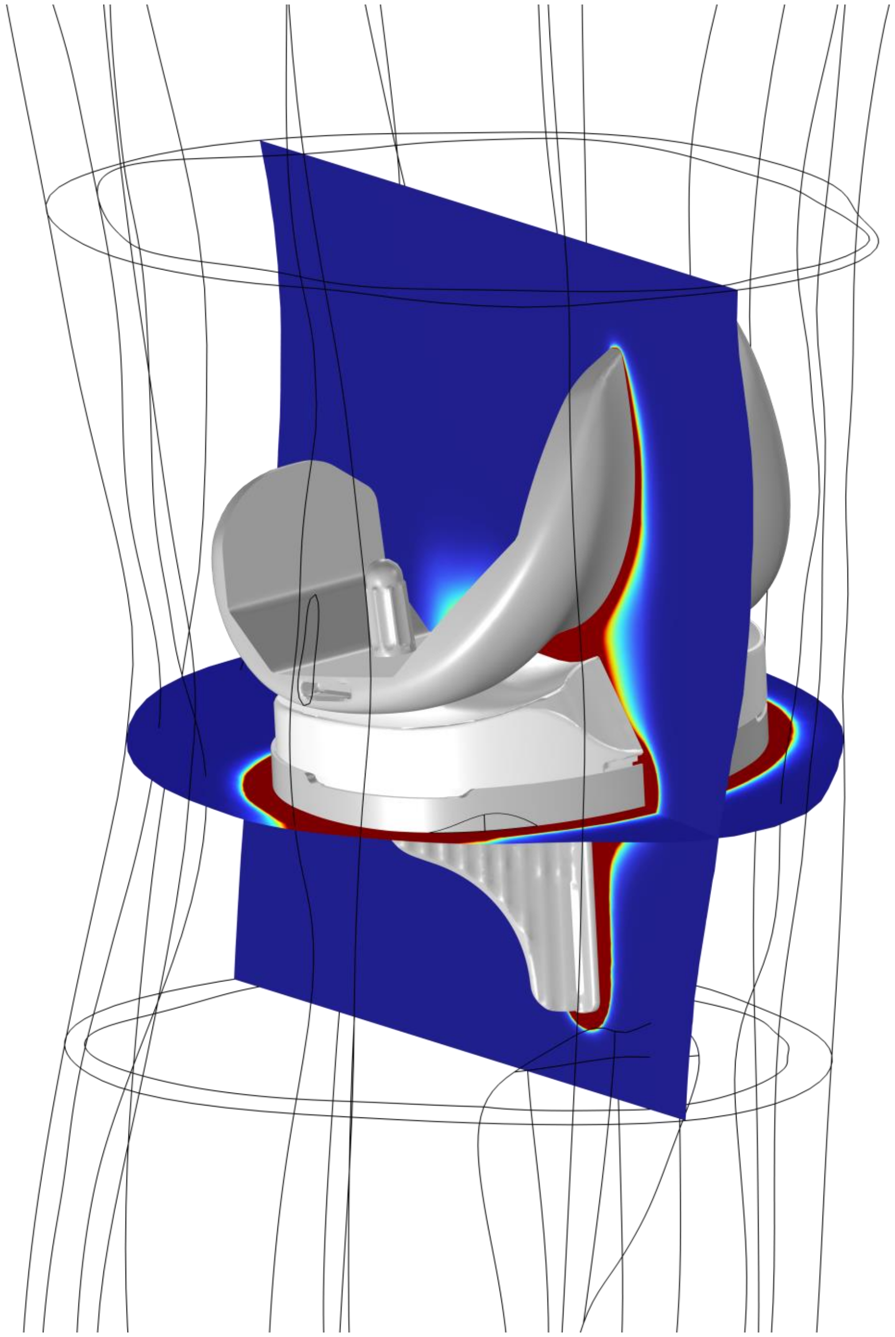
Electromagnetic Heating Simulation of Medical Treatment for Infections After Knee Replacement Surgery

Josh Thomas, Luke Gritter, and Kyle Koppenhoefer
from AltaSim Technologies

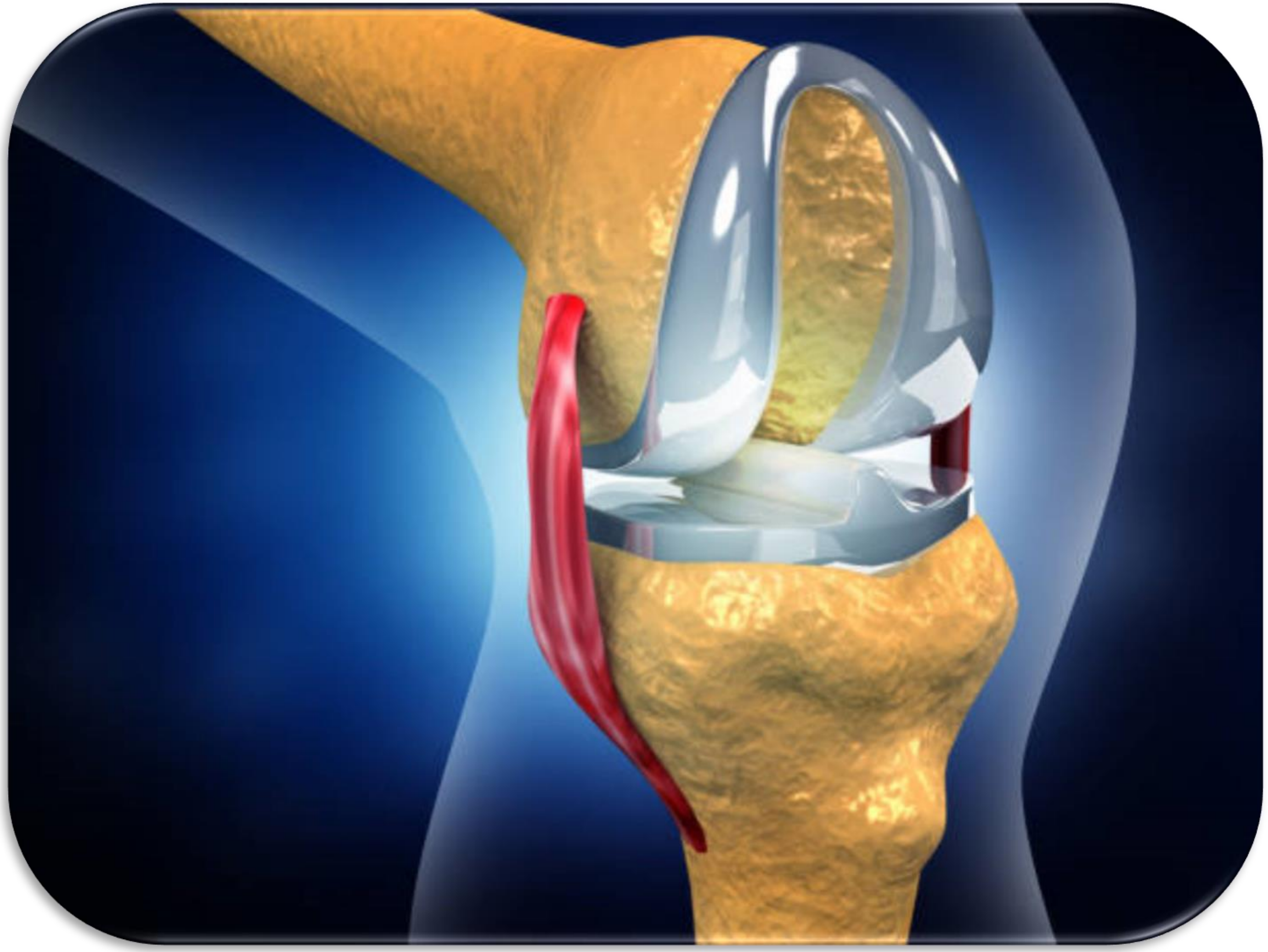
Bibin Prasad, John Tepper, and Rajiv Chopra
from Solenic Medical



