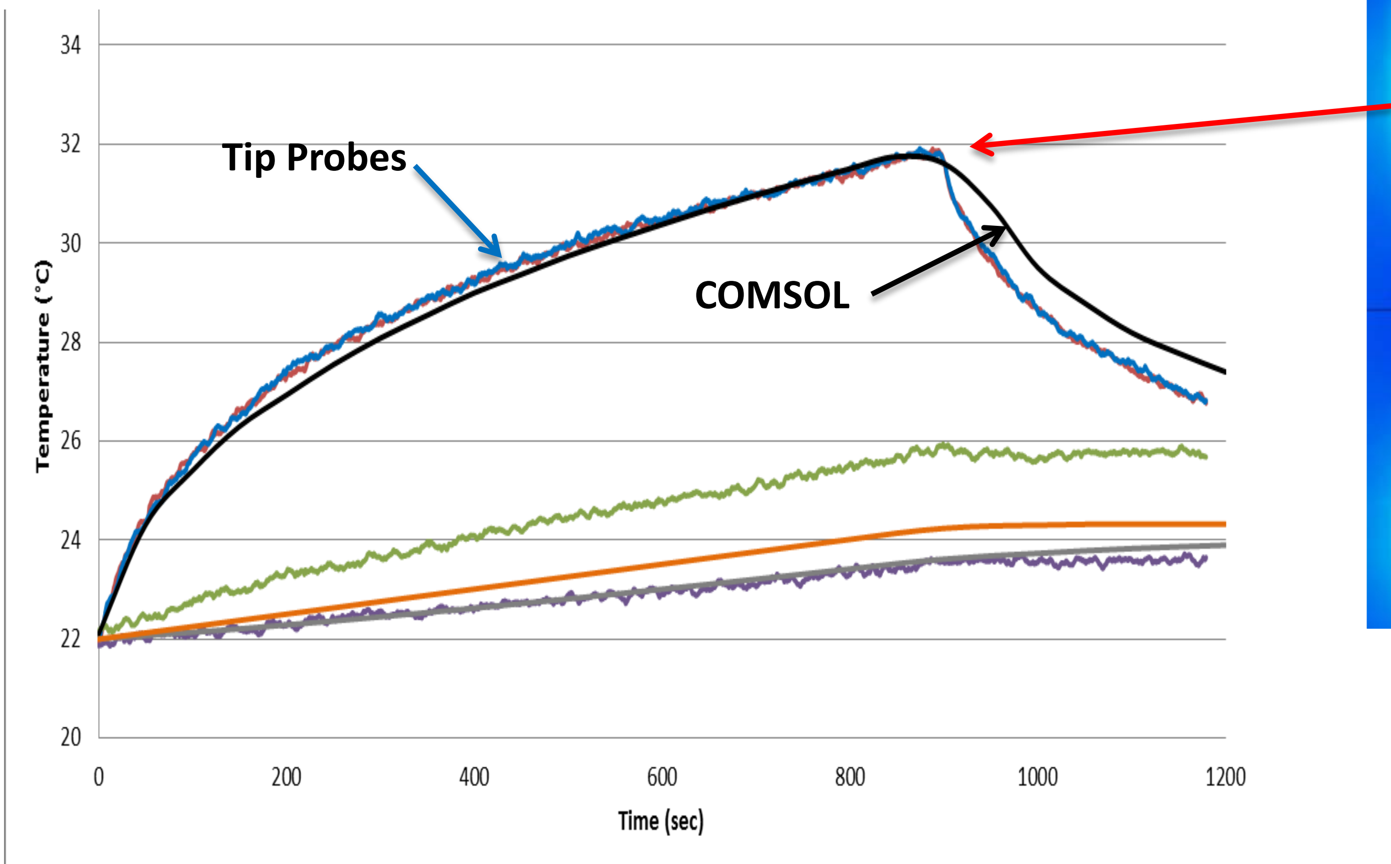
Calibration/Validation

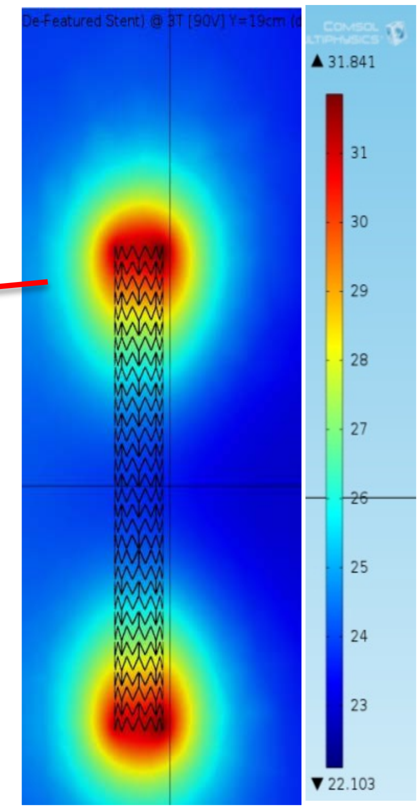




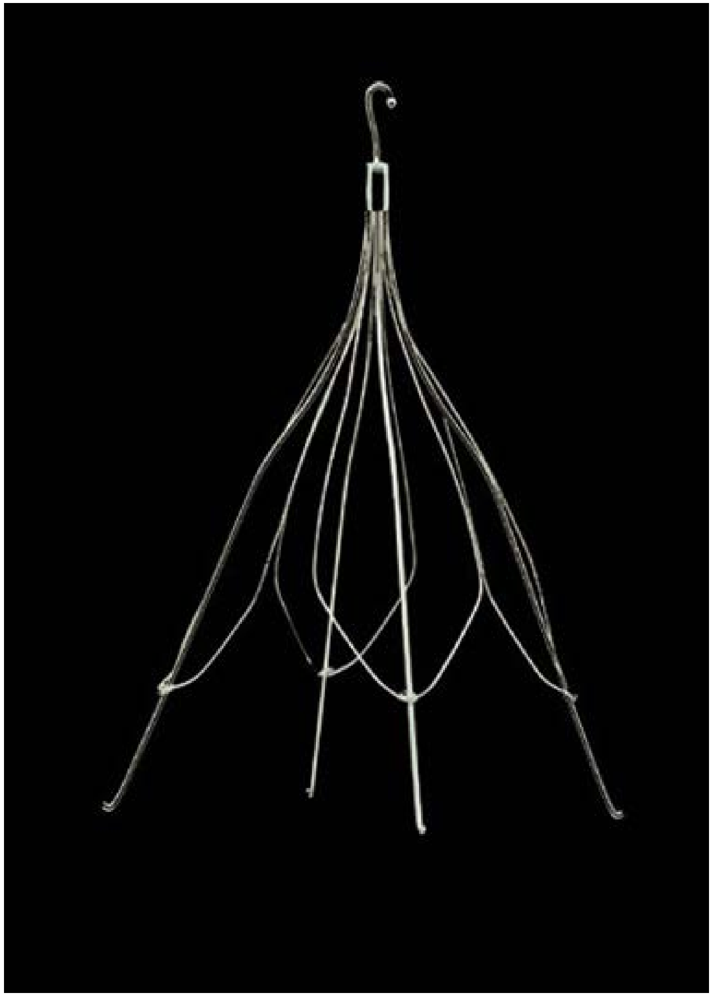
Validation (80mm Zilver Stent)

3T Scanner (RF Coil Powered Equivalent ; Calibration Rod)
[no perfusion or arterial blood flow]





