

Effect of size and geometry of gold nanostructures in performance of laser-based hyperthermia: a multiscale-multiphysics modelling

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Abstract. The importance of hyperthermia as a promising method in disruption and removal of cancerous cells is well understood. One of the effective options of concentration of heat within a specific tissue is using laser and exploiting absorption properties of metallic nanostructures. In this report, the geometrical effect of gold nanostructures in the performance of laser based hyperthermia has been analyzed. The analysis is based on the consideration of absorption properties of gold nanostructures, interaction of laser light with a specific tissue containing nanostructures and the effect of generated heat on elevation of temperature inside the tissue. The analysis is performed using Mie theory (for extraction of absorption/scattering properties of nanostructures), Monte Carlo (MC) (interaction of light inside the tissue) and solving the heat equation (considering the elevation of temperature inside the tissue). We have compared the effect of a laser beam on the maximum temperature inside the tissue and the results indicate that focusing the beam size of the laser to half width will culminate in a 50% elevation of maximum temperature in the tissue, while the average temperature raise inside the tissue will not be altered.

1. Introduction

Hyperthermia forms one of the most effective methods in the treatment of refractory cancers using a non-chemical approach [1,2]. Killing cancerous tissues and cells with a minimum side effect to healthy cells is the main objective of this method. Regarding the different resources for generation of heat, using laser with metallic nanoparticles can be considered to be a powerful candidate for localized heat generation. Metallic nanostructures with different sizes and geometries have different extinction spectra which can be considered as tunable sources for absorption of light in different wavelengths. In this regard, gold nanostructures are brilliant candidates considering not only their absorption peaks in visible and near-IR region but also because of their bio compatibility. In this work we have studied the



effect of size and geometry of gold nanostructures on the efficiency of hyperthermia in different tissues. Our approach consists of three steps. First the absorption and scattering efficiency and cross section of nanostructures are calculated based on Mie theory or discrete dipole approximation (DDA) method. The second part consist of using the Monte Carlo (MC) method wherein we calculate the absorption of light in the tissue by considering different types and concentrations of gold nanostructures. In the last part, in order to calculate the effect of this absorption on the elevation of temperature of the tissue, we have solved the Bio-Heat equation for the tissue with the absorption profile obtained at the second step. Considering different thermal and optical properties of tissues and selection of proper laser with appropriate wavelength, the results of the simulation can be fruitful in the design and selection of appropriate nanostructure and the laser parameters.

2. Modelling

Figure 1, depicts the chart of our multiphysics model in a simple manner. In the first part, considering the geometry and structure of the metallic nanostructure, the absorption and scattering cross section were calculated for different wavelengths and the results were stored for the Monte Carlo calculations. The method of calculation in this step, considering the interaction of electromagnetic wave with the structure, was based on solving Maxwell's equation. The method of Mie and DDA were exploited for calculation of absorption or scattering cross sections. The theoretical detail of the computational method can be found in the references [3,4]. In the second part, in order to model the propagation of photon bunches inside the tissue containing nanoparticles, the Monte Carlo method was exploited. Basically, the MC approach for propagation of photons inside a medium is based on taking into account the chances of probable events which may occur for the bunch of photons. Scattering and absorption are events which can occur inside the medium while reflection and refraction occur at the interfaces of different boundaries. The effect of each probable event is calculated based on the properties of the media accordingly. Each medium is presented in the MC code with its refraction index (n), absorption coefficient (μ_a), scattering coefficient (μ_s), and anisotropy (g). In order to consider different concentration of nanostructures, the parameters were calculated considering the quantities in the first step. Details of the method and its incorporation can be found in the relevant references such as [5]. The results of the MC part will be the absorption profile of the light intensity inside the tissue according to the different parameters of the tissue and the incorporated nanoparticle. Taking into account the absorbed intensity, the third part of the model calculates the temperature distribution inside the tissue by solving the Bioheat equation in two dimensions. The basics of the Bioheat model is discussed in reference [6]. The first and second parts of the simulation were performed using our own code developed in the Matlab environment. The Bioheat equation was solved with the Finite Element Method (FEM) using the COMSOL Multiphysics 5.1.

