Ice Ice Baby: Determining Optimum Cooling Parameters for Neonatal Asphyxia Hypothermia Therapy

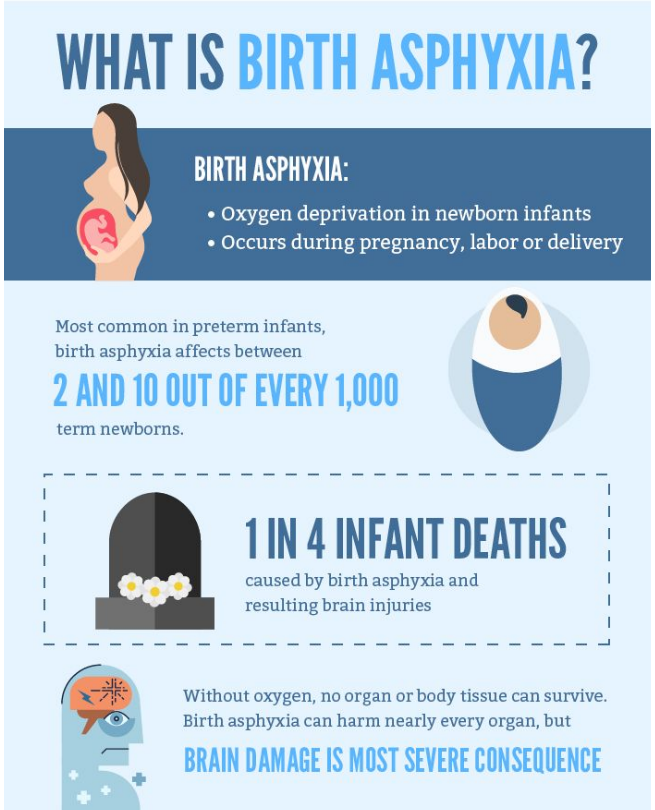
Daniel Wieczorek
Capstone Advisor: Dr. Melissa Wrobel

ENGINEERING
HONORS PROGRAM
UNIVERSITY OF MICHIGAN

NAP
Neonatal Asphyxia Project

Physiology behind Neonatal Asphyxia

- The issue: Neonatal Asphyxia is a leading cause of neonatal death in India
- The reason: Inadequate oxygenation during or shortly after birth
- The symptoms: Seizures, pale skin, ↓ heart and respiratory rates, shock
- The treatment: Hypothermia therapy



WHAT IS BIRTH ASPHYXIA?

BIRTH ASPHYXIA:

- Oxygen deprivation in newborn infants
- Occurs during pregnancy, labor or delivery

Most common in preterm infants, birth asphyxia affects between

2 AND 10 OUT OF EVERY 1,000

term newborns.

1 IN 4 INFANT DEATHS

caused by birth asphyxia and resulting brain injuries

Without oxygen, no organ or body tissue can survive. Birth asphyxia can harm nearly every organ, but

BRAIN DAMAGE IS MOST SEVERE CONSEQUENCE

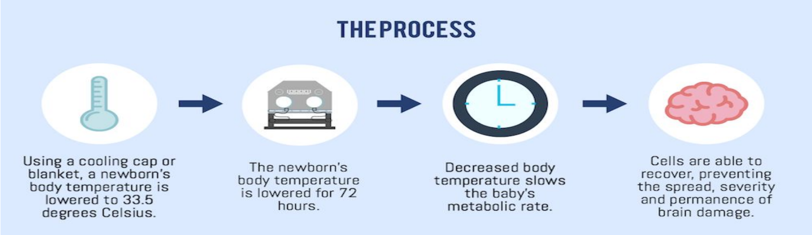
NAP's Problem & Need Statements

- Problem statement: Approximately 3.6 million neonates around the world are affected by asphyxia annually. In India, neonatal asphyxia is responsible for 25% of newborn deaths.
- Need statement: There is a need for a device to effectively mitigate the brain injury caused by neonatal asphyxia in low-resource communities.

Cooling requirements

- Must cool neonate to 33-34℃ (306-307 K)
- Takes 60-120 minutes to cool the patient
- Must keep the neonate’s body temperature steady at 33-34 ℃ for 72 hours unless manually adjusted

HASYA
newborn care centre
Step to Care



THE PROCESS

Using a cooling cap or blanket, a newborn’s body temperature is lowered to 33.5 degrees Celsius.

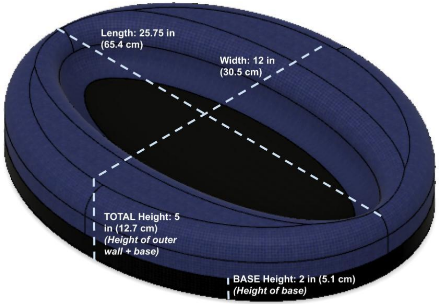
The newborn’s body temperature is lowered for 72 hours.