Vena Cava Filters



50 mm

Tulip

Celect

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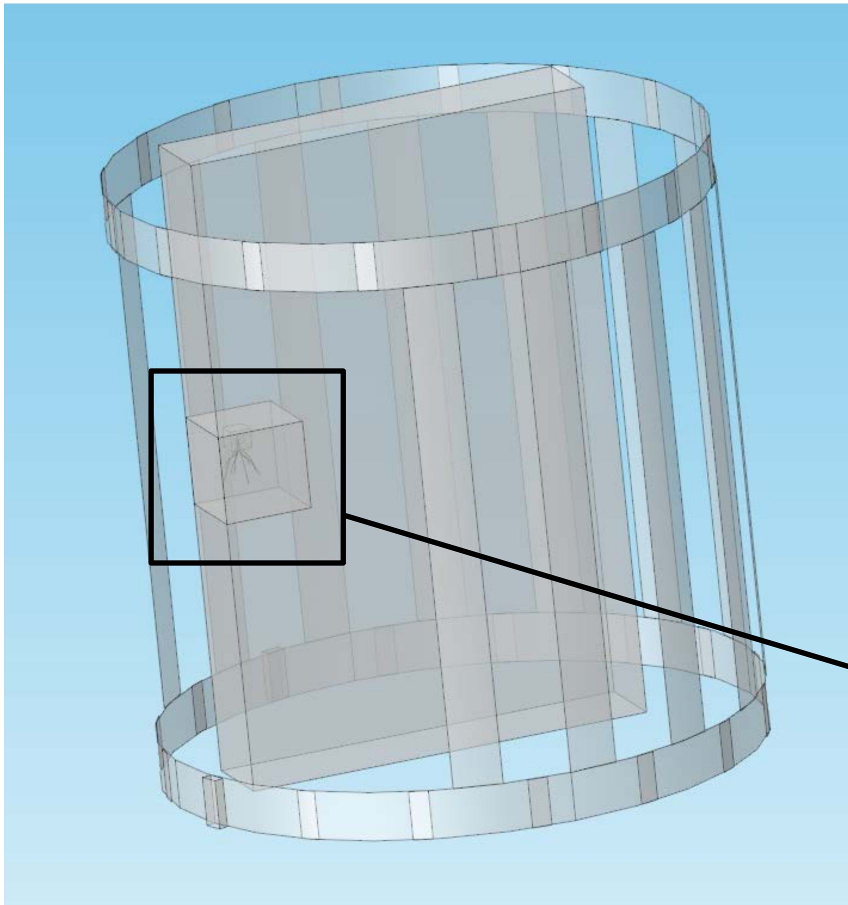