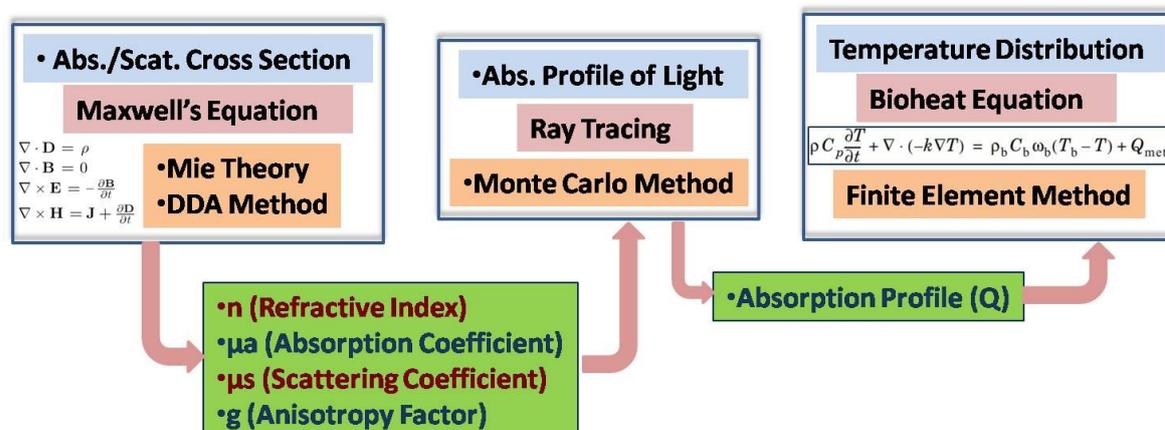


Figure 1. Multiphysics Modelling Procedure.

3. Results

Considering different types of gold nanostructures for application in hyperthermia, we selected the structure of Silica-Gold core shell. By means of SiO₂ as core and gold layer as the shell, the absorption peak can be tuned easily with changing the radius of each layer accordingly. Figures 2 and 3 depict the extinction efficiency for four different configurations of the core-shell structures based on the Mie theory. In order to consider the dispersion behaviour of permittivity of gold, we used the Drude-Lorentz model accordingly [4]. Considering the window with maximum transmission of light inside a tissue, we selected the 800 nm wavelength for excitation of the tissue. Based on the selection of excitation wavelength, we performed the simulation for (D=80nm, T=7nm) based on the relative maximum extinction in 800nm. In order to study the effect of the beam size of laser in the elevation of temperature inside the tissue, we performed the simulation for beam diameters of 2mm and 4 mm. Regarding the tissue structure we selected the prostate tissue and the related parameters were extracted from experiment results [7]. At the top section of figure 4, the intensity of absorption profile of laser light inside the tissue is depicted considering the cancerous tissue (with Core shell) between two layers of normal tissue. We have assumed that the gold nanoparticles were delivered to the cancerous tumor with a uniform distribution without any agglomeration. Accordingly, by considering the effect of injected gold nanostructures inside the tumorous part of the tissue by modifying the absorption and scattering coefficients, the energy of laser energy was more absorbed inside this part of the tissue. Regarding the excitation, we stimulated the tissue for one second duration of laser pulse. Figure 4 depicts the temperature distribution of the tissue when the laser light was applied for two laser beam diameters at different times (one second after excitation and at the end of simulation). Figure 5 illustrates the average temperature and the maximum temperature over the surface of tumour structure, considering two different diameters of the laser. As it is observed in figure 4, the maximum temperature for smaller laser beam is more than the larger beam, although the average temperature raise is equal in both cases. The elevation of maximum temperature for the shrunk beam to half its value was 50%.

