Design of a CFD based module to simulate Cryosurgical treatment of tumor tissues

Anshul Thakkar (152210, anshulthakkar2018@gmail.com)

Devis Lodhwal (152218, lodhwaldevis@gmail.com)

Mentor: Dr. Sonam Singh

ABSTRACT

This project proposes a computational fluid dynamics (CFD) based module for simulating Cryosurgical treatment of tumor tissues utilizing real segmented tumor images. The module uses deep neural network (DNN) in python and the COMSOL Multiphysics platform to enhance the accuracy and realism of the simulations.

INTRODUCTION

Cryosurgery, a minimally invasive therapeutic technique, utilizes extreme cold, usually generated by liquid nitrogen or argon, to destroy abnormal tissue such as tumors. Traditionally valued for its efficacy in treating conditions like prostate cancer, skin lesions, and retinal disorders, cryosurgery faces challenges in precision and safety, particularly regarding the preservation of surrounding healthy tissues. Enhancements in simulation technologies have the potential to revolutionize this field by providing unprecedented control over the surgical process. Our project aims to develop a simulation module that integrates Computational Fluid Dynamics (CFD) with real-time medical imaging and deep learning to optimize cryosurgery.

DEVELOPMENT OF CFD MODEL

This model simulates the flow and thermal dynamics of cryogenic fluids used in cryosurgery. We focus on accurately modeling the heat transfer and phase change phenomena that occur when cryogenic temperatures interact with biological tissues. The model includes variables such as fluid properties (e.g., viscosity, thermal conductivity), tissue properties (e.g., heat capacity, thermal conductivity), and boundary conditions that represent the cryoprobes and biological interfaces.

Table 2 Thermal and physical properties of biological tissue [2,4]

Item	Units	Value
Specific heat capacity of unfrozen tissue	J/m^3 °C	3.6×10^3
Specific heat capacity of frozen tissue	J/m^3 °C	1.8×10^3
Thermal conductivity of unfrozen tissue	W/m °C	0.5
Thermal conductivity of frozen tissue	W/m °C	2.0
Latent heat	J/kg	4.2×10^6
Blood perfusion rate	ml/s/ml	0.0005
Metabolic rate of the liver	W/m^3	4200
Temperature of lower phase change	°C	−1
Temperature of upper phase change	°C	−8
Density of unfrozen tissue	kg/m^3	1000
Density of frozen tissue	kg/m^3	1000
Blood density	kg/m^3	1000

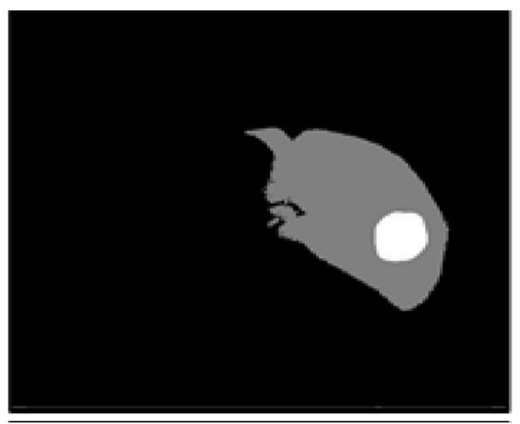
Model parameters (Nabaei and Karimi, 2018; Nazemian and Nabaei, 2020).

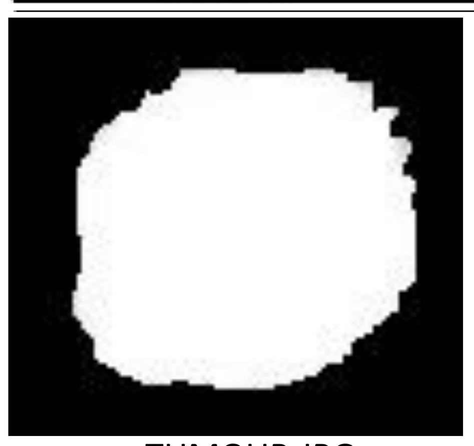
Parameter	Description	Unit	Magnitude
k	Conductivity of the tissue	W m^{-1} °C^{-1}	k_u = unfrozen = 0.5 k_f = frozen = 2
c	Specific heat of the tissue	J kg^{-1} °C^{-1}	c_u = unfrozen = 3600 c_f = frozen = 1800
c_b	Specific heat of the blood	J kg^{-1} °C^{-1}	3600
ρ	Density of the tissue	kg m^{-3}	ρ_u = unfrozen = 1000 ρ_u = frozen = 998
w_b	Blood perfusion rate	s^{-1}	Liver = 0.0005
Q_m	Metabolic heat generation	W m^{-3}	Liver = 4200
Q_{lf}	Latent heat of fusion	MJ m^{-3}	250
T_{mu}	Upper limit of the phase transition	°C	−1
T_{ml}	Lower limit of the phase transition	°C	−8