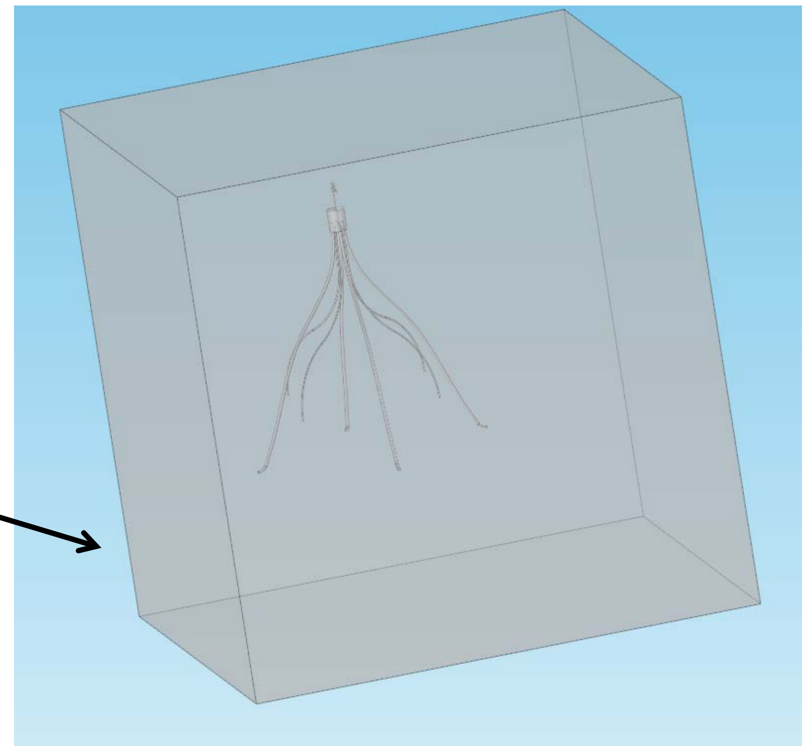
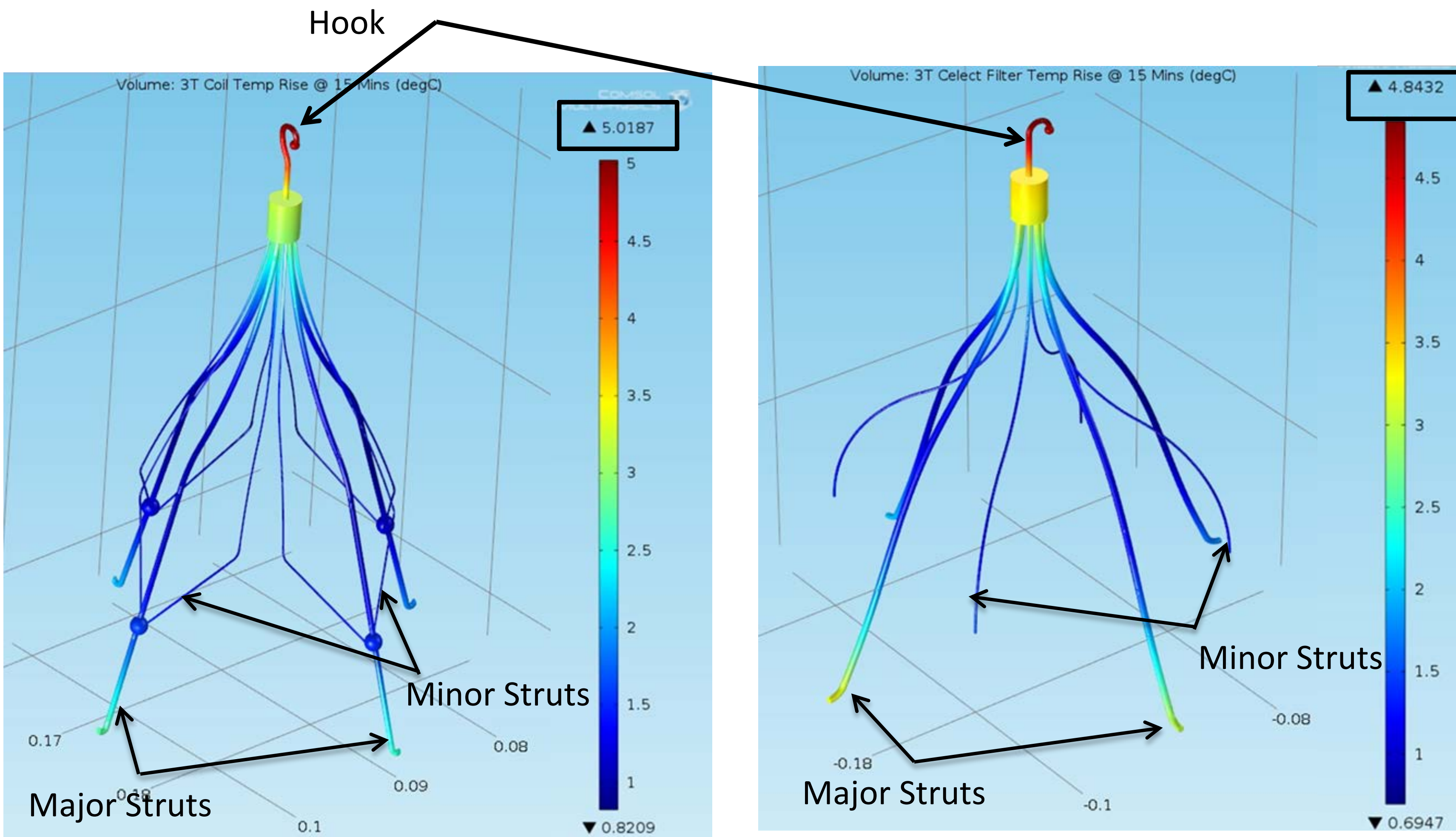
Filters imported into Model of ASTM Phantom

