3D Simulation of the Laser Interstitial Thermal Therapy in Treatment (LITT) of Brain Tumors

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Abstract: Due to the restriction of the number of probes that a patient can tolerate and the inaccurate information provided by the invasive temperature measurements, which provide information only at discrete points, a mathematical model simulation is more effective to help physicians in planning their thermal treatment doses. This simulation will maximize therapeutic effects while minimizing side effects. Prior to the treatment, it will provide a precise idea of the predicted reaction depending on selected doses; so new treatment strategies can be proposed and evaluated.

The objective of this study is to simulate the Laser Interstitial Thermal Therapy in Treatment (LITT) of brain tumors. The thermal effect of the laser during coagulation lasts around one second and its temperature is between 50 and 90C. LITT has the following results; the desiccation and retraction of the tissue to destroy tumor phenomena.

Keywords: Laser Interstitial Thermal Therapy in Treatment, thermal damage, brain cancer, bioheat transfer simulation.

1. Introduction

COMSOL Multiphysics Simulation Software will be used to simulate the mathematical model which includes thermal conduction (based on either Fourier's law or modified Fourier's law), constant blood perfusion and evaporation as a boundary condition. The Heat Transfer Module will be used with a material library model for brain and probe solid materials. The Brain material with tumors will be defined with their density, conductivity, specific heat, diffusivity, relative permittivity, relative permeability and electrical conductivity values. A new material Laser delivery probe will also be defined as source energy.

Expected results are thermal distribution throughout the biological tissues during the heating and temperature distribution. We will also compare thermal conduction results on Fourier's law vs. modified Fourier's law. An expected result is the estimation of the volume of tissues damaged during the treatment.

Furthermore predicting the result of the laser interstitial thermal therapy in treatment of brain cancer depending on scenarios discussed between physicians and patients will improve the health care system by providing a personalized and focused treatment. Using the laser energy source, light is emitted from a diffusive tip of an optical fiber probe that is inserted into the center of a brain tumor

Using COMSOL v5.1, we build apps for physicians' use. Our COMSOL Multiphysics model is turned into an application with its own interface using the tools provided with the Application Builder desktop environment. Physicians will use their laptops or smart phones to access and run the application remotely.

2. Materials and Methods

2.1 Simulation model

A cylinder 2.54 cm radius by 2.54 cm thickness Brian tissue, as shows in Figure 1, is heated up to 10 seconds by a 5 W laser. The initial temperature of the brain tissues is considered 293.15 K. The tissue is modeled as a Cylinder of radius r_{mat} and height thickness, 3D, Bioheat Transfer (ht), Time dependent of range (0,0.1,15) seconds. These values can be changed by the user of the model to simulate in real-time.

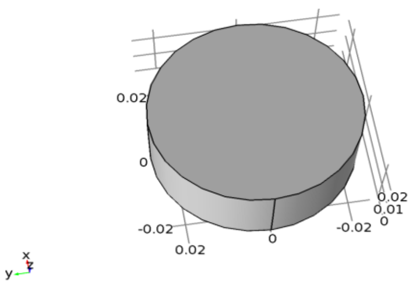

Figure 1. A cylinder 2.54 cm radius by 2.54 cm thickness Brian tissue is heated up to 10 seconds by a 5 W laser.

2.2 Laser procedure

The laser beam [6] is modeled as a heat source in the plane with Gaussian profile gp1 (figure 2). This model uses the built-in Gaussian Pulse functions, which enforces that the integral under the curve equals unity. The emissivity of the surface of the brain tissue is approximately 0.8. At the operating wavelength of the laser, it is assumed that absorptivity equals emissivity. The heat load due to the laser is multiplied by the emissivity.

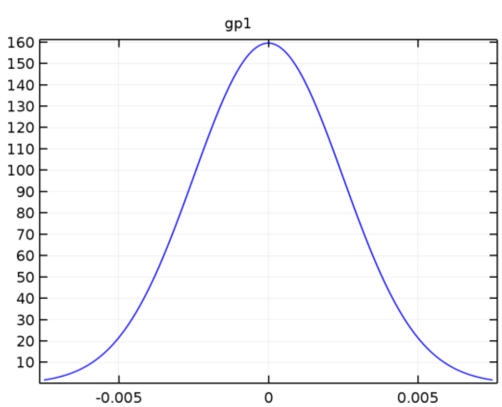

Figure 2. The Gaussian Pulse with location 0 and Standard deriation equal r_{spot}.

