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Model of optical phantoms thermal response upon irradiation with 975 nm dermatological laser

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ABSTRACT

We have developed a numerical model describing the optical and thermal behavior of optical tissue phantoms upon laser irradiation. According to our previous studies, the phantoms can be used as substitute of real skin from the optical, as well as thermal point of view. However, the thermal parameters are not entirely similar to those of real tissues thus there is a need to develop mathematical model, describing the thermal and optical response of such materials. This will facilitate the correction factors, which would be invaluable in translation between measurements on skin phantom to real tissues, and gave a good representation of a real case application.

Here, we present the model dependent on the data of our optical phantoms fabricated and measured in our previous preliminary study. The ambiguity between the modeling and the thermal measurements depend on lack of accurate knowledge of material's thermal properties and some exact parameters of the laser beam. Those parameters were varied in the simulation, to provide an overview of possible parameters' ranges and the magnitude of thermal response.

Keywords: numerical modeling, tissue-mimicking phantoms, thermography, lasers in medicine, dermatology
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1. INTRODUCTION

The development of optical measurement methods and instrumentation requires their calibration. In case of biomedical applications, the calibration is usually performed using optical phantoms, which resemble the tissues in their optical properties. Numerous phantoms have been developed, suited for specific needs of the technique they are intended for, such as spectroscopy, optical coherence tomography, fluorescence, optoacoustics, and others [1-6].

Here we focus on laser therapy, where the phantoms are utilized due to their optical and thermal properties. We have proposed a potential application of such phantoms in this field, where their optical properties can be precisely tuned, while the thermal response of such phantoms is tested [7]. We have found the need for an optical-thermal model describing their response, so that they could be utilized as a skin substitute.

Here we present a model which matches measured changes in the temperatures of the phantoms upon 975 nm dermatological laser [8] irradiation. The spatial and temporal heat distributions mere measured with an IR camera. The modeling included variable parameters of the laser focus spot, the heat capacitance and heat conductivity of phantoms.

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2. MATERIALS AND METHODS

2.1 Optical tissue phantoms

We have developed optical tissue phantoms with different reduced optical scattering coefficient μ_s' and absorption coefficient μ_a and thickness, for testing the effects of absorption, scattering, and thickness independently during laser irradiation. The resulting properties of produced phantoms are presented in Table 1, along with parameters used in the simulations. The procedure for making the phantoms follows our previously established protocol [9-10]. Briefly, they are based on the polyvinylchloride-plastisol (PVC-P) matrix, which acts as a scaffolding and compromises the bulk of the phantom. The zinc oxide (ZnO) are utilized as a scattering agent. Their size and concentrations used in the matrix material are tailored to match the scattering to that of an average human skin [11].

The μ_a and μ_s' parameters were previously measured using a double integrating sphere spectrophotometer (OL-750, Optronic Laboratories, USA), and later retrieved using the Inverse Adding-Doubling algorithm, as our standard procedure [12]. The optical properties of the phantoms, which were later used in the simulation, at the target wavelength of 975 nm, are shown in Table 1. The scattering coefficients are similar to those mentioned in the literature [13-14], when averaging for the bulk of the skin, including dermis and epidermis.

However, the thermal properties are not an exact match with the properties of skin. Hence the need for the established model, to be able to recalculate the response of a phantom, to match to that what a real skin would have. According to references [15-19], the thermal conductivity of PVCP is 0.14–0.28 $Wm^{-1}K^{-1}$, while the dermis and epidermis are 0.293 – 0.322 $Wm^{-1}K^{-1}$ and 0.209 $Wm^{-1}K^{-1}$, respectively. The thermal capacitance for skin is also higher, at 3200 $Jkg^{-1}K^{-1}$, while for PVCP it is about 1200–2000 $Jkg^{-1}K^{-1}$, at 298 K. We propose that these discrepancies are possible to be overcome if we apply a correction factor to the phantom measurements, based on the developed model.

Table 1. Optical parameters of produced optical tissue phantoms used in the simulations

\	Phantom 1	Phantom 2	Phantom 3
μ_a	2.04 cm^{-1}	1.94 cm^{-1}	0.42 cm^{-1}
μ_s	106.5 cm^{-1}	103.5 cm^{-1}	134.5 cm^{-1}
g	0.8		
n	1.44		
L	2 mm	1 mm	1 mm
R_s	0.033		
R_d	0.246	0.247	0.44
A	0.648	0.47	0.157
T	0.074	0.25	0.37
Q_0	$5 \cdot 10^6$ $W \cdot m^{-3}$		
D	10, 12, 14 [mm]		
C_p	1000, 1500, 2000 [$J\ kg^{-1}K^{-1}$]		
k	14, 28, 42 [$W\ m^{-1}K^{-1}$]		