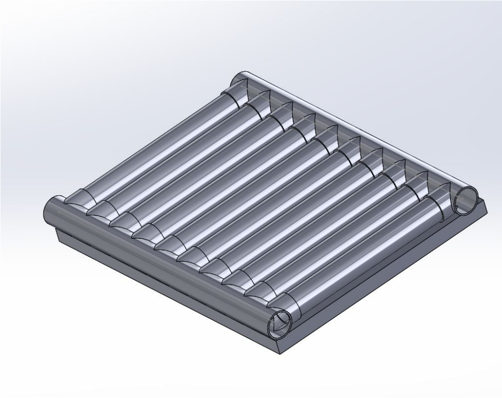
Decreased body temperature slows the baby’s metabolic rate.

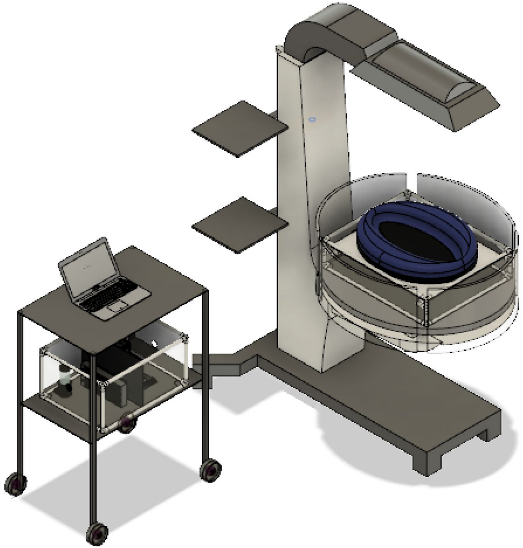
Cells are able to recover, preventing the spread, severity and permanence of brain damage.

Yellow shading indicates requirements addressed in this capstone project

One of NAP’s Current Solutions





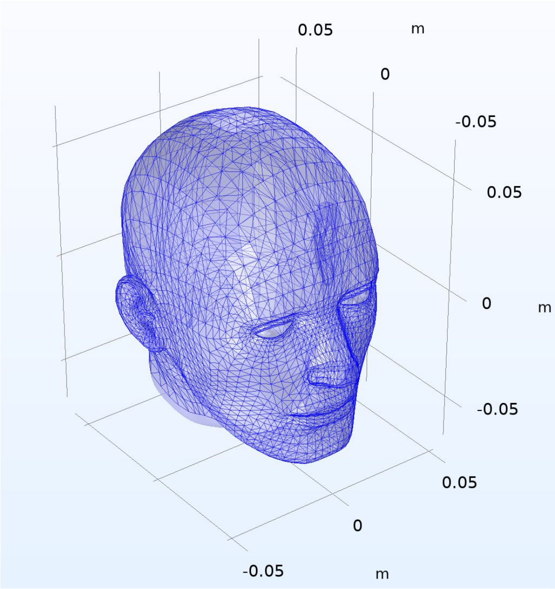


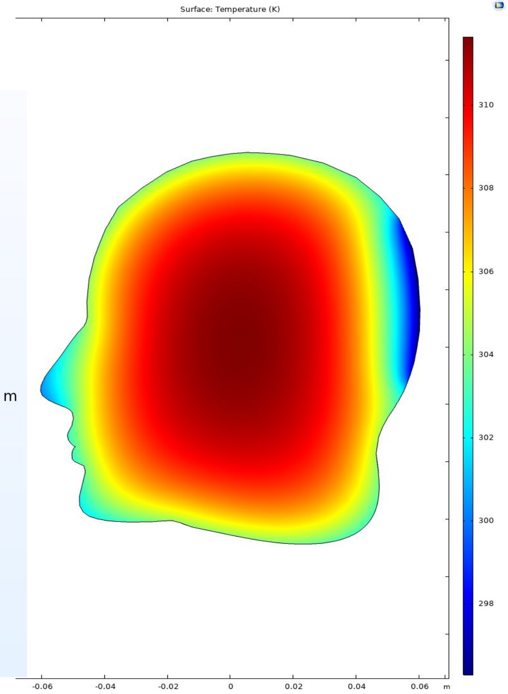
Goals of this capstone project

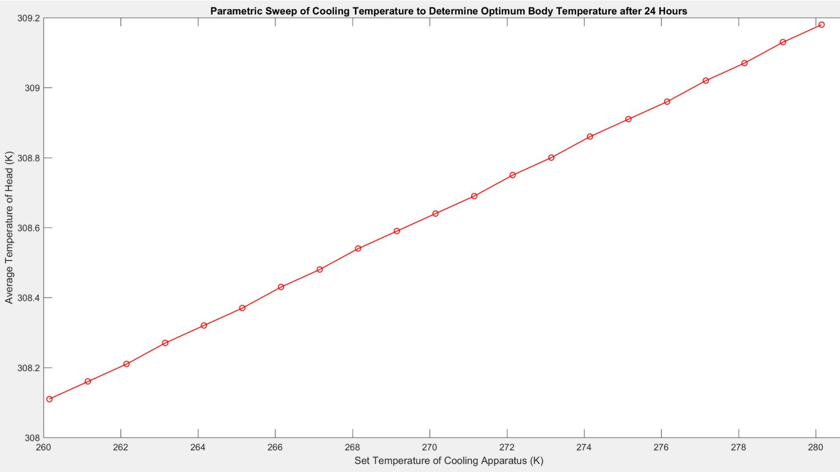
1. Develop detailed model of neonate and tube bed prototype assembly
    - Model heat flow and temperature throughout infant’s head
    - Model fluid flow throughout the tube bed apparatus
    - Couple heat flow and fluid flow