Introduction

Project Challenge

Develop a device to therapeutically treat knee replacements



Project Situation

- Start-up medical device company
- Identified significant medical issue
- Needed
  - Successful first physical prototyping
  - FDA approval of design
- Customer lacked internal simulation capabilities

PROJECT GOALS:

1. Rapidly show proof of concept
2. Model to support FDA approval of the device

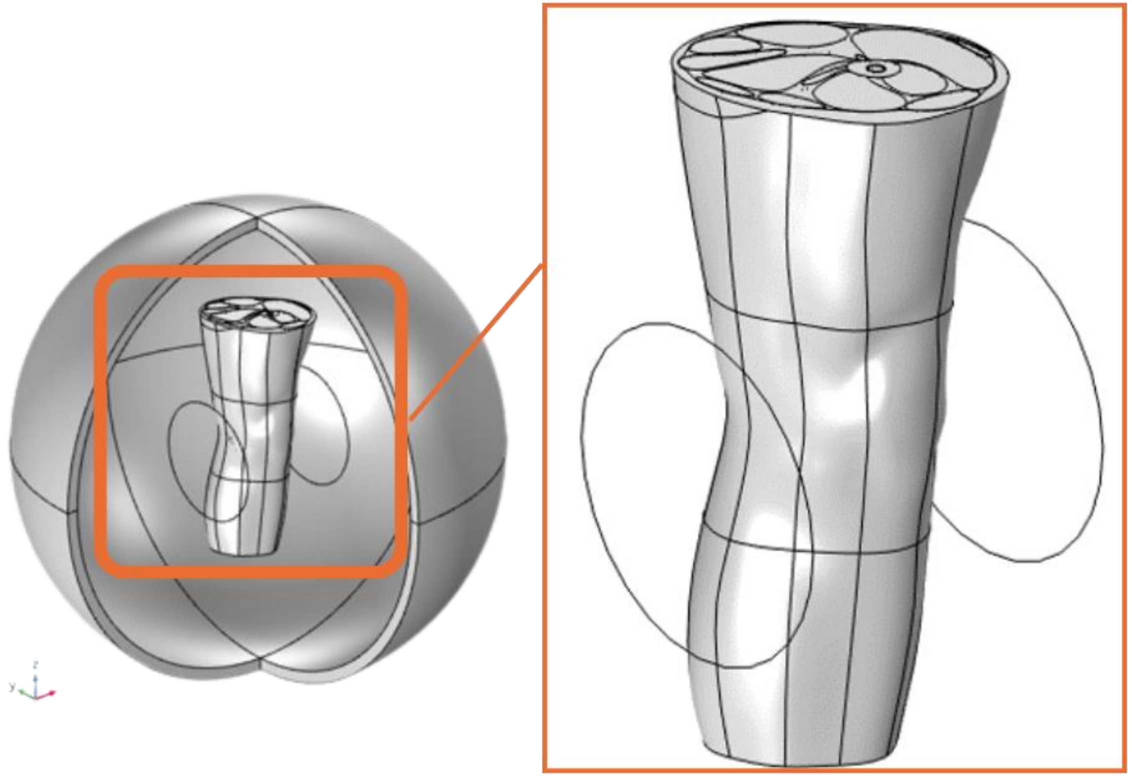
Methods and use of COMSOL Multiphysics®

Model Summary

- Current in a Helmholtz coil excites heating of implant metal
- Temperatures near metal implants provide therapeutic benefit
- Quantification of damage in tissue is critical for FDA

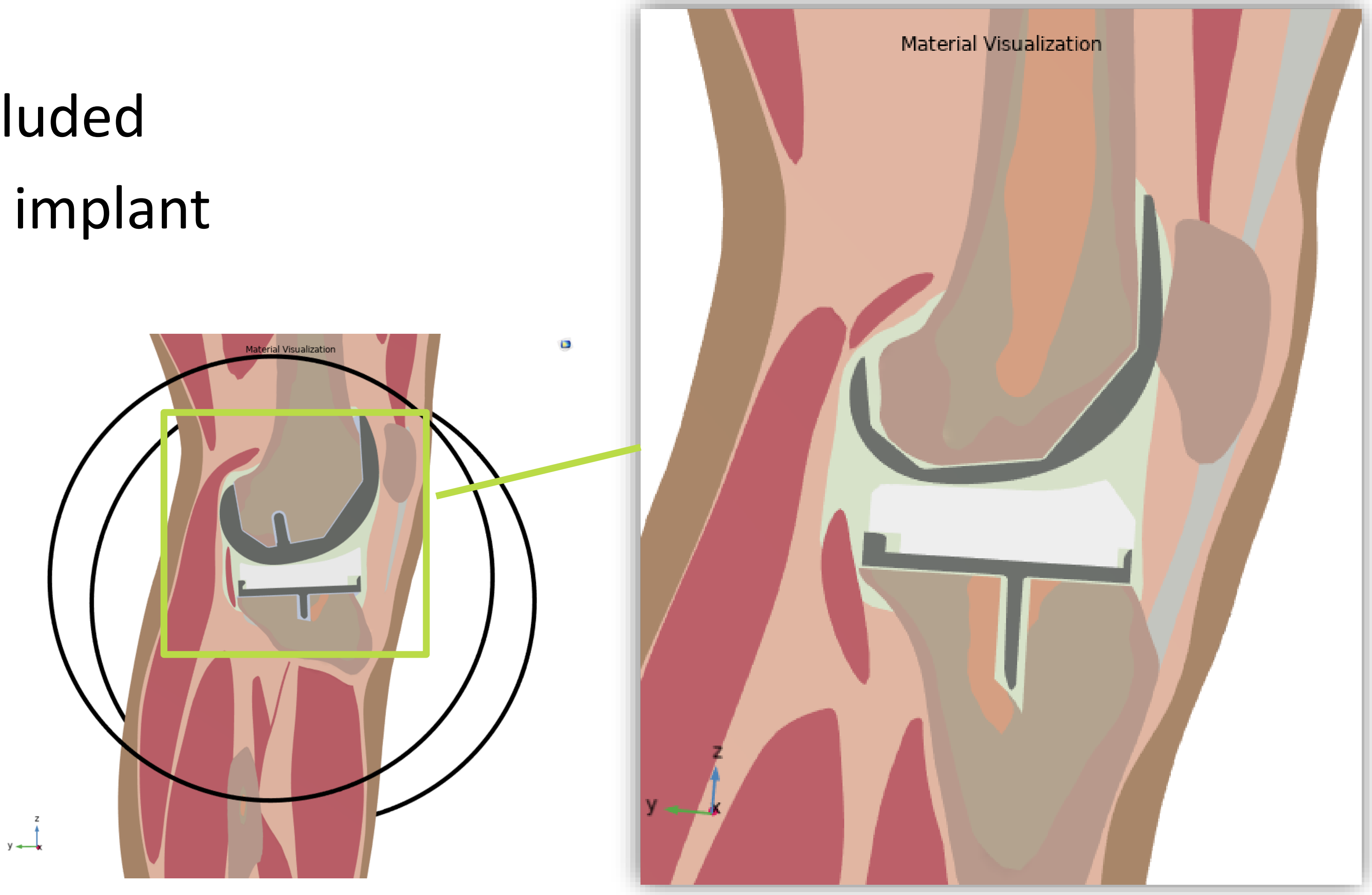
Geometry

- Magnetic fields physics included in all regions including spherical air space around knee
- Helmholtz coils on either side of knee
- Surgically replaced knee joint and surrounding tissue from mid-calf to mid-thigh