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The waveform function wv1 is a Triangle with Angular frequency and Phase equal 0 and the Amplitude equal 1.

We used from the COMSOL library, an analytic heat function hf is defined as following (figure 3):

$$hf(x,y,t) = P_{laser} * gp1(x - wv1(t)) * gp1(y)$$

Where P_{laser} is the source power, $gp1$ is Gaussian pulse function, $wv1$ is the waveform function.

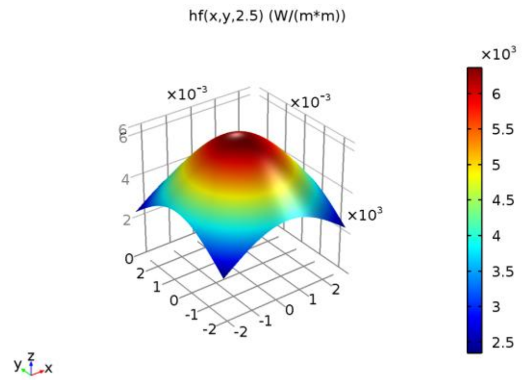

Figure 3. Analytic heat function hf.

2.3 Modeling in COMSOL Multiphysics

2.3.1 Geometrical description of the model

We will start with the thermal conduction using Fourier's law for our first step of the simulation (results presented here) then upgrade to the modified Fourier's law. We will then compare the results of these two simulations.

2.3.2 Heat distribution

The LITT of Brain Tumors was modeled by the bio-heat equation in a 3D geometric study, using the bioheat transfer application mode with time dependent COMSOL 5.1.

Table 1 describes the physical parameters used by our Comsol numerical simulation.

Heat Equation

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

$$q = -k\nabla T$$

Where T is temperature (K), C_p is the heat capacity J/(kg*K)), ρ is the density of the brain tissue (kg/m^3), and k is the thermal conductivity of brain tissue (W/(m*K)), Q is heat source, Q_{bio} is the perfusion and metabolic heat source.

The Perfusion Equation

$$Q_{bio} = \rho_b C_b \omega_b (T_b - T) + Q_{met}$$

Where Q_{bio} is the perfusion and metabolic heat source, ρ_b is the blood Density, C_b is Specific blood heat , Q_{met} is Metabolic heat source, ω_b is Blood perfusion rate, T_b is the blood flow rate, T is time (s), Q_{met} is the metabolic heat source.

Table 1. Settings of Qbio parameters.

Description	Value
Arterial blood temperature	310.15[K]
Specific heat, blood	3650[J/(kg*K)]
Blood perfusion rate	0.866[l/s]
Density, blood	1035 kg/m³
Metabolic heat source	0

We condider that the metoblic heat and external heat sources are negligible in respect to the laser inducted heat.

The initial temperature of the brain tissues was considered as T_0=293.15 K.

The thermo-optical parameters were considered constant during the thermal process.

2.3.3 **Mesh**

The brain tissue is meshed using a triangle swept mesh as shown in Figure 4.

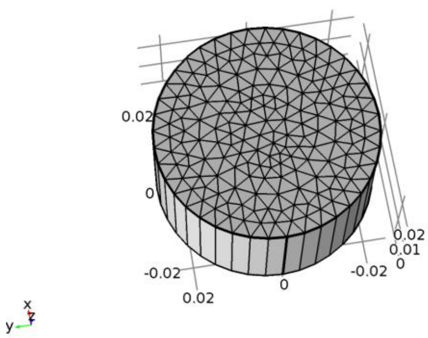

Figure 4. Mesh of the model simulation.

2.3.4 Thermal damage

We used integrated Thermal damage function on the Heat Transfer Module. Simulation includes damage integral analysis from Energy absorption. The Parameters Frequency factor and Activation factor are defined in table 2. The damage is calculated from the Arrhenius law:

We used the following defined functions used on the COMSOL 5.1:
Fraction of necrotic tissue:

$$\theta_d = \min(\max(0{,}1 - e^{-\alpha}), 1)$$

Where α Is a Discontinuous Lagrange (constant) shape function (which describes the degree of tissue injury).