3. EXPERIMENTAL

The modeling was performed to match the experimental results of our previous preliminary study on dynamic photothermal therapy utilizing optical tissue phantoms [7,20-21]. The detailed description of the experimental procedure, the laser system and the IR camera is provided therein. In short, a laser system based on a high-power laser diode with 975 nm wavelength was used to irradiate the phantoms [8]. The system is capable of generating impulses within a specified range of parameters: the length of the pulse (τ = 100 ns ÷ 300 ms with step $\Delta\tau$ = 100 ns), and the pulse period (t = 50 ÷ 500 ms with step Δt = 10 ms), and output power level, P = 0 ÷ 20 W. The laser settings for the experiment were as follows: τ = 25 ms, t = 50 ms, N = 60, P = 10 W.

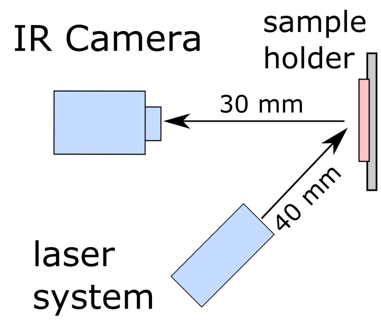

Fig. 1. Set-up for measurement of thermal effects on phantoms.

4. MODELING

The evolution of spatial distribution of temperature field in time is found from the solution of three-dimensional equation of non-stationary heat conductivity in a region limited by the dimensions of the phantoms. The initial condition is described in the form $T_{init} = T_0$. The distribution of the absorbed power $Q(x,y,z)/Q_0$ was calculated by method of Monte Carlo. The simulation was performed with Monte Carlo code described in the references[22-23] for a Gaussian form of incident beam.

Parameters of the simulation are such: number of photons = 500 000; number of points over z coordinate – 100; number of points over radial coordinate – 200 (50 mm). For each phantom three sets of calculations with different 1/e radius of the Gaussian beam at surface were performed for 1) 5 mm, 2) 6 mm, and 3) 7 mm.

In this case, the coordinates of axis position of the laser beam irradiating the phantom were determined by the location of experimentally recorded maximum of phantom surface temperature from the measured heat distributions [7] shown in Fig. 2(a), 3(a) and 4(a). The results of calculating the absorbed power function for three phantoms are shown in Fig. 2(b), 3(b) and 4(b), respectively. On the phantom surfaces, adiabatic boundary conditions are given that describe the assumption of negligible losses due to natural convection during the experiment. In general, the technique for modeling the biotissue under laser irradiation, adapted to solve the problems being formulated in this paper, is described in [24].

Variation of thermal parameters of phantoms and the laser beam diameter for a given distribution of absorbed power function in the simulation leads to the production of temperature distributions family. Then the problem of identifying reliably unknown parameters reduces to constructing a residual function, a comparative analysis of calculated results with the experimental results and the choice of the solution with the smallest discrepancy. In the simplest case, the maximum temperature on the surface of the phantom can be chosen as such a sensitive parameter.

The resulting dependences of the maximum temperature on the diameter of the laser beam, the thermal conductivity and the specific heat of the phantom material are shown in Fig. 5. As can be seen, the revealed criticality of the maximum temperature level to a change in these parameters allows us to determine with a high degree of reliability a set of parameters in which agreement with the experimental data is maximum for both the phantom 1 (Fig.5a) and phantom 2 (Fig.5b), and exactly: D = 14 mm; k = 0.14 W $cm^{-1}K^{-1}$; C = 2000 J $kg^{-1}K^{-1}$.

The complication of the residual function due to the increase in the number of points in which the difference between the experimental and calculated temperatures is recorded will increase the sensitivity and efficiency of this method.