3T Scanner (128 MHz RF Coil)





Temp @ 15 Minutes Heating
3T Scanner (no venous blood flow or perfusion)



Tulip **Celect**

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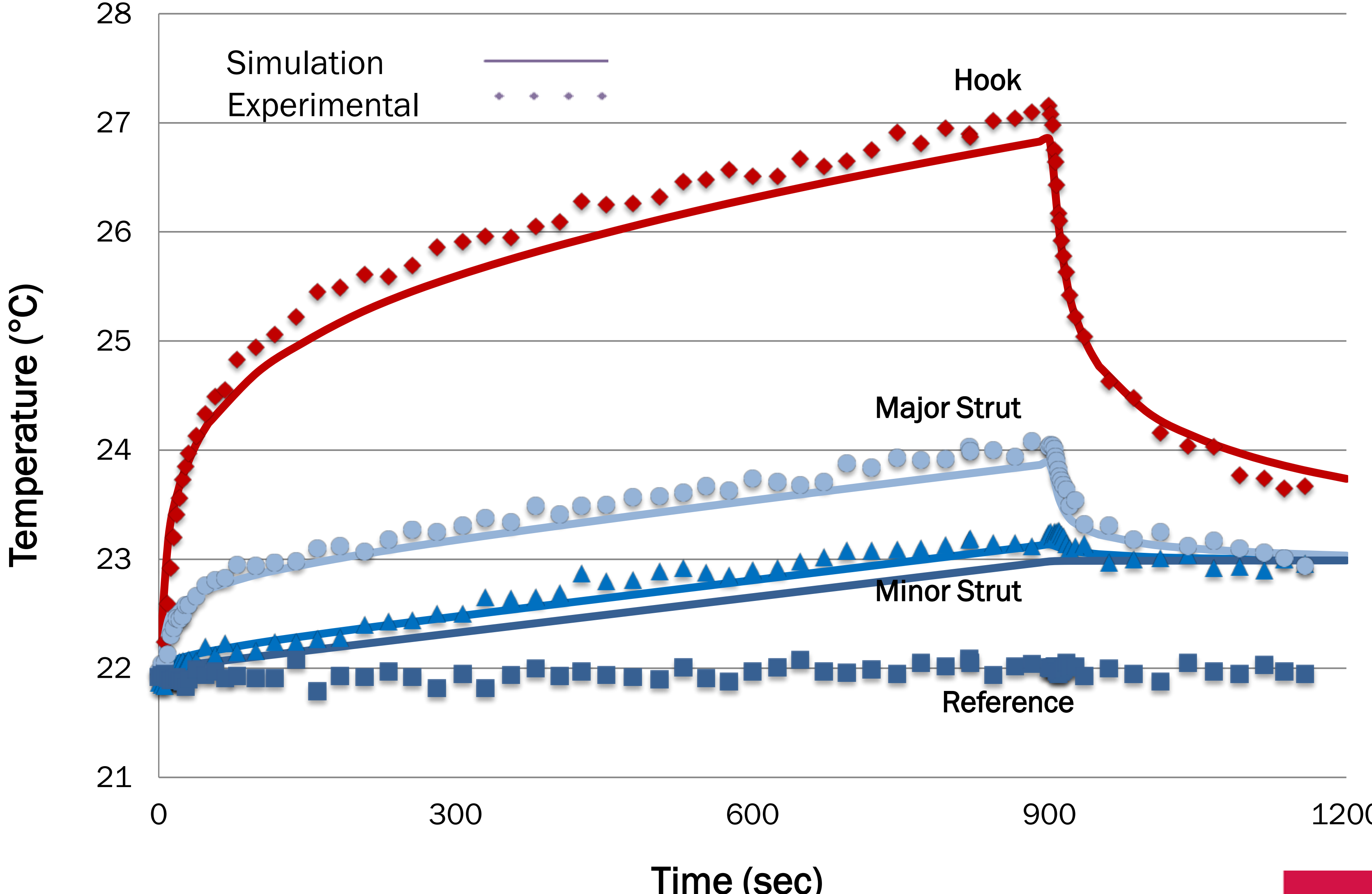
Direct Validation: Tulip Filter



