Multiphysics simulation approach for photo-acoustics temperature monitoring in rodents head during photothermal therapy


To cite this version:
K. Metwally, A. Cappart, G. Ndjeohya, J. Cheng, A. Da Silva, et al.. Multiphysics simulation approach for photo-acoustics temperature monitoring in rodents head during photothermal therapy. European Conferences On Biomedical Optics (ECBO), Jun 2019, Munich, Germany. hal-02376621

HAL Id: hal-02376621
https://hal.science/hal-02376621
Submitted on 22 Sep 2022
Multiphysics simulation approach for photo-acoustics temperature monitoring in rodent's head during photothermal therapy


Multiphysics simulation approach for photo-acoustics temperature monitoring in rodent's head during photothermal therapy

K. Metwally\textsuperscript{a,b}, A. Cappart\textsuperscript{a}, G. Ndjejoha\textsuperscript{b}, J. Cheng\textsuperscript{b}, A. Da Silva\textsuperscript{a}, and S. Mensah\textsuperscript{b}

\textsuperscript{a}Aix Marseille Univ, CNRS, Centrale Marseille, Institut Fresnel, Marseille, France
\textsuperscript{b}Aix Marseille Univ, CNRS, Centrale Marseille, LMA, Marseille, France

ABSTRACT

A multiphysics model was developed to model the increase in temperature during photothermal treatment (PTT) in mouse brain. The model includes also a numerical model for Photoacoustic thermometer during the hyperthermia therapy. The coupling of different physics was investigated.

Keywords: Radiative Transfert Equation, Monte Carlo simulations, Acoustic wave propagation, Bioheat equation

1. INTRODUCTION

The multiphysics model takes into account the exact morphology of rodents head, via the co-registration of a Mouse brain atlas using different imaging modalities such as magnetic resonance imaging (MRI) for tissue, Micro-computer tomography (Micro-CT) for blood vessels and (CT) for skull. Acoustic propagation was introduced as well to test the effect of Blood Brain Barrier (BBB) opening, and simulated under both assumptions of linear and nonlinear. BBB opening is introduced by the blood vessel spatial position and effective pressure inside it. Optically, Monte Carlo simulations were preformed to study the energy deposition of optical excitation inside a rodents head. PhotoAcoustic pressure measurement was also introduced in the simulations. The whole process is developed to propose a complete simulation of the increase in temperature during PTT.

2. MATERIAL AND METHODS

The flow chart shown in Fig. 1 summarizes the developed for Glioblastoma treatment of brain cancer. A multiphysics model was developed to evaluate in advance the effect of different therapeutic agents for hyperthermia treatment.

2.1 Coregistration

In order to develop a realistic multiphysics model based on the exact morphology of rodents head, a co-registration step of multimodal imaging atlas\textsuperscript{a} was implemented, in which, a mouse brain atlas for tissue,\textsuperscript{1} blood vessels\textsuperscript{2} and skull\textsuperscript{3} were co-registered using point reference registration method.

Further author information: (Send correspondence to Anabela Da Silva)

Anabela Da Silva: E-mail: anabela.dasilva@fresnel.fr, Telephone: +33 4 91 28 84 82

Serge Mensah: E-mail: mensah@lma.cnrs-mrs.fr
2.2 Governing equations

Theoretical mathematical models were solved and segregated for each included physics. On the one hand, the k-wave software \(^4\) was used to model the acoustic propagation of PA wave generation in heterogeneous acoustic media. BBB opening is introduced by the blood vessel spatial position and effective pressure inside it was modeled with the acoustic propagation equation:

\[
\frac{\partial u}{\partial t} = -\frac{1}{\rho_0} \nabla p, \\
\frac{\partial p}{\partial t} = -(2\rho + \rho_0)\nabla u - u\nabla \rho_0, \\
p = c_0^2(\rho + d\nabla \rho_0 + \frac{B}{2A} \rho_0^2 - L\rho), \\
A = \rho_0 c_0^2, B = \rho_0^2 \left[\frac{\partial^2 P}{\partial \rho^2}\right]
\]

On the other hand, a Monte Carlo simulation approach was adopted to solve the Radiative Transfert Equation for light propagation through the tridimensional heterogeneous medium:

\[
\frac{1}{c} \frac{\partial \phi(x, \hat{s}, t)}{\partial t} = q(x, \hat{s}, t) - [\hat{s} \nabla + \mu_a(x) + \mu_s(x)]\phi(x, \hat{s}, t) + \mu_s(x) \int \Theta(\hat{s}, \hat{s'})\phi(x, \hat{s'}, t) d\hat{s'}
\]

where, \(\mu_a\) and \(\mu_s\) are the optical absorption and scattering coefficients of the medium.

The co-registered volume integrates a voxel-based 3D model of brain tissues with its optical properties. It demonstrates that brain heterogeneity has moderate to significant impact on the optical fluence distribution in rodent’s head and therefore affects the photothermal therapy results.

Once the optical fluence (\(J/cm^2\)) has been calculated, the deposited absorbed energy (\(J/cm^3\)) can be calculated as \(W = \mu_a \phi\) and the thermoelastic stress confinement could be assumed to calculated the PA pressure, where the thermal conduction and stress propagation are ignored: \(P = \frac{\beta c^2}{C_p} W\), where, \(\beta\) is the thermal expansion coefficient, \(c\) is the sound speed and \(C_p\) is the specific heat capacity. Then the acoustic propagation was simulated under both assumptions of linear and nonlinear.
Under continuous laser exposure, the deposited energy is the source term that influences the thermal behavior model in biological perfused tissues by the Pennes’s bioheat equation:

\[
\nabla k \nabla T + \rho_b c_b w_b (T_{a0} - T) + Q = \rho c \frac{\partial T}{\partial t}
\]  

(2)

where \(k\), \(\rho\) and \(c\) are the biological tissue thermal conductivity, density and specific heat. Values for blood are given by \(\rho_b\) and \(c_b\); \(w_b\) is the tissue blood perfusion rate which represents the volume of fluid (i.e. blood) that passes per unit time and per tissue volume. \(Q\) represents the energy deposition by any external heat source such as the metabolic heat production in tissues. In this work, we consider \(Q\) is laser deposited energy. \(T_a\) is the temperature of blood in the main arteries which is assumed constant and equal to \(37.3^\circ C\). \(T\) is the local tissue temperature, which is a function of the spatial position and the time.

3. RESULTS AND DISCUSSION

The evolution of temperature as a function of time can be demonstrated as shown in Fig. 2 for a given case study.

![Figure 2. Evolution of temperature during photothermal therapy](image)

4. CONCLUSION

A multiphysical model was developed to quantify and evaluate therapeutic agents efficacy in photothermal therapy in rodents head.

ACKNOWLEDGMENTS

This work has been done within the framework of the Cancer Plan (GRAVITY project: Glioblastoma Risk Attrition by VectorIzed ThermotherapY) ITMO Cancer AVIESAN (Alliance Nationale pour les Sciences de la Vie et de la Sante, National Alliance for Life Sciences & Health).

REFERENCES