5. RESULTS AND CONCLUSION

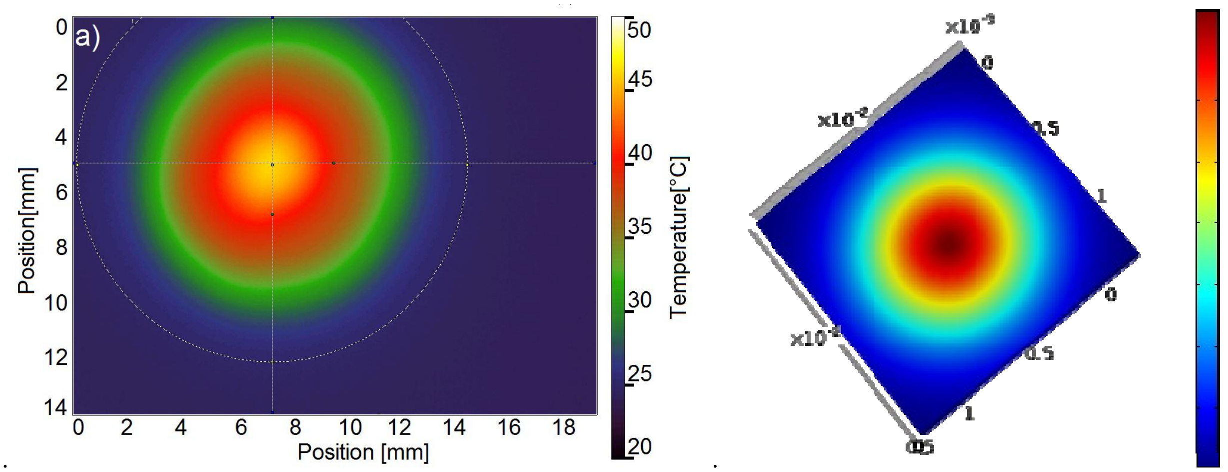

Fig. 2. Phantom "1": Spatial distribution of temperature (a), from [7], and the spatial distribution of the absorbed power Q/Q_0.

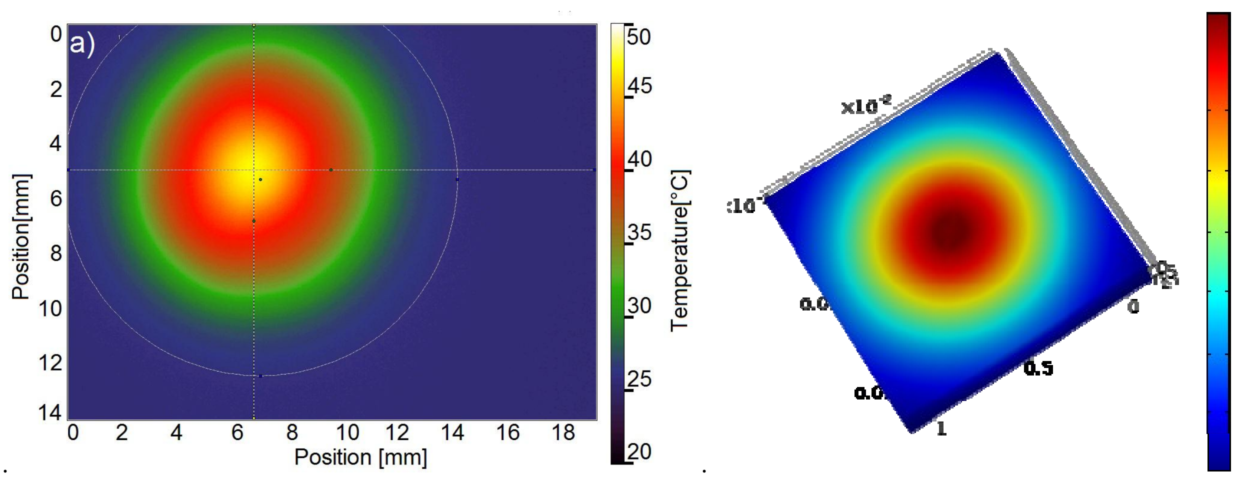

Fig. 3. Phantom "2": Spatial distribution of temperature (a), from [7], and the spatial distribution of the absorbed power Q/Q_0 (b).