ORIGINAL AND SIMULATED TUMOUR

CT SCAN

SEGMENTED IMAGE





TUMOUR.JPG

TUMOUR.SVG

PDF FUNCTION GOVERNING TEMPERATURE DISTRIBUTION

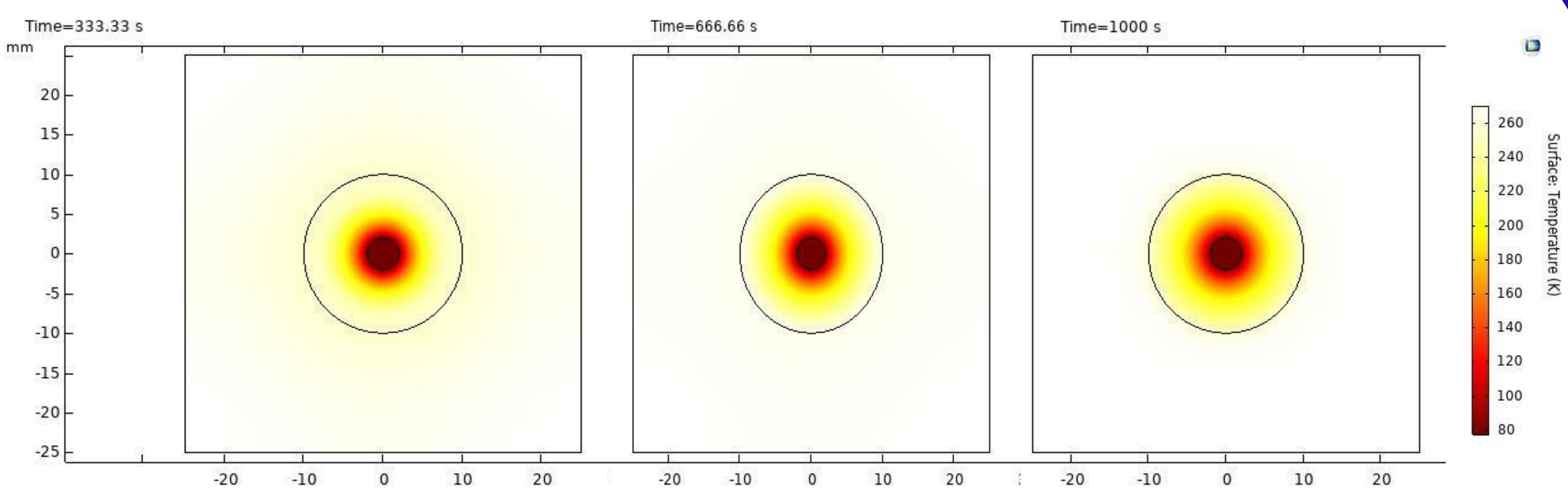
$$\rho c \frac{\partial T}{\partial t} = k\nabla^2 T + w_b \rho_b c_b (T_b - T) + Q_m$$

$$c = \begin{cases} c_u & T_{mu} < T \\ \frac{c_u + c_f}{2} + \frac{Q_{lf}}{(T_{mu} - T_{ml})} & T_{ml} \leqslant T \leqslant T_{mu} \\ c_f & T < T_{ml} \end{cases}$$

$$k = \begin{cases} k_u & T_{mu} < T \\ \frac{k_u + k_f}{2} & T_{ml} \leqslant T \leqslant T_{mu} \\ k_f & T < T_{ml} \end{cases}$$

$$\rho = \begin{cases} \rho_u & T_{mu} < T \\ \frac{\rho_u + \rho_f}{2} & T_{ml} \leqslant T \leqslant T_{mu} \\ \rho_f & T < T_{ml} \end{cases}$$

OBSERVATIONS



CONCLUSION

Our project integrates computational fluid dynamics, deep learning for medical imaging segmentation, and showcasing improved surgical precision and patient safety. COMSOL Multiphysics simulation aids in understanding thermal interactions, enhancing treatments. This approach advances cryosurgery technology, redefining surgical planning for better precision and safety. Its wider adoption could redefine tumor ablation standards.