2. Optimize cooling parameters
    - Temperature applied to neonate for cooling
    - Radius of tubes in prototype assembly
    - Velocity of water flowing through tubes in prototype assembly

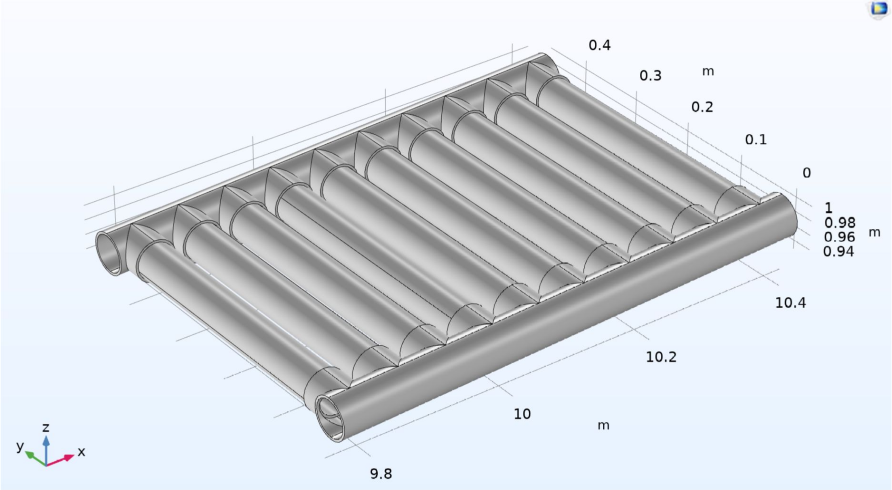
Individual heat flow simulation reveals 306-307K cannot be reached