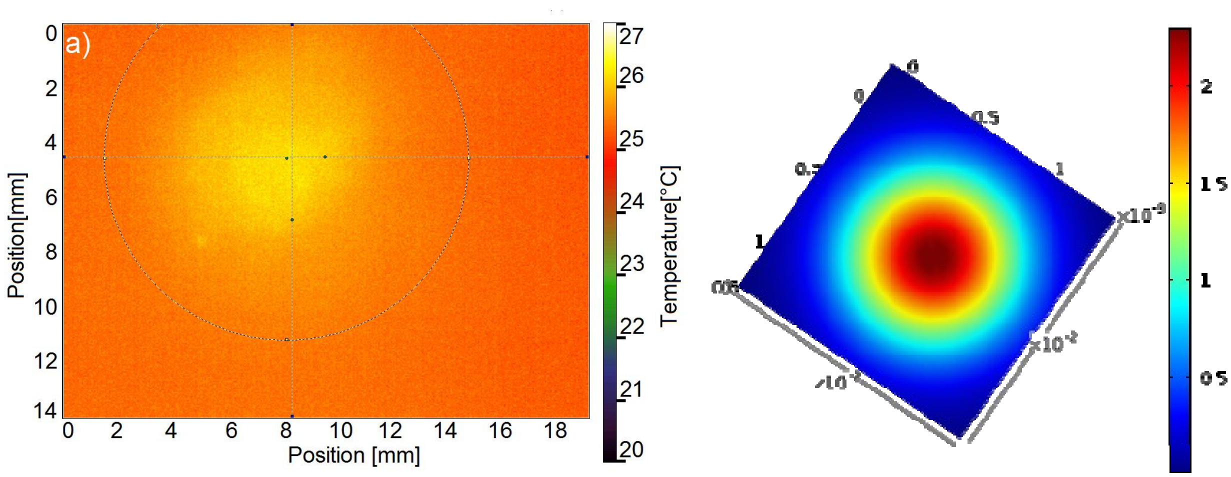

Fig. 4. Phantom "3": Spatial distribution of temperature (a), from [7],The spatial distribution of the absorbed power Q/Q_0 (b).

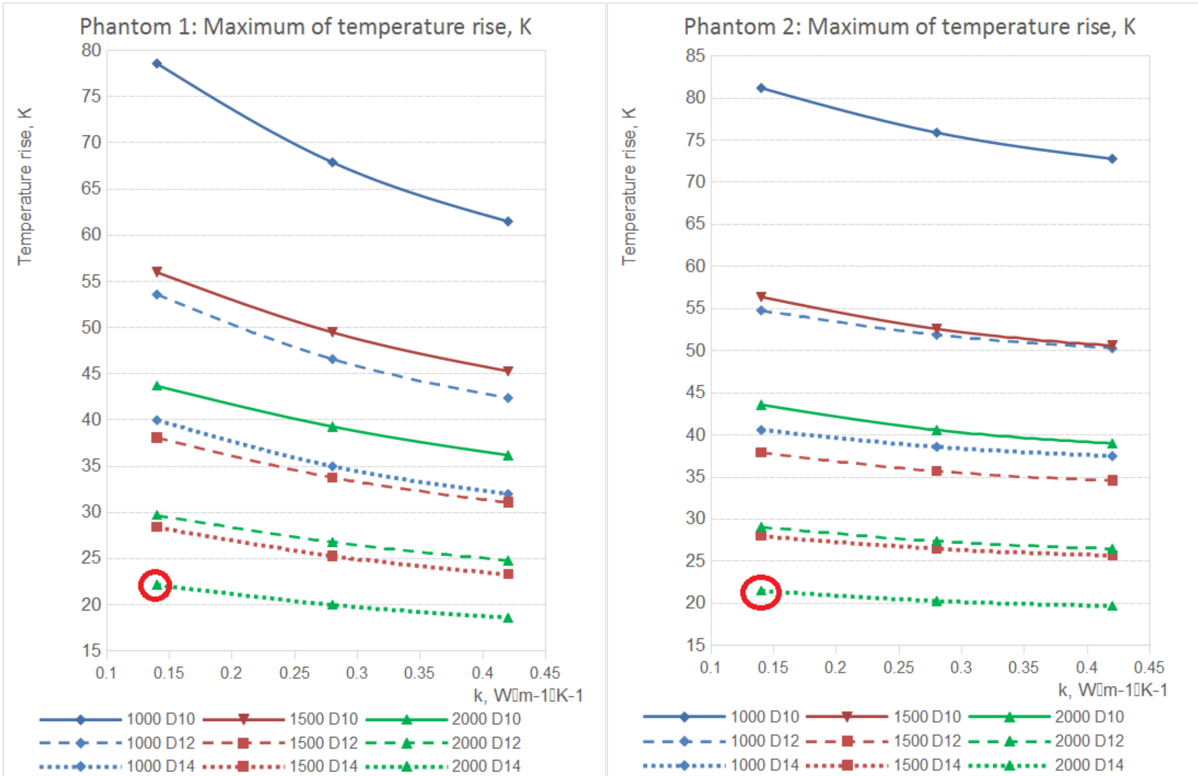

Fig. 5. Results of numerical simulation of peak temperature rise after 3s of heating for phantom "1" (a), and phantom "2" (b). The red circle denotes the matching between modeling and measurements.

The numerical model describing the optical and thermal behavior of optical tissue phantoms upon laser irradiation is developed. The evolution of spatial distribution of temperature field in time is found from the solution of three-dimensional equation of non-stationary heat conductivity in a region limited by the dimensions of the phantoms. The method of identifying reliably unknown phantom parameters is described. It reduces to constructing a residual function, a comparative analysis of calculated results with the experimental results and the choice of the solution with the smallest discrepancy. The effectiveness of the described method of parameter identification is demonstrated on practical examples.

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