Table 2: The Physical parameters used in our COMSOL numerical simulation. (Thermal properties of brain from [9])

Name	**Expression**	**Value**	**Description**
r_{mat}	1[in]	0.0254 m	material inner radius
Thickness	25400[um]	0.0254 m	mat inner thickness
r_{spot}	8[mm]	0.008 m	Radius of laser spot size
p_{laser}	5[W]	5 W	Laser power
Period	10[s]	10 s	Time of laser to move back and forth
Emissivity	0.8	0.8	surface emissivity of mat1
Temp	310.15[K]	310.15 K	Initial Temperature
Heat Capacity	3636[J/(kg*K)]	3636[J/(kg*K)]	Brain Heat Capacity
Density	1050[kg/m^3]	1050[kg/m^3]	Brain Density
Thermal conductivity	0.51[W/(m*K)]	0.51[W/(m*K)]	Brain Thermal conductivity
A	7.39e39[1/s]	7.39e39	Frequency factor
dE	2.577e5[J/mol]	2.577e5	Activation energy

3. Simulation Results

During the simulation, the physician can play with the input values to Control the thermal ablation during a laser surgery/cancer treatment.

Figures 5 to 8 show the heat distribution during the simulation which will help physicians to predict and organize the treatment.

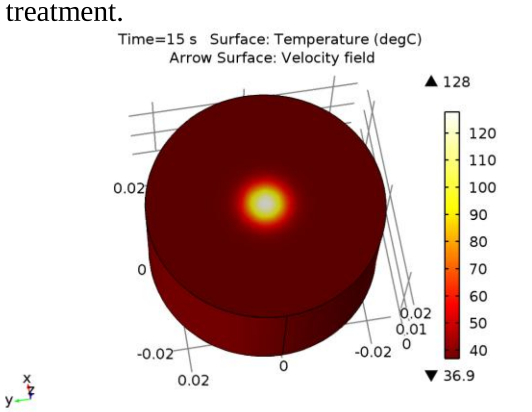

Figure 5. Temperatre during 15 seconds at the Surface of the Brain Tissue.

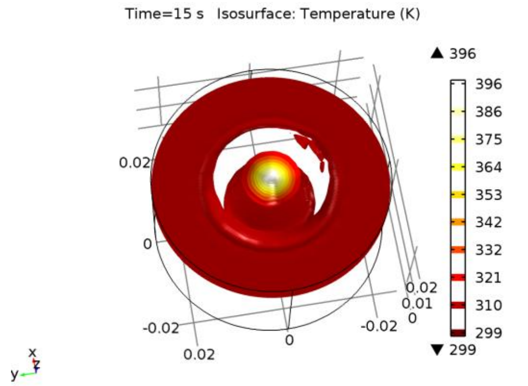

Figure 6. Temperatre during 15 seconds at the Surface of the Brain Tissue (Isothermal Contours (ht)).

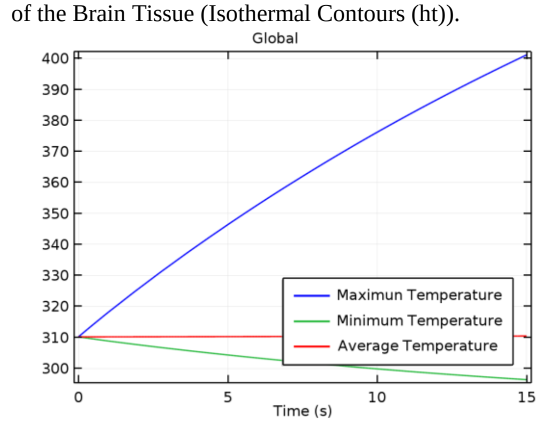

Figure 7. Global Max/Min/Average Temperature (K) of the Tissue during 15 seconds.

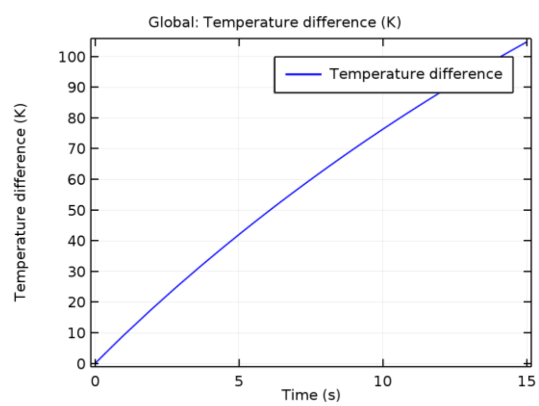

Figure 8. Global Temperature difference (K) of the tissue during 15 seconds.

Such model shows also the impact of the thermal damaged tissues during the simulation.