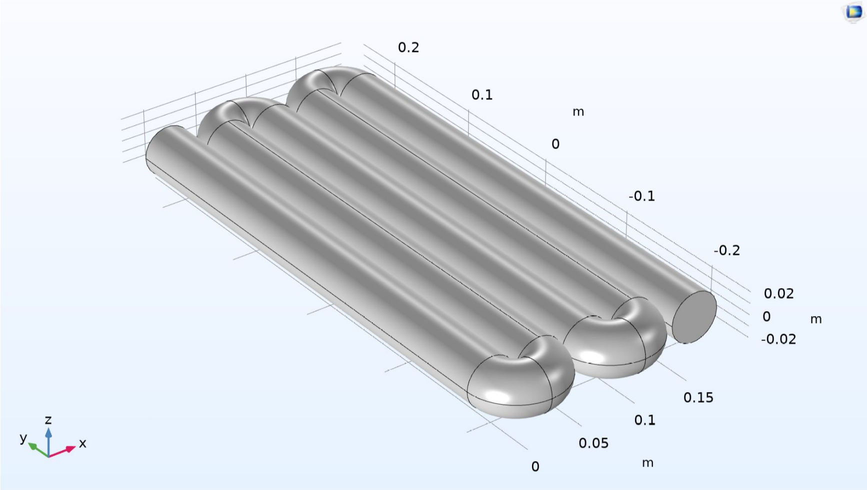




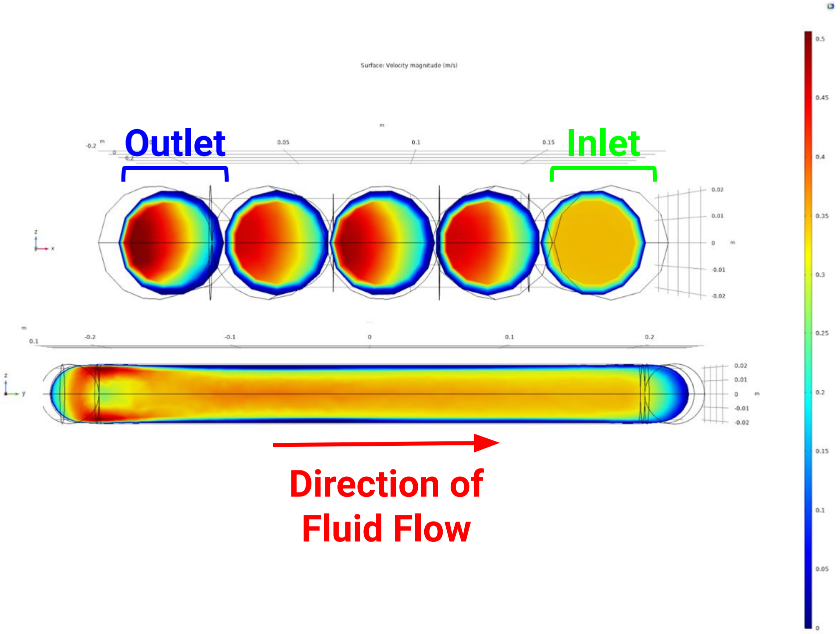


Early attempts of fluid flow simulations led to simplification of model

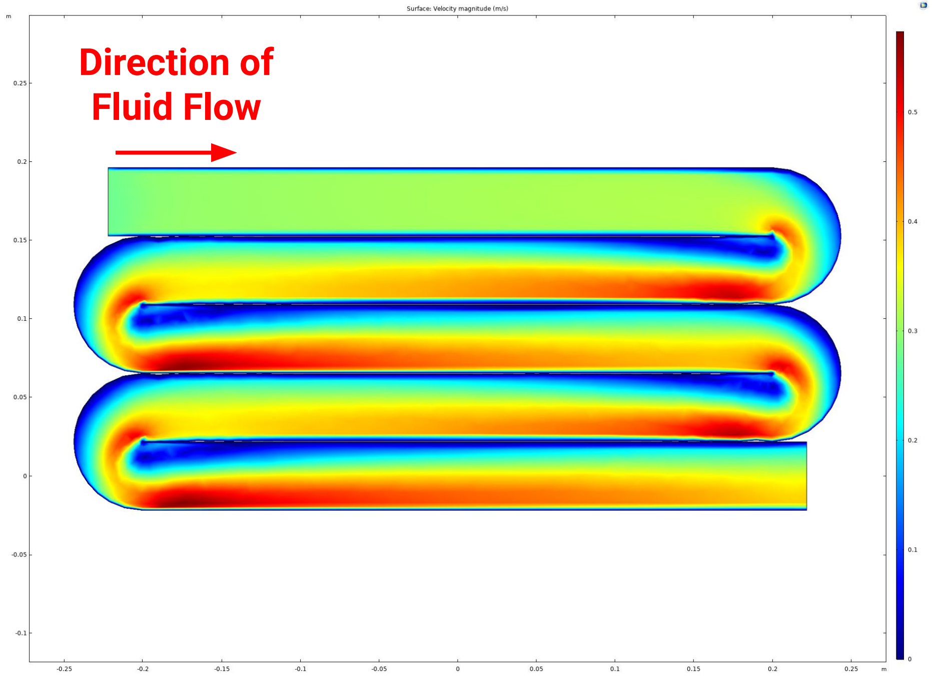




Fluid flow simulations reveal stagnation points around curves of tube bed

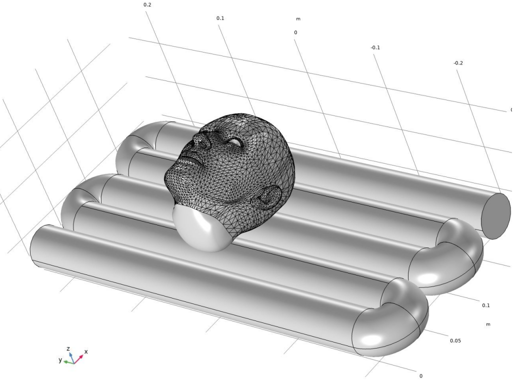


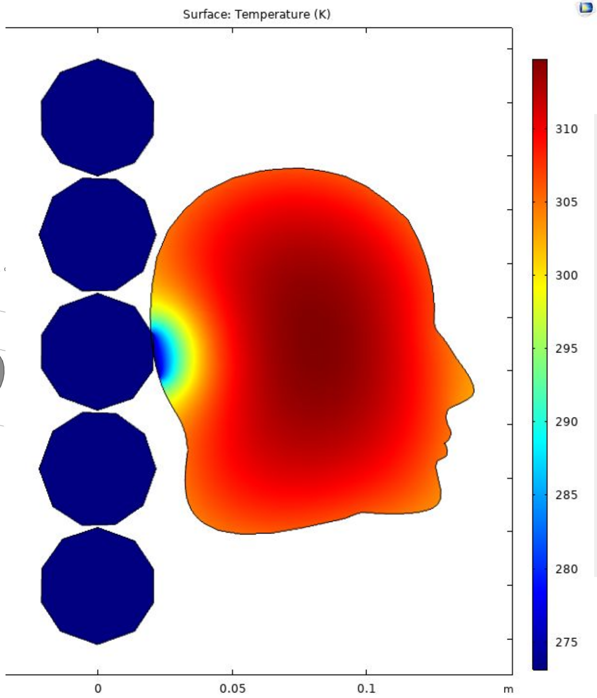
Direction of Fluid Flow

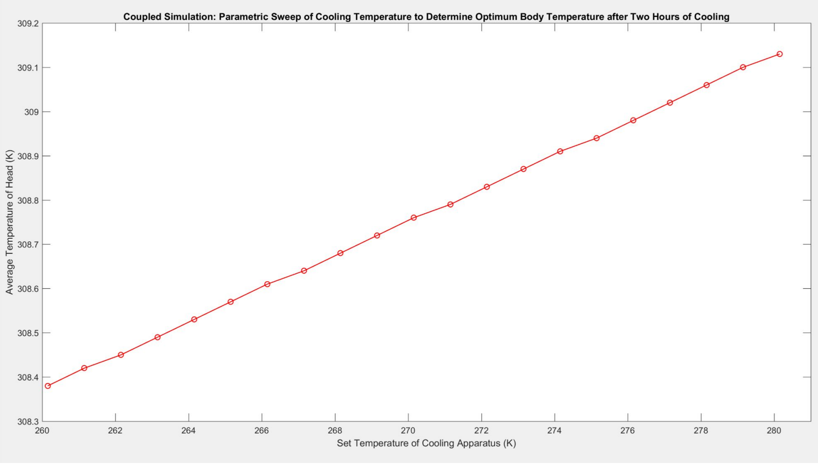


Direction of Fluid Flow

Coupled heat and fluid flow simulation also reveals 306–307 K cannot be reached

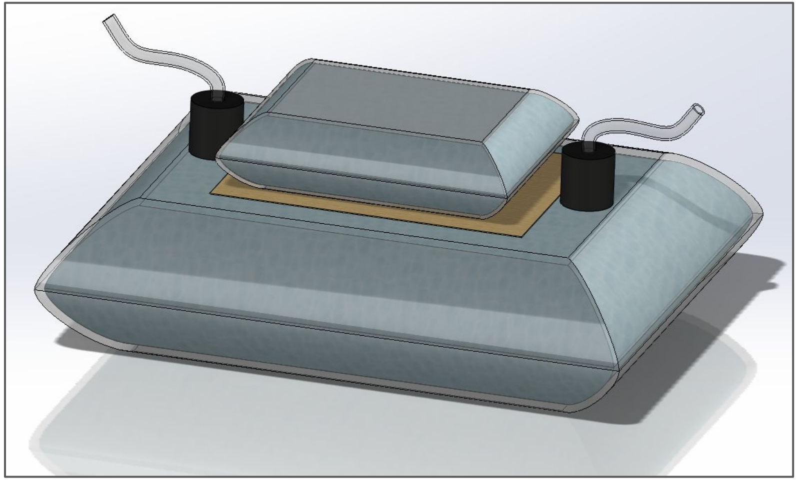






Summary of takeaways, limitations, and next steps