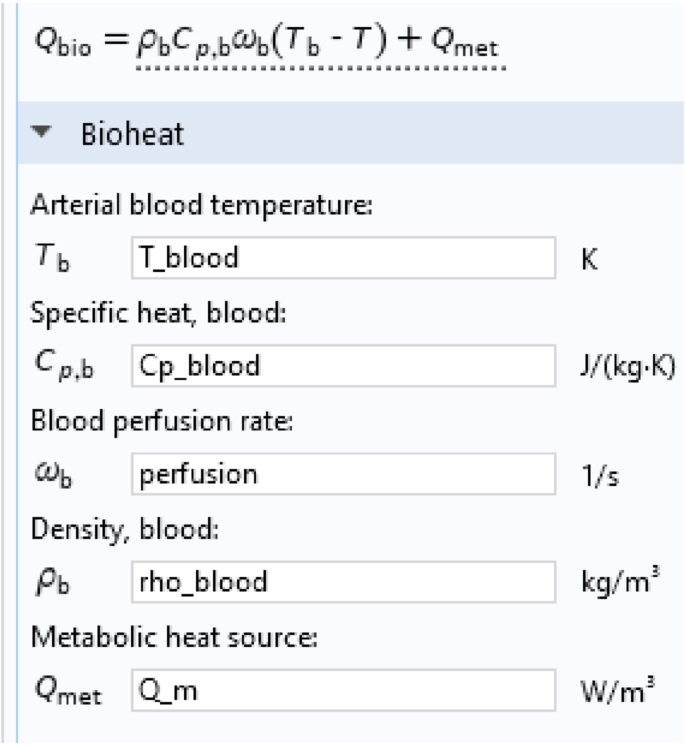
Detailed Anatomical Model

- Individual tissues included
- Femoral, tibial metal implant
- Plastic insert



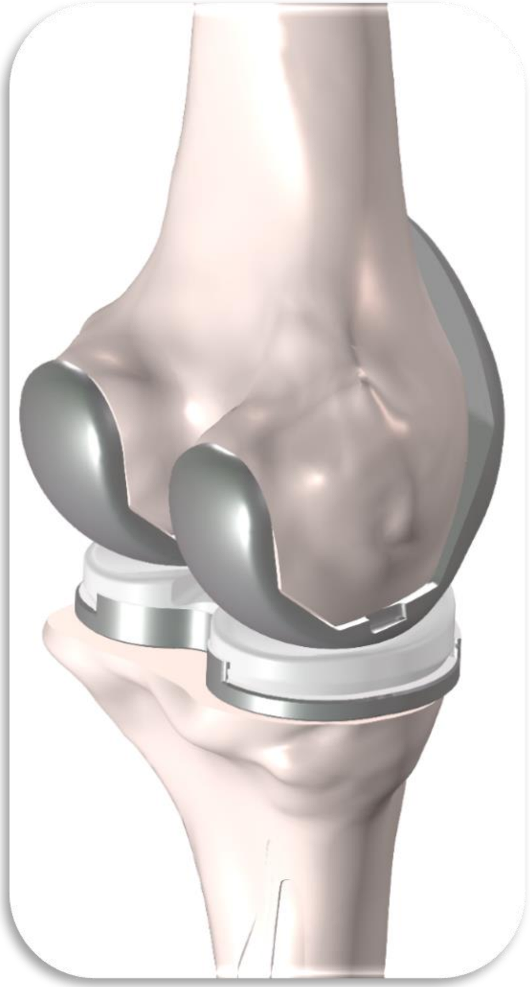
Bioheat Physics Included

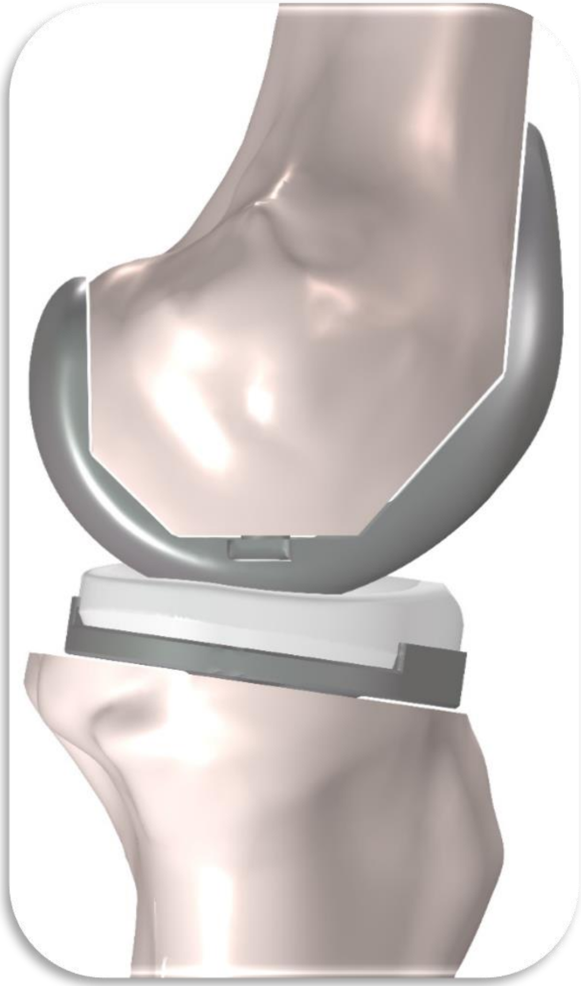
- Blood perfusion rate and Metabolic heat source specific to tissue type



Specific to tissue type from the literature

Cement Geometry





- No CAD for cement regions that provide a permanent surgical connection between metal and bone
- Custom PDE implementation to calculate the extent of cement gap fill between metal and bone