Conclusions

- Accurately Simulate Device/Tissue Temperature due to RF heating with COMSOL Multiphysics©
  - Safety: Prevent excess cell death
  - Determine worst case(s)
    - Many devices have multiple size(s)/length(s)
  - Reduce Testing Burden
    - Historically required to test in both 1.5T & 3T scanners
    - Non-trivial device orientations & geometries
  - Find Location of Maximum Heating
    - Need to know where to locate thermocouples
      - Not all devices are "one dimensional" like
        - » Vena Cava Filters
  - *Provide Understanding*
  - Virtual Bench Testing
    - Simulation in-lieu of testing!

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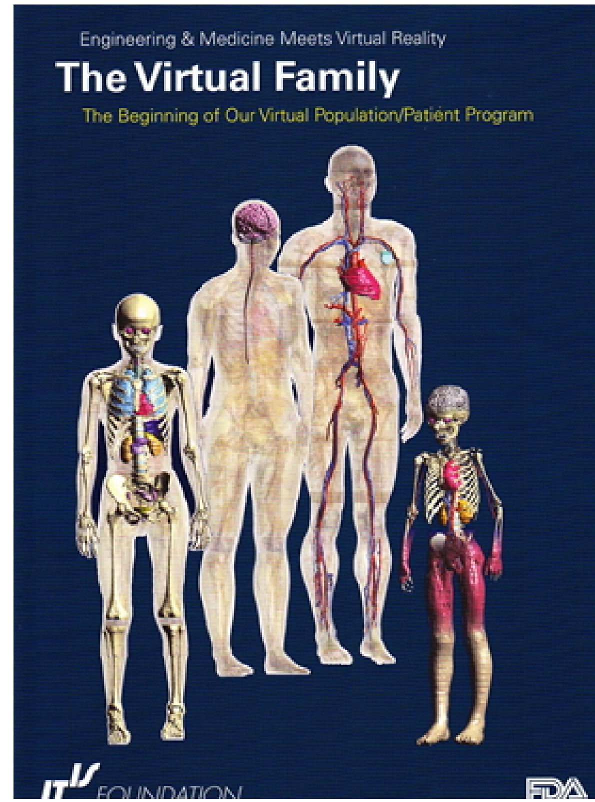
Continuing Developments

- **Further Validation @ OSU**
  - 3D E-field accuracy
  - Thermocouple positional sensitivity
- **Upgraded RF Coil Specifications**
  - Confidential relationship with Siemens
- **New Generation 70cm Diameter RF Coils**
  - Current generation are 60cm
- **Higher Field Scanners (> 3T)**
  - Fields tend to be more localized
- **Multi-channel RF Coils**
  - Birdcage coils have limited homogeneity
- **Stent Geometry Idealizations**
  - 3D not yet practical for many applications
- **Generalized Blood Perfusion**
  - Capillary Cooling effect
- **Vascular/Arterial Flow**
  - Coupled CFD
- **Static Magnetic Force Acting on Implants**
  - B_0 field not RF Coil
- **Virtual “Digitized” Human Anatomies**
  - This is where the FDA and industry is moving



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