- Takeaways: Tube bed cannot reach required cooling temperature based on this model
- Limitations of this model: Simplified assessment of body temperature, metabolic settings, and isothermal fluid flow
- Next steps: Use model to assess NAP's other prototype



NAP's other prototype: Waterbed

Acknowledgements

Special thank you to Dr. Wrobel, the Neonatal Asphyxia design team, and the Engineering Honors Program for supporting me in the completion of this capstone project

The End

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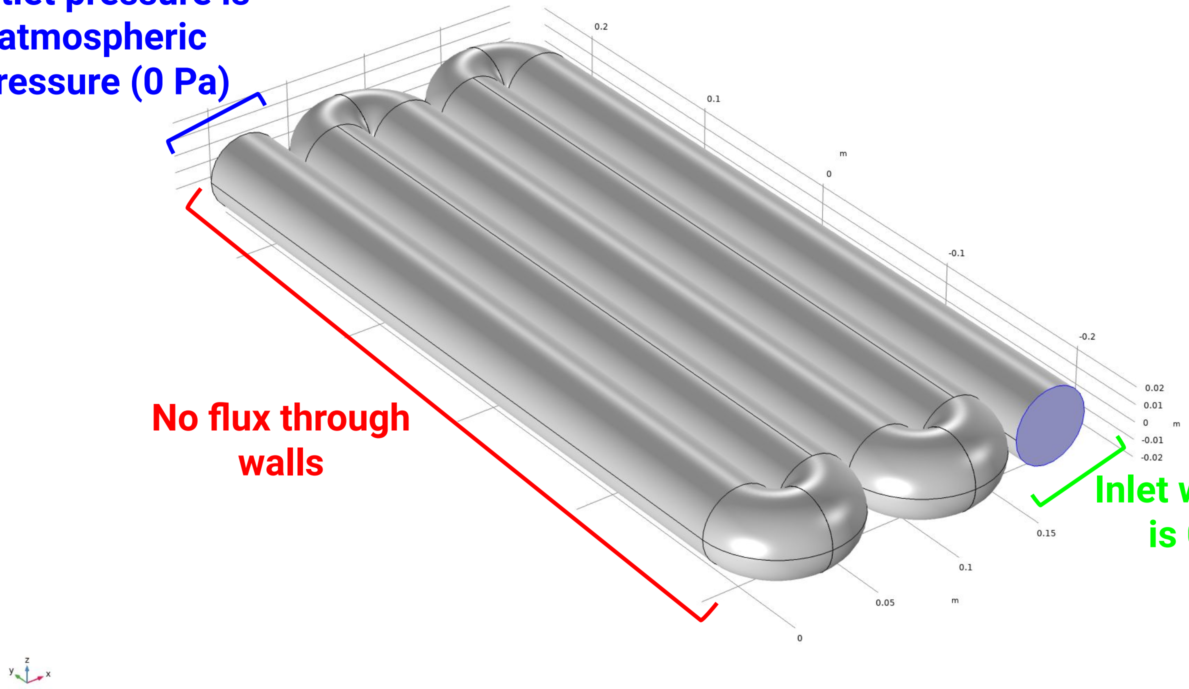
Pocket Slides