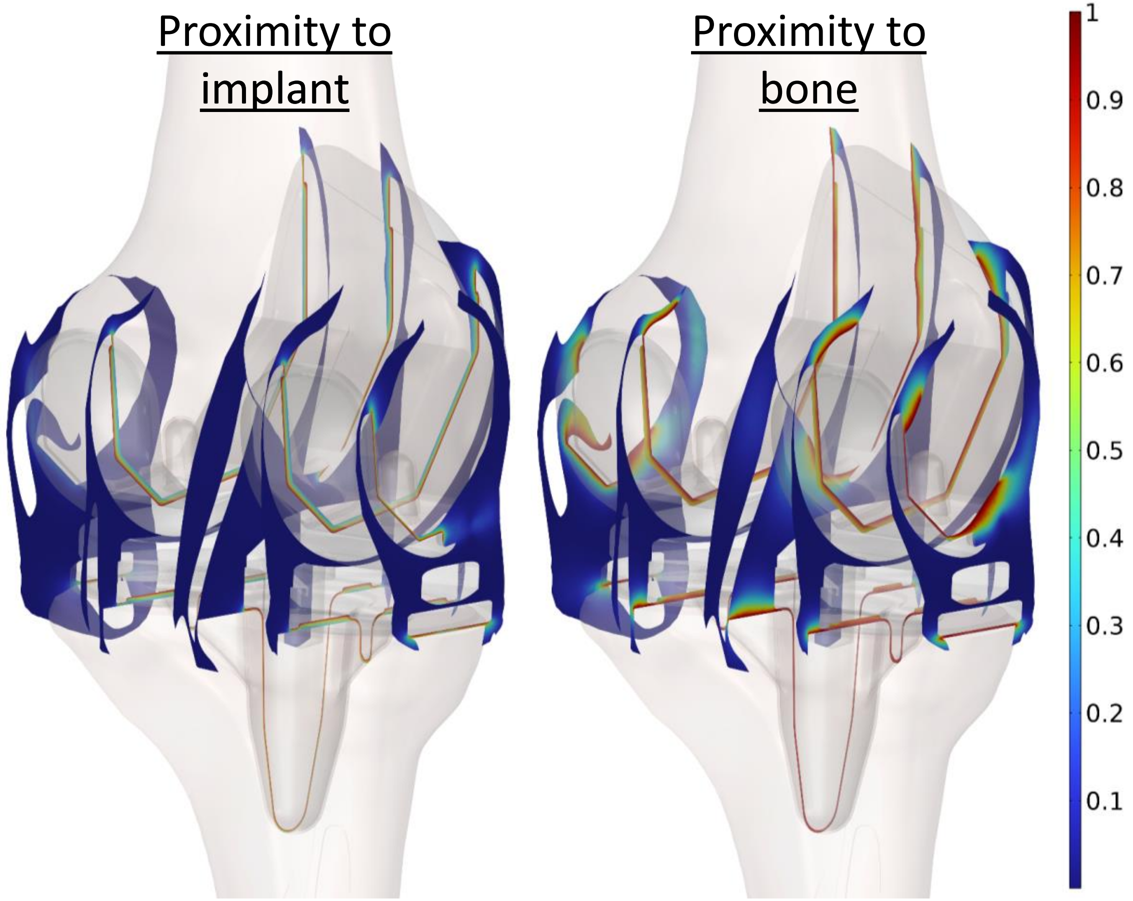
Used two reaction-diffusion equations to calculate proximity

- PDEs for proximity variables p1 and p2:

$$\nabla \cdot [-(C_1 \cdot h)^2 p_1] = -p_1$$

$$\nabla \cdot [-(C_2 \cdot h)^2 p_2] = -p_2$$

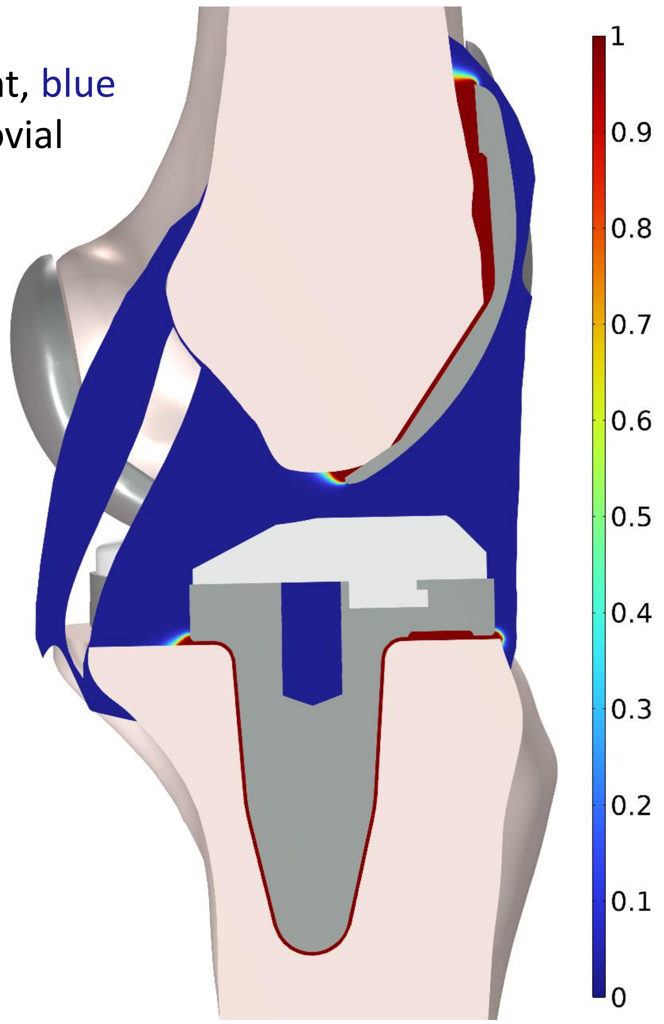
- C_1 and C_2 are smoothing factors on order of 1; h is local element size
- Proximity variables are set to 1 on boundaries that contact cement



Calculated material properties from proximity variables

- Boolean variable is function of product of proximity variables:
  - Variable definition: $\varphi = \mathrm{flc1hs}(10^{p_1 p_2} - 1.16\,, 0.15)$
  - Smooth transition from cement (φ = 1) to synovial fluid (φ = 0)
  - Expression is arbitrary and visually tuned
- Material properties smoothly transition between cement and synovial fluid: $k = k_{fluid} + \left(k_{cement} - k_{fluid}\right)\varphi$