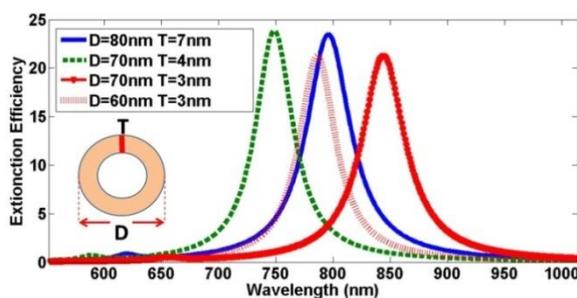


Figure 2. Extinction Efficiency of Core Shell of SiO₂-Au Core Shell.

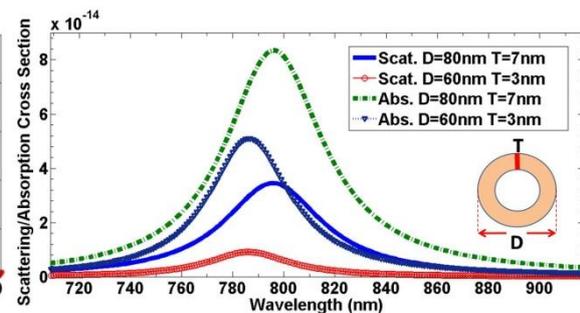


Figure 3. Scattering / Absorption Cross Section of SiO₂-Au Core Shell.

4. Conclusion

A multiscale/ multiphysics model is proposed for the calculation of temperature distribution in tissues employing laser excitation and application of metallic nanostructures. The model is adapted to include all the parameters including the material, the size and the geometry of the nanostructure, the optical and thermal properties of the tissue. Using the model, we have simulated the effect of laser beam on the efficiency and side effects of hyperthermia. The results indicate that there is an elevation of 50% in the maximum temperature in the tissue by decreasing the diameter of the beam to half. The model has potential application for formulating the process of laser hyperthermia based on metallic nanostructures.