Fluid Flow Boundary and Initial Conditions



Outlet pressure is atmospheric pressure (0 Pa)

No flux through walls

Inlet water velocity is 0.278 m/s

Equations and assumptions used in fluid flow simulation

$$Re = \frac{\rho v R}{\mu} = 606$$

$$\left.\begin{array}{l} \rho = \textit{Density of water} = 1000\ (kg \cdot m^{-3}) \\ v = \textit{Maximum water velocity} = 0.278\ (m \cdot s^{-1}) \\ R = \textit{Radius of tubing} = 2.1825\ cm \\ \mu = \textit{Dynamic viscosity of water} = 0.001\ (Pa \cdot s) \end{array}\right\}$$

Used laminar flow module in COMSOL

Navier-Stokes Equations for Incompressible Newtonian Fluid:

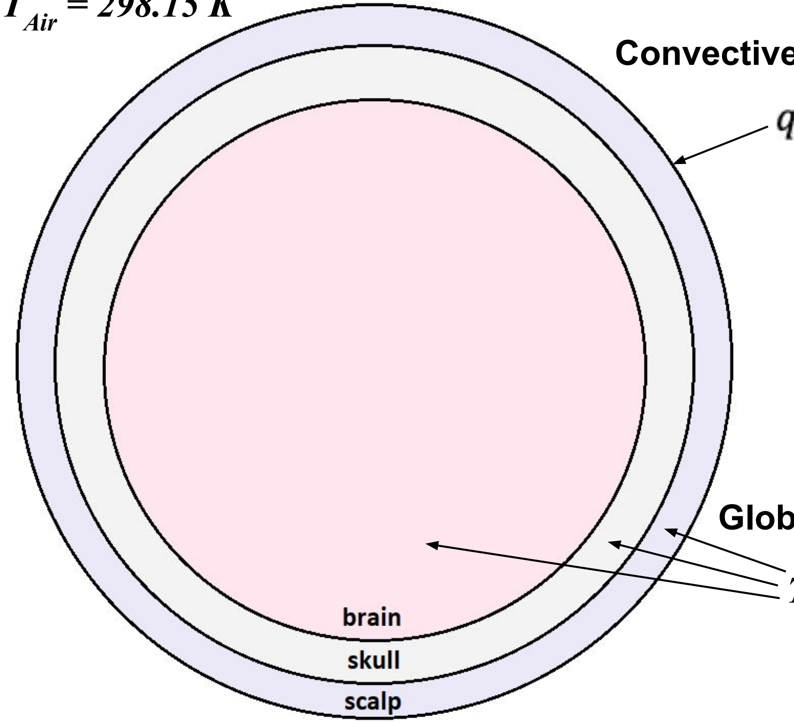
Conservation of Momentum:

$$\rho\left(\underset{\text{Time-dependent term}}{\boxed{\frac{d\vec{v}}{dt}}} + \underset{\text{Convective term}}{\boxed{\vec{v}\cdot\nabla\vec{v}}}\right) = \underset{\text{Pressure Gradient}}{\boxed{-\nabla p}} + \underset{\text{Body Forces}}{\boxed{\rho\vec{g}}} + \underset{\text{Viscous Term}}{\boxed{\mu\nabla^2\vec{v}}}$$

Conservation of Mass:

$$\underset{\text{Mass Accumulation Term}}{\boxed{\nabla\cdot\vec{v}}} = 0$$

Heat boundary and initial conditions play critical role in heat transfer simulations



$T_{Air} = 298.15\ K$

Convective Cooling Boundary Condition

$$q_0 = h(T_e - T_i)$$

$h = 20\ W \cdot m^{-2} \cdot K^{-1} =$ Heat transfer coefficient

$T_e =$ External domain temperature (K)

$T_i =$ Internal domain temperature (K)

$q_0 =$ Heat loss through boundary $(W \cdot m^{-2})$

Global Initial Condition

$T_0 = 310.15\ K$

Bioheat partial differential equation

Heat Transfer in Tissue

$$\underset{\text{Bioheat transfer}}{\boxed{\rho C_p \frac{\partial T}{\partial t}}} = \underset{\text{Heat Diffusion Rate of Tissue}}{\boxed{\nabla(k\nabla T)}} + \cancelto{0}{Q_s} + \cancelto{0}{Q_p} + \underset{\text{Metabolic Heat Source}}{\boxed{Q_m}}$$