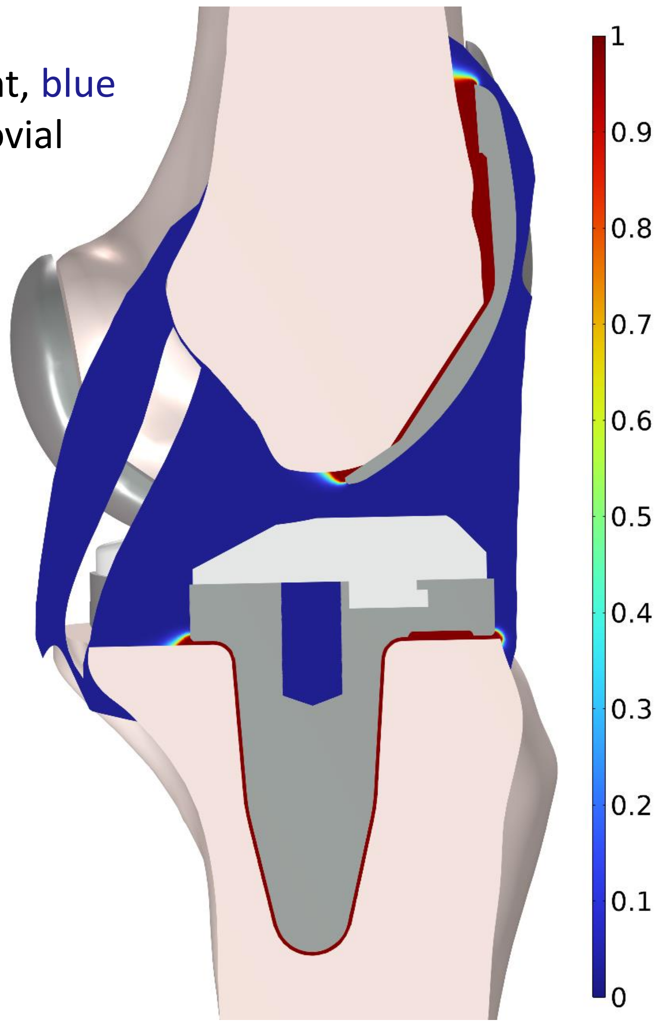
Red is cement, blue is synovial fluid



Calculated material properties from proximity variables

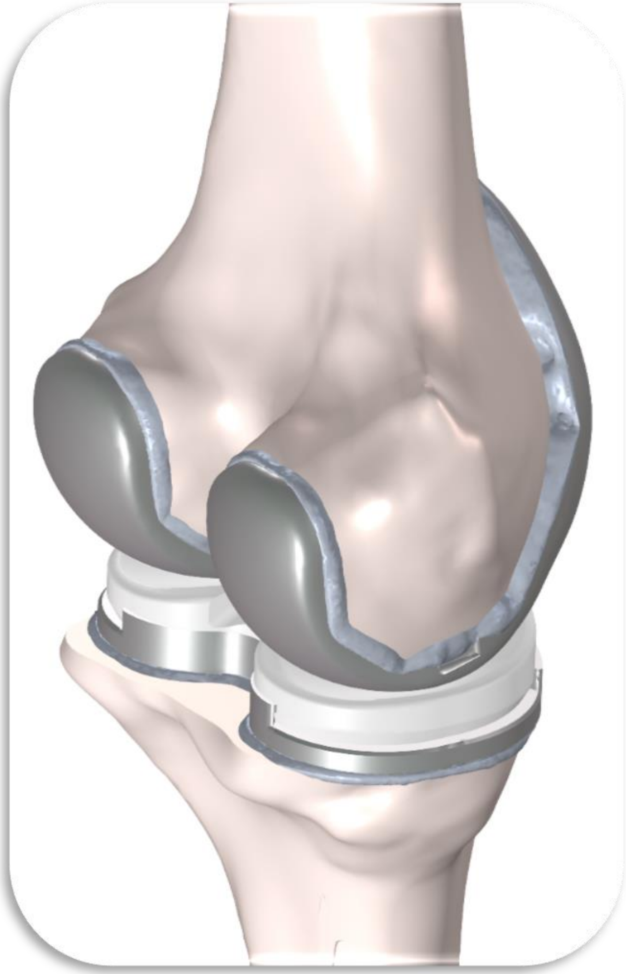
- Boolean variable is function of product of proximity variables:
  - Variable definition: $\varphi = \mathrm{flc1hs}(10^{p_1 p_2} - 1.16\,, 0.15)$
  - Smooth transition from cement (φ = 1) to synovial fluid (φ = 0)
  - Expression is arbitrary and visually tuned
- Material properties smoothly transition between cement and synovial fluid: $k = k_{fluid} + (k_{cement} - k_{fluid})\varphi$

Red is cement, blue is synovial fluid



Approach Produces Cement Distribution

- Cement fills all gaps between bone and implant
- Overfill at edges is relatively small
- Gives good approximation to expected cement distribution from "spread, press, wipe" process used by surgeons



Multiphysics Analysis

Magnetic Fields

$$\nabla \times \mathbf{H} = \mathbf{J}$$
$$\mathbf{B} = \nabla \times \mathbf{A}$$
$$\mathbf{J} = \sigma \mathbf{E} + \mathbf{J}_e$$

Heat Transfer

$$\rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q + Q_{ted}$$
$$\mathbf{q} = -k \nabla T$$

$$Q_{bio} = \rho_b C_{p,b} \omega_b (T_b - T) + Q_{met}$$

- Magnetic fields interact with metal implants causing heating
- Frequency domain solution simulates heat source
- Transient temperature rise simulated via energy equation with metabolic heating and perfusion cooling effect