Figures 9 to 11 show the fraction of the necrotic tissue, the degree of tissue injury

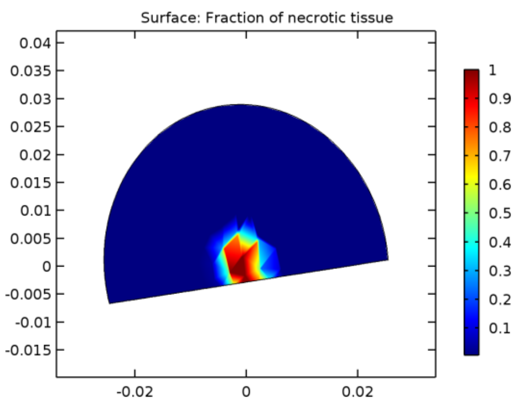

Figure 9. 2D Fraction of necrotic tissue

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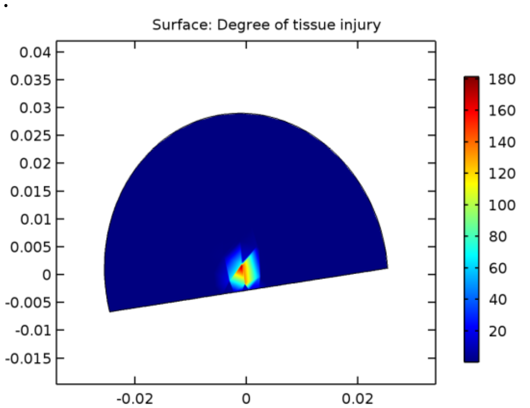

Figure 10. 2D Degree of tissue injury.

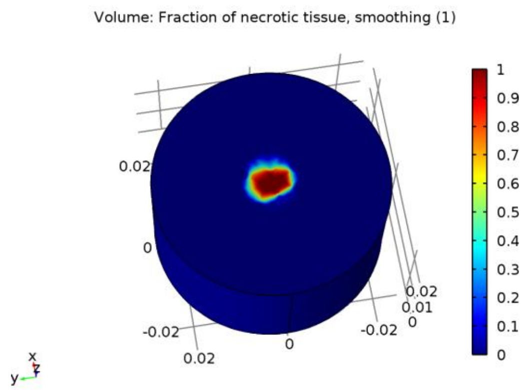

Figure 11. Volume: Fraction of necrotic tissue, smoothing (1)

4. Apps for physicians' use

Using Comsol v5.3, we build apps for physicians' use. Our COMSOL Multiphysics model is turned into an application with its own interface using the tools provided with the Application Builder desktop environment. Physicians will use their laptops or smart phones to access and run the application remotely (Figures 11 and 12).

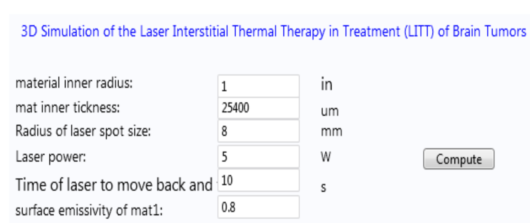

Figure 11. The Output 0f the Apps. You enter the parameters, select compute to execute your simulation in real-time.

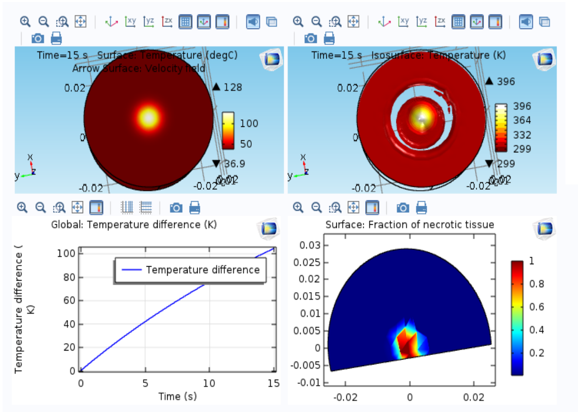

Figure 12.The Output from the Apps after the user select compute.

5. Conclusion

Controlled thermal ablation is a big challenge during a laser surgery/cancer treatment. A tool to help physicians predict and organize the treatment will be helpful.

In this paper, we proposed a simulation model of the LITT with physicians' interaction via Comsol Apps. Such model shows the impact of the heat distribution and thermal damage of the tissue during the simulation.

6. References

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