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Investigation of thermal distribution for pulsed laser radiation in cancer treatment with nanoparticle-mediated hyperthermia

Ameneh Sazgarnia [a], Nadia Naghavi [b,*], Hoda Mehdizadeh [b], Zahra Shahamat [a]

[a] Medical Physics Research Center, Bu-Ali Research Institute, Mashhad University of Medical Sciences, Mashhad, Iran
[b] Department of Electrical Engineering, Faculty of Engineering, Ferdowsi University of Mashhad, Mashhad, Iran

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ABSTRACT

In this paper, we have simulated the efficacy of gold/gold sulfide (GGS) nanoshells in NIR laser hyperthermia to achieve effective targeting for tumor photothermal therapy. The problem statement takes into account the heat transfer with the blood perfusion through capillaries, and pulsed laser irradiation during the hyperthermia. Although previous researchers have used short laser pulses (nanosecond and less), in order to prevent heat leakage to the neighbor tissues, we have examined the effect of millisecond pulses, as the extent of the target volume to which hyperthermia is induced is usually larger and also the lasers with this specification are more available. A tumor with surrounding tissue was simulated in COMSOL software (a finite element analysis, solver and simulation software) and also in a phantom made of agarose and intralipid. The tumor was irradiated by 10, 20 and 30 laser pulses with durations of 15, 50 and 200 ms and fluences of 20, 40 and 60 J/cm^2. Experimental tests performed on a phantom prove the ability of the applied numerical model to capture the temperature distribution in the target tissue. We have shown that our simulation permits prediction of treatment outcome from computation of thermal distribution within the tumor during laser hyperthermia using GGS nanoshells and millisecond pulsed laser irradiation. The advantage of this simulation is its simplicity as well as its accuracy. Although, to develop the model completely for a given organ and application, all the parameters should be estimated based on a real vasculature of the organ, physiological conditions, and expected variation in those physiological conditions for that application in the organ.

1. Introduction

Heat has long been utilized as a therapeutic tool in medicine. Laser-induced thermotherapy aims at achieving the local destruction of lesions, relying on the conversion of the light absorbed by the tissue into heat (Sturesson, 1994). Hyperthermia is applied as an adjuvant technique for cancer treatment. In hyperthermia, the targeted tissue must be elevated to temperatures in the range of 46–50 °C to cause cancerous cell death due to enzymatic processes (Lopez, 2006). Laser heating can result in both tumor necrosis (and possibly apoptosis) and in accelerated tumor growth, depending on the accuracy of heating and on the rise in tumor temperature on illumination with laser light. Specifically, heating up to 39–45 °C may lead to the acceleration of biological reactions accompanied by the production of shock-heating proteins and by intense growth of the tumor. Temperature rise to 46–50 °C is accepted as optimal for hyperthermia treatment (Terentyuk et al., 2009).

One challenge in hyperthermia treatment is localization of heat in the target area to destroy cancerous cells without significantly affecting the surrounding healthy tissue. Recent developments of nanoparticle technology and its application in hyperthermia therapies enable more selective heating and lower thermal doses to be employed to achieve a more precise control of the thermal energy delivered to the tumor region. Nanoparticle mediated hyperthermia results in more effective tumor eradication and minimal destruction of surrounding healthy tissue (Feng et al., 2005). Many studies were focused on different aspects of the laser radiation in various human tissues with embedded nanoparticles (Khlebtsov et al., 2006; Maksimova et al., 2007; Khlebtsov and Dykhman, 2010; Huang and El-Sayed, 2010; Rupesh et al., 2014; Sanjeev et al., 2014).

In this study, the distribution of temperature under exposing gold nanoparticle labeled cells to NIR laser radiation is determined by simulating the absorption of light by nanoparticles acting as point-wise local heat sources, and by thermal diffusion over

* Corresponding author.
E-mail address: n.naghavi@um.ac.ir (N. Naghavi).

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