Thermal Boundary Conditions

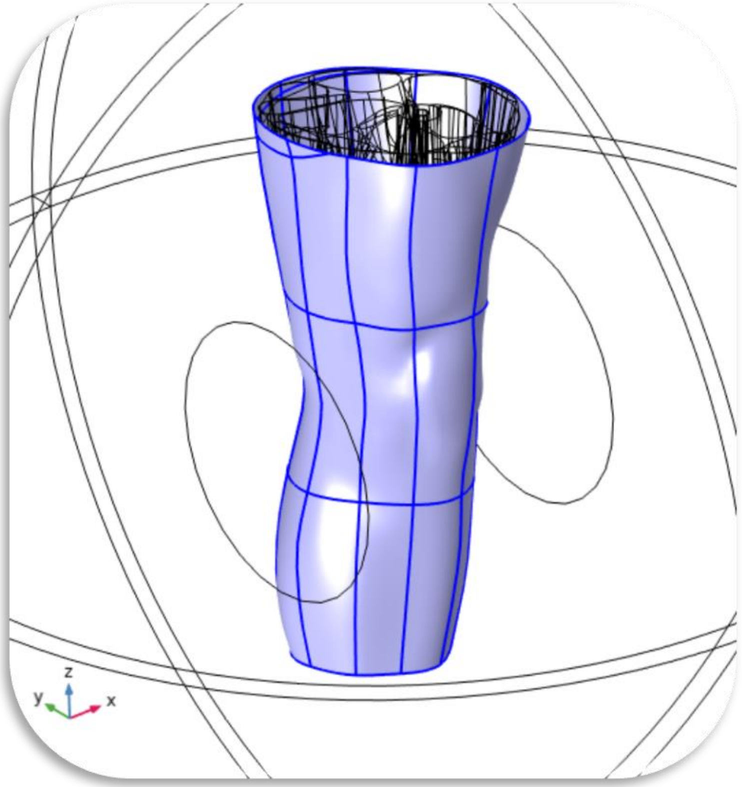
Convective heat flux on outside of skin

$$-\mathbf{n}\cdot\mathbf{q} = q_0$$

$$q_0 = h(T_{ext} - T)$$

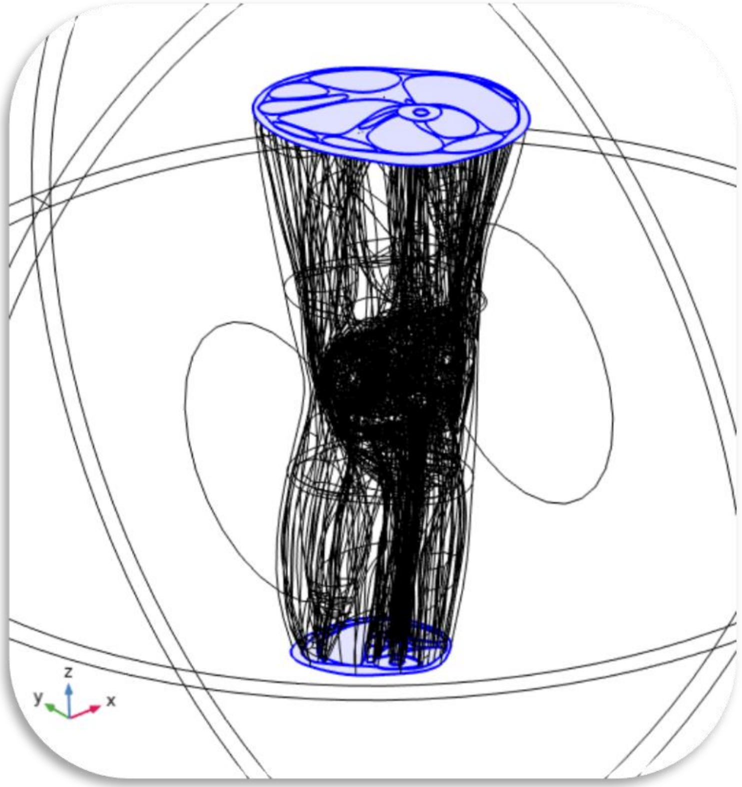
h = 5 W/m²/K

T_{ext} = 30°C

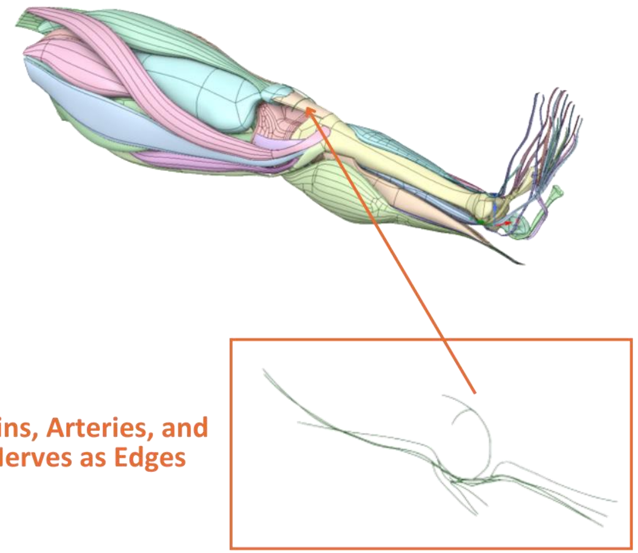


Body temperature assumed at ends where the model is truncated

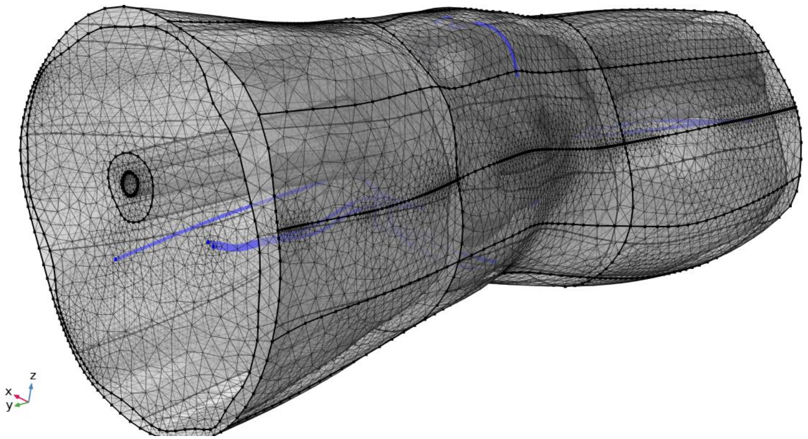
T_{body} = 37°C



Arteries, Nerves, and Veins Added as 1D Edges



Veins, Arteries, and Nerves as Edges



$$\int_{S(R)} Q\,ds = A_l Q_l - \nabla_t \cdot A_l \mathbf{q}_l$$

$$\mathbf{q}_l = -k_l \nabla_t T$$

$$A_l = \pi r_l^2$$

$$\lim_{\partial s \to 0} \int_{\partial s} Q\,ds = A_l Q_l - \nabla_t \cdot A_l \mathbf{q}_l$$

Line Heat Source

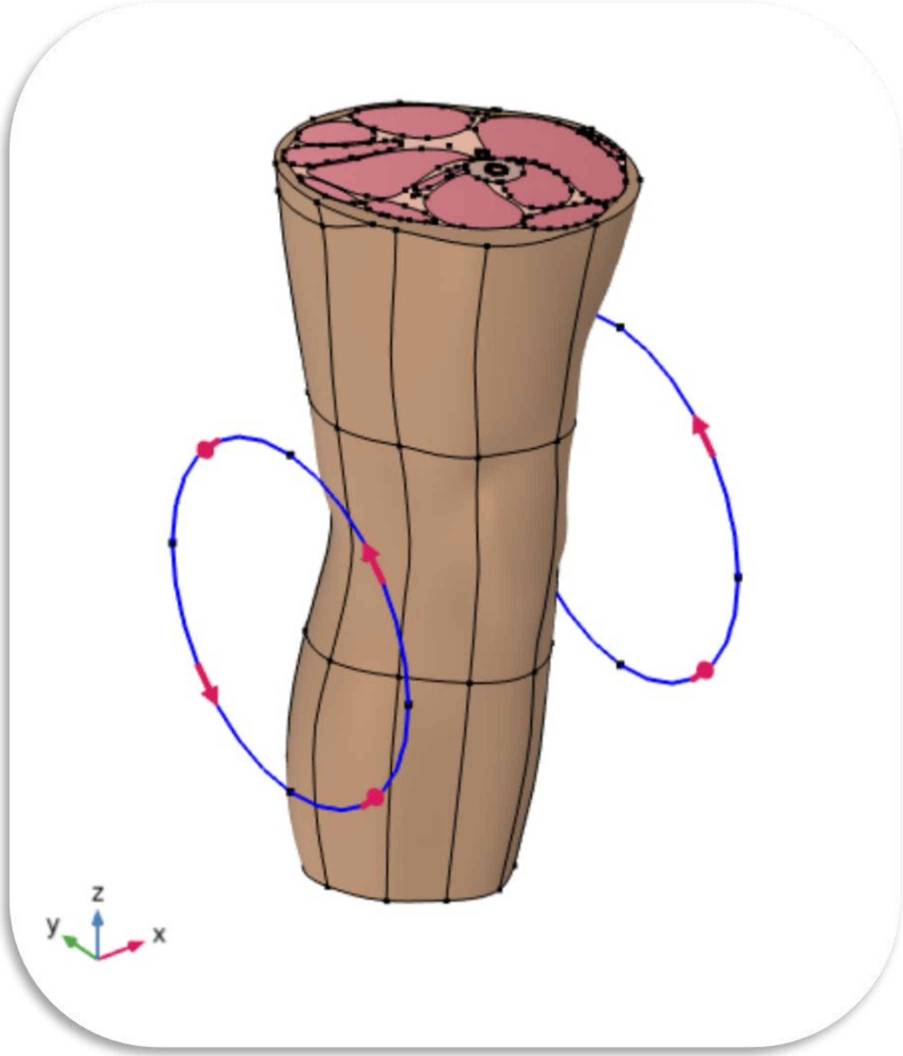
Heat source:

General source

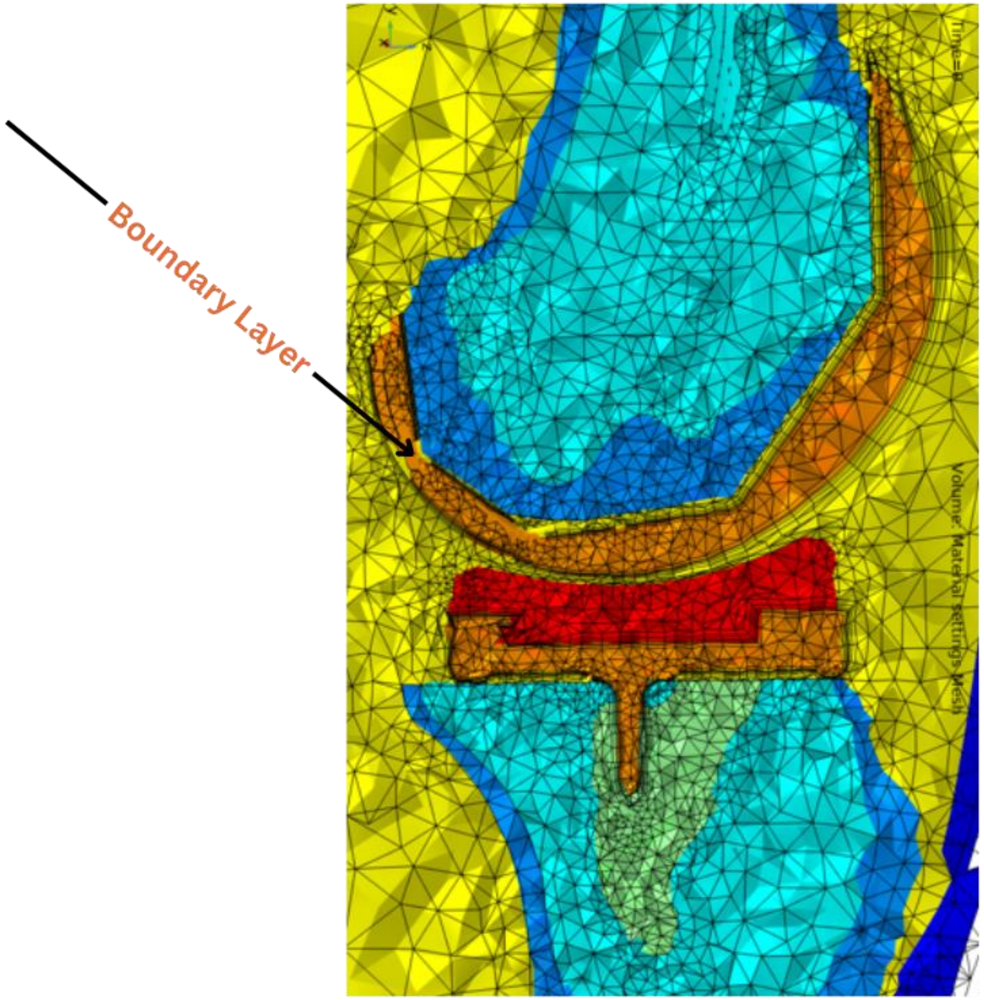
Q_l rho_blood*Cp_blood*perfusion*(T_blood-T)+Q_m_edge W/m³