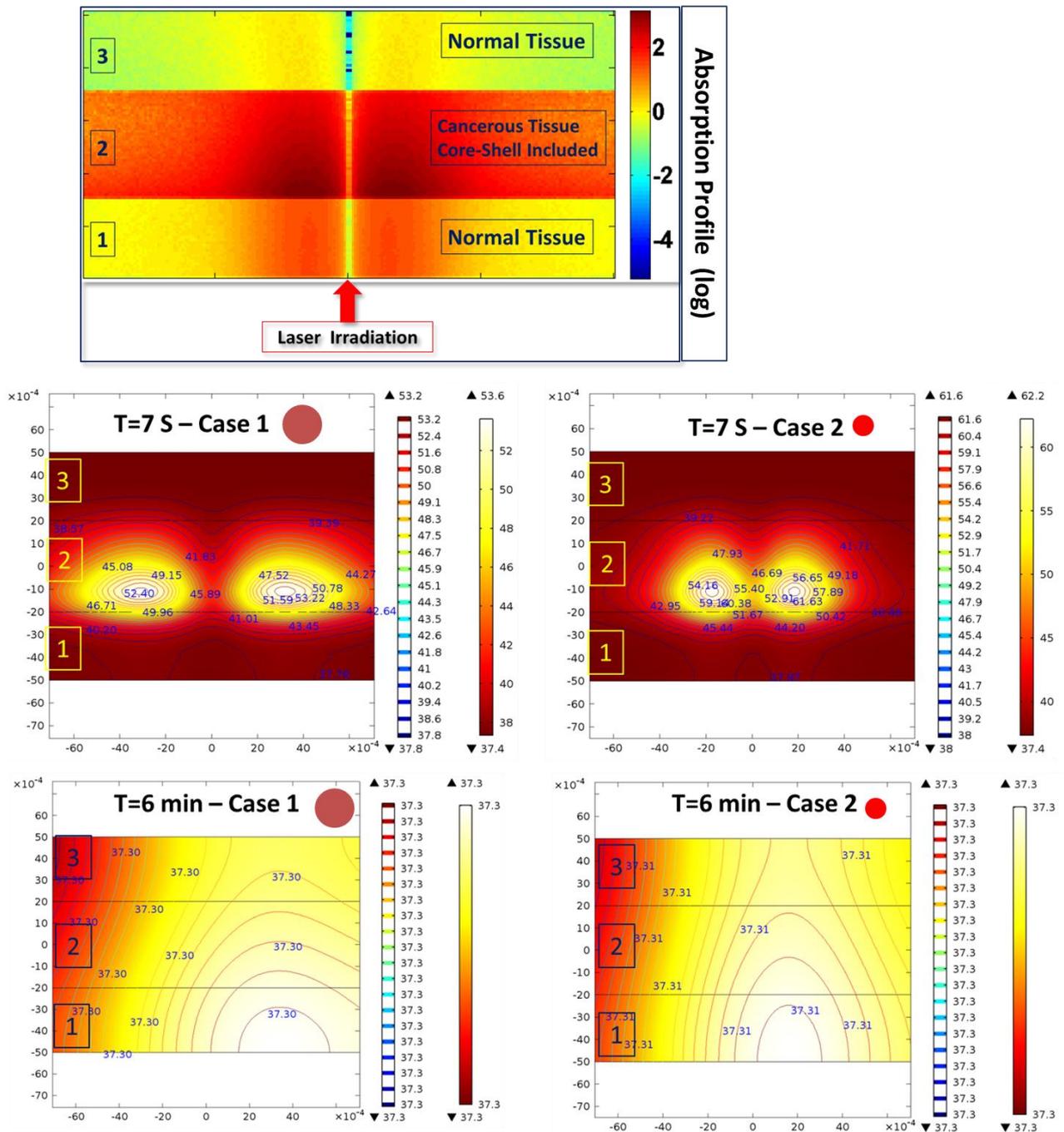


Figure 4. (Top) Intensity Profile of Absorbed Light inside the tissue structure (1&3 Indices show Normal Tissue and 2 Represents Cancerous Tissue (Including SiO₂-Au Core Shell)) (Bottom) Temperature Profile inside the Tissue Structure. (Case 1,2 represent Laser Beam Diameter of 2mm and 4mm.)

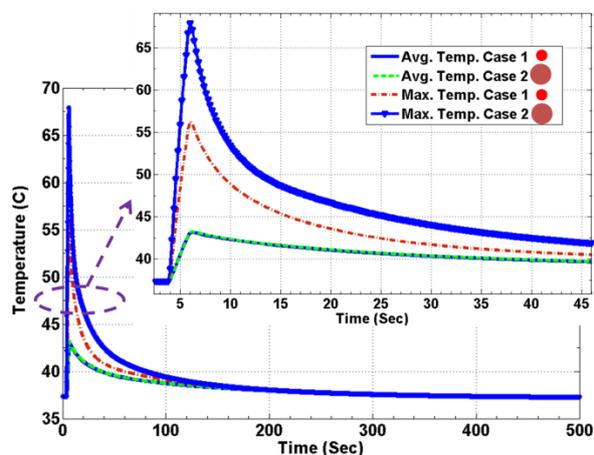


Figure 5. Average and Maximum Temperature inside the Cancerous Tissue for Laser beam size of 2mm (Case 1) and 4mm (Case 2).

References

- [1] Ahmed K, Tabuchi Y and Kondo T 2015 *Apoptosis* **20** 1411–9
- [2] Cihoric N *et al* 2015 *International Journal of Hyperthermia* **31** 609–14
- [3] Draine B T, Flatau P J 1994 *J. Opt. Soc. Am. A.* **11** 1491-9
- [4] Bohren C F and Huffman D R 2007 *Absorption and Scattering of Light by Small Particles* (New York: Wiley-VCH Verlag GmbH)
- [5] Wang L V and Wu H 2007 *Biomedical Optics: Principles and Imaging* (New York: Wiley-VCH Verlag GmbH)
- [6] Xuan Y and Roetzel W 1997 *Chemical Engineering & Technology* **20** 268-76
- [7] Pu Y, Wang W, Al-Rubaiee M, Gayen S K and Xu M 2012 *Applied spectroscopy* **66** 828-34