$\rho = \textit{Density of tissue} = 1100\ (kg \cdot m^{-3})$

$C_p = \textit{Tissue heat capacitance} = 4450\ (J \cdot kg^{-1} \cdot K^{-1})$

$k = \textit{Tissue thermal conductivity} = 0.53\ (W \cdot m^{-1} \cdot K^{-1})$

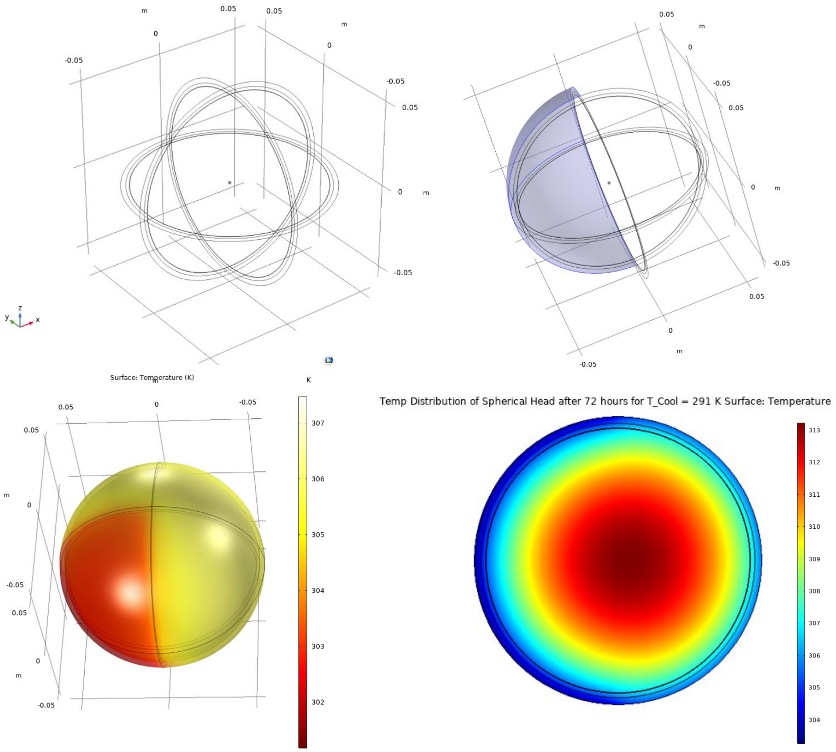
$T = \textit{Temperature}\ (K)$

$Q_s = \textit{Heat source within the medium} = 0\ (W \cdot m^{-3})$

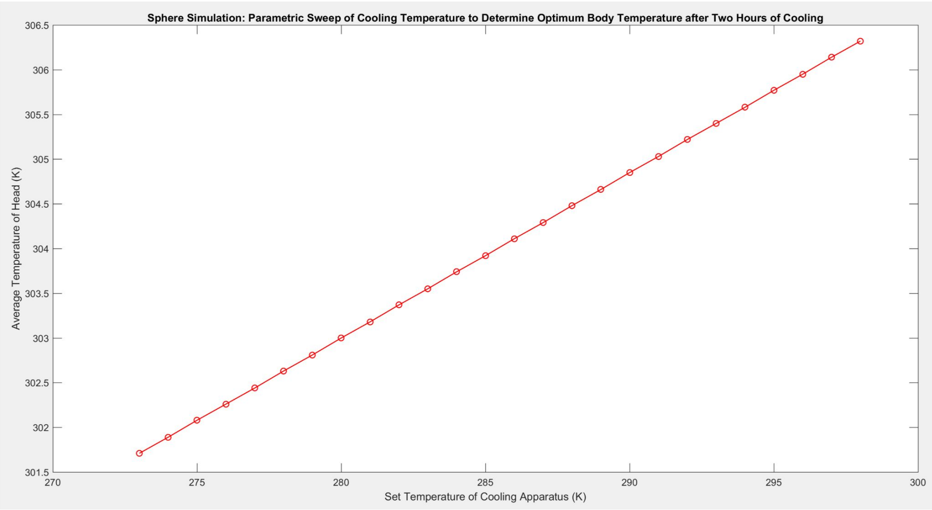
$Q_p = \textit{Heat change due to blood perfusion} = 0\ (W \cdot m^{-3})$