Physical Loading on System

- Helmholtz coil
- Applied current at a specified frequency



Meshing



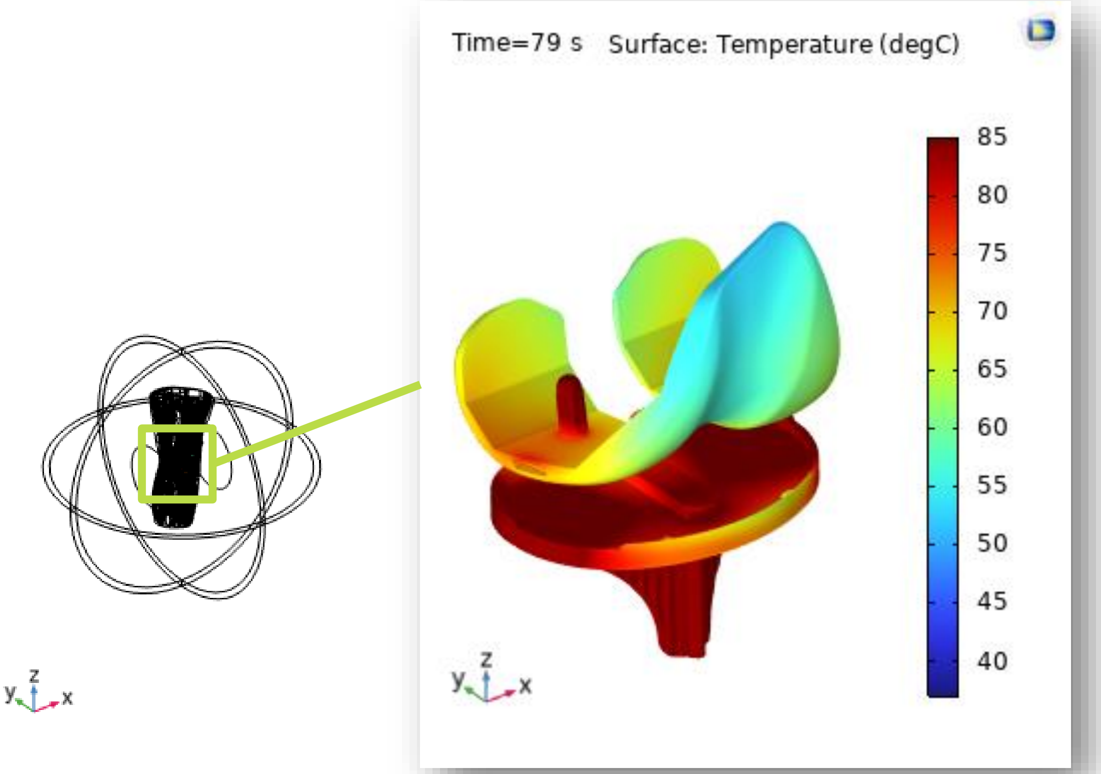
Colors Represent Different Material Regions

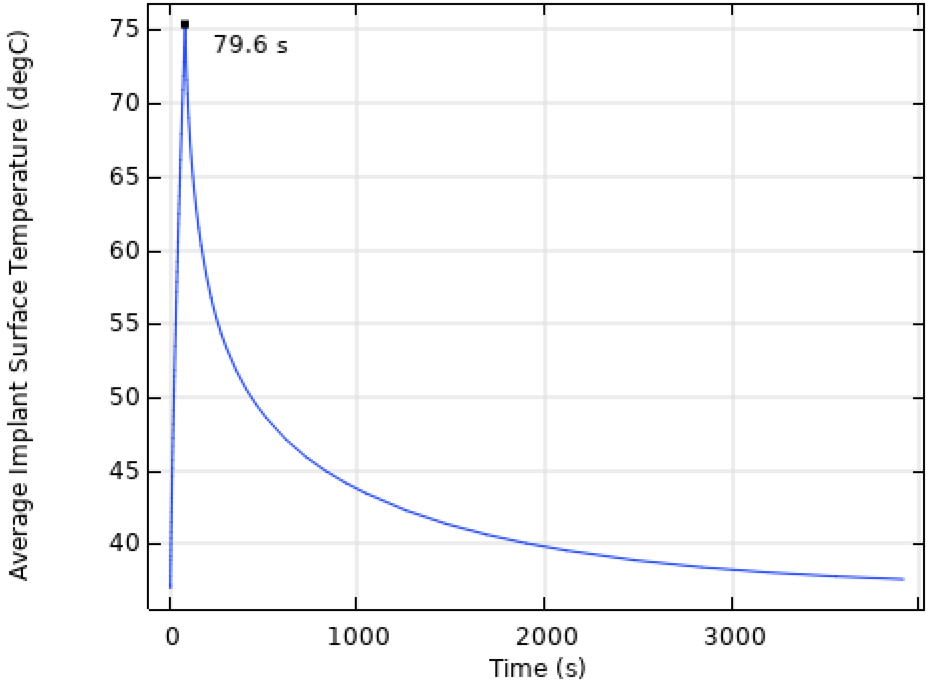
- Free tetrahedral baseline mesh
- Boundary layer mesh added to efficiently discretize field gradients near the implant