$Q_m = \textit{Heat source due to metabolic activity} = 10010\ (W \cdot m^{-3})$

Preliminary simulation of heat flow using sphere

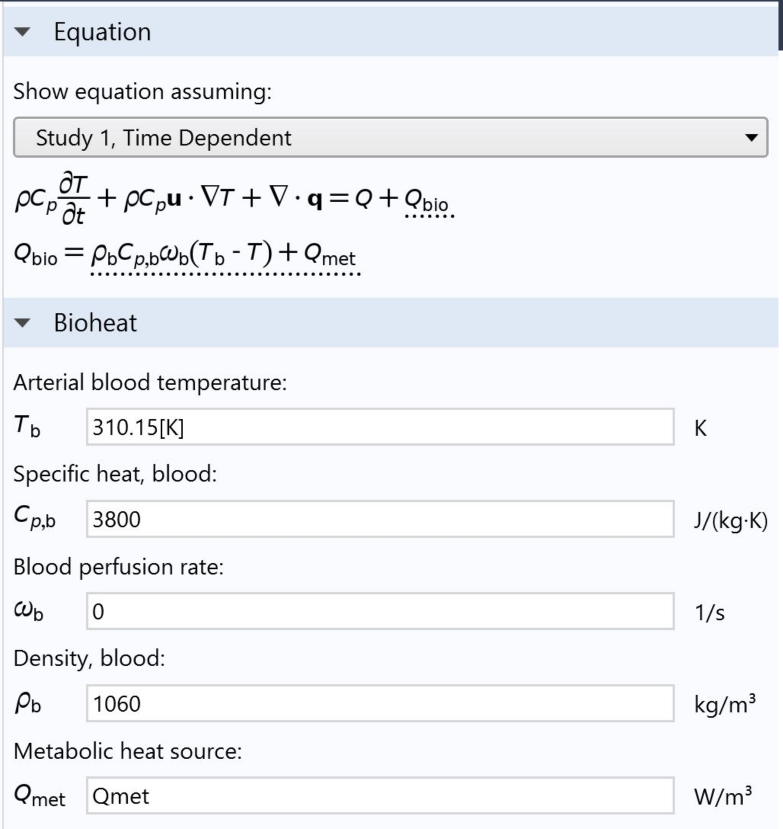


Temp Distribution of Spherical Head after 72 hours for T_Cool = 291 K Surface: Temperature



Sphere Simulation: Parametric Sweep of Cooling Temperature to Determine Optimum Body Temperature after Two Hours of Cooling

Parametric sweeps at room temperature reveal that optimum metabolic setting is 10010 W/m³



Equation

Show equation assuming:

Study 1, Time Dependent

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q + Q_{\mathrm{bio}}$$

$$Q_{\mathrm{bio}} = \rho_{\mathrm{b}} C_{p,\mathrm{b}} \omega_{\mathrm{b}} (T_{\mathrm{b}} - T) + Q_{\mathrm{met}}$$

Bioheat

Arterial blood temperature:

T_{b} 310.15[K] K

Specific heat, blood:

$C_{p,\mathrm{b}}$ 3800 J/(kg·K)

Blood perfusion rate:

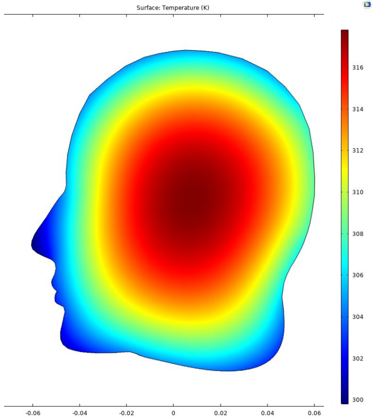
ω_{b} 0 1/s

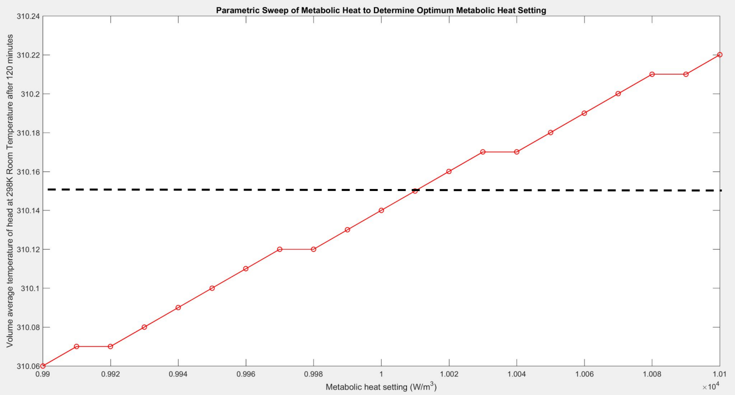
Density, blood:

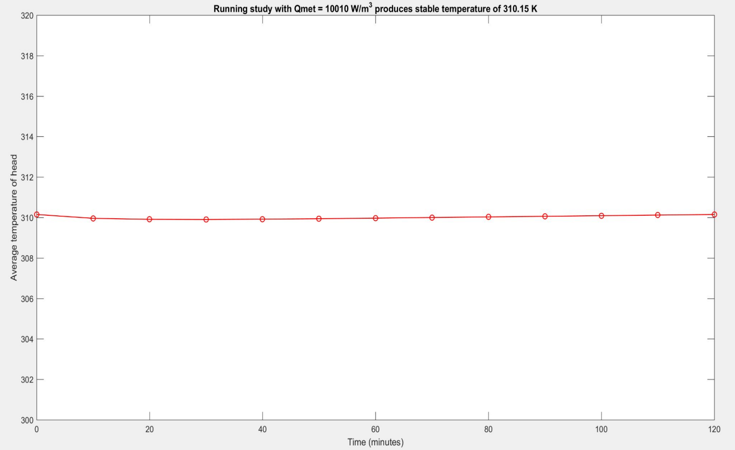
ρ_{b} 1060 kg/m³

Metabolic heat source:

Q_{met} Qmet W/m³




Parametric Sweep of Metabolic Heat to Determine Optimum Metabolic Heat Setting


Running study with Qmet = 10010 W/m³ produces stable temperature of 310.15 K