Results

Thermal Results

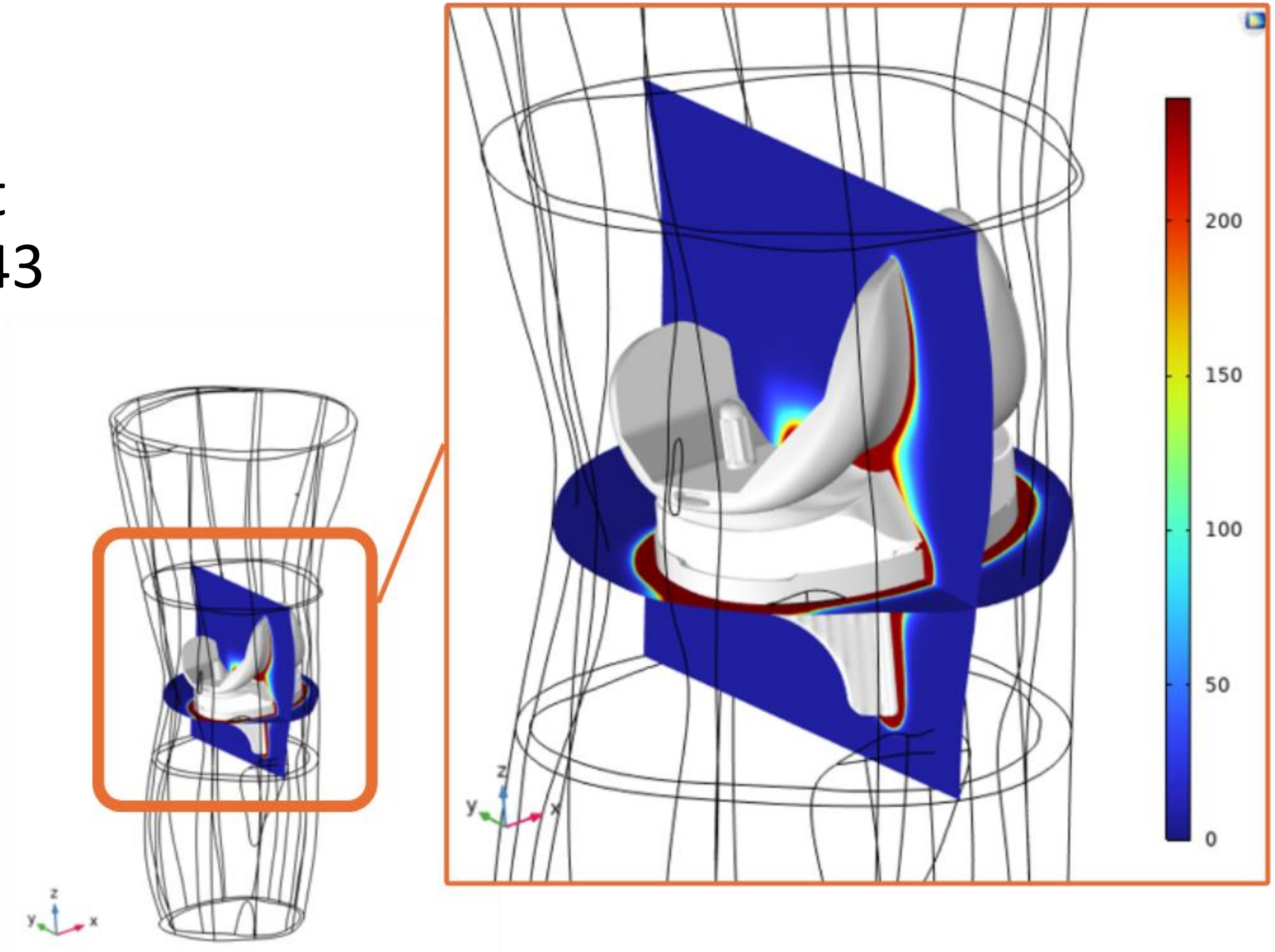
- Heating occurs for 79.6 seconds then cool down for the remainder of the hour





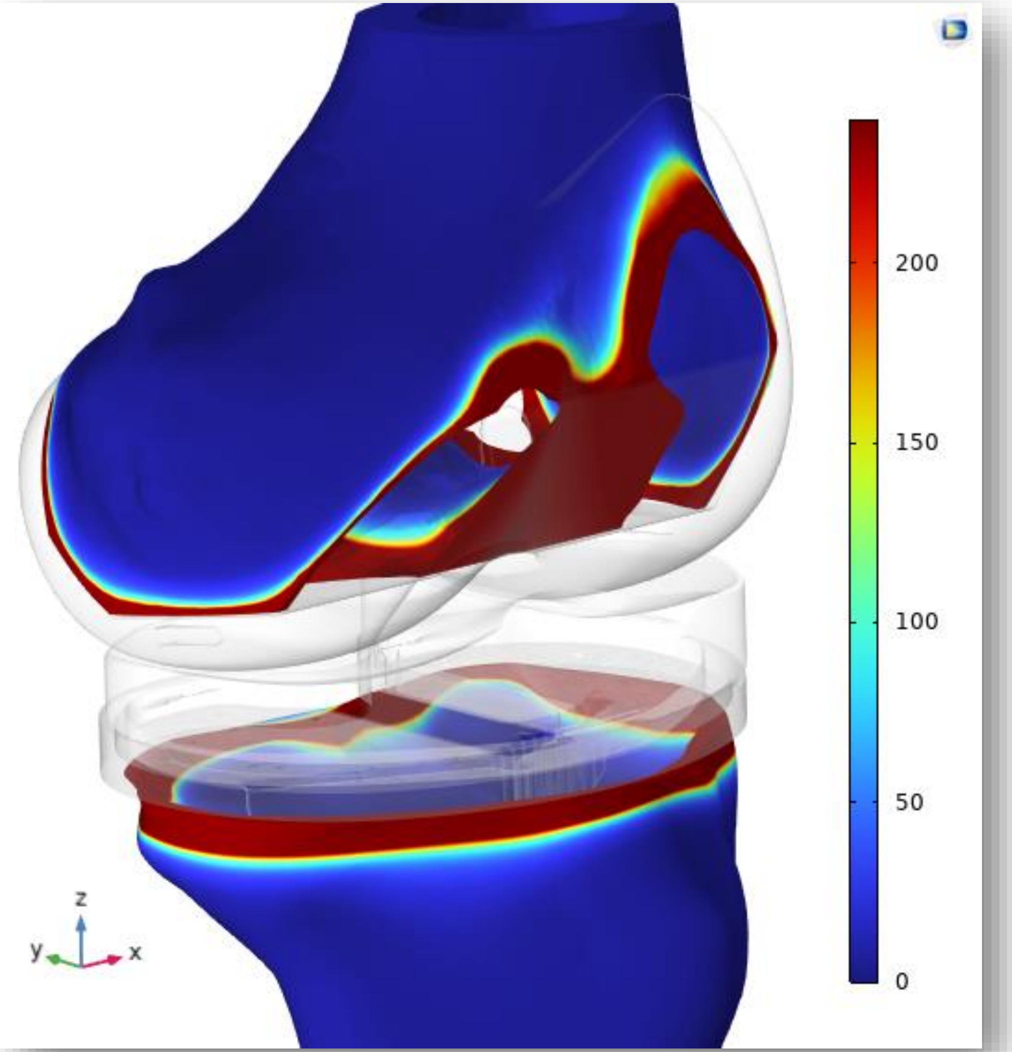
Damage Results

- Cumulative Equivalent Minutes at 43°C, CEM43
- Tissue damage after treatment



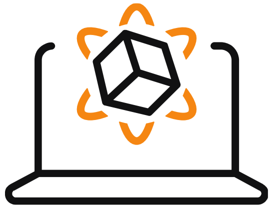
Cortical Bone Damage

- Damage to the femur and tibia cortical bone



Conclusions

AltaSim Technologies' Solution



- Became simulation team for customer
- Developed simulations that produced workable design
- Provided simulations to customer and trained internal engineers to develop additional simulations

Customer – Private equity / device under FDA review

Simulation Consulting

Simulation Apps

ALTASIM TECHNOLOGIES
REALIZING TOMORROW'S TECHNOLOGY

How We Work

We meet you where you are

Training

Coaching

ALTASIM TECHNOLOGIES
REALIZING TOMORROW'S TECHNOLOGY

To get in touch call us at (614) 861-7015 or email at info@altasimtechnologies.com or visit https://altasimtechnologies.com/ to learn more.

Connect with Us!