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Numerical Investigation of Laser-Induced Thermotherapy in Human Tissue

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Abstract

Advance of laser in medical application has motivated the widespread to use of thermal to treat a wide variety of cosmetic dermatologic problem. This is also the well-known tool in the fight against the signs of ageing and the specifically technic which results in heating from the absorbed light energy. However, excessive laser irradiation can cause acute injuries if thermo-physiologic response to thermotherapy during laser irradiation is not well understood. Therefore, it is interesting to investigate on the laser- induced thermal effect in skin during laser irradiation. In this study, a transient thermal model based on unsteady bio-heat transfer equation coupled with Beer-Lambert's law is developed and numerically solved. Then heat transfer in layered skin exposed to laser irradiation is analyzed. The effects of laser irradiation time, wavelengths and laser intensity on the temperature distributions in the layered skin during laser irradiation are systematically investigated. The obtained values provide an indication of limitations that must be considered during laser-induced thermotherapy in practical treatment.

Keywords: laser, irradiation, bioheat transfer, tissue, skin, thermotherapy

1. Introduction

In certain medical treatment applications laser light sources are used to generate thermal effects in tissue. In these treatments, the most important issue is to control the temperature increase and distribution over the living tissue; otherwise, high temperatures could potentially cause undesired thermal damages in the surrounding pathology. The thermal response of the tissue that is exposed to laser light mainly depends on the thermal and optical properties of each tissue, the light source and the other parameters. In medical treatment applications with light, prediction of thermal response of tissue can be realized by utilizing simulation tools such that selection of laser light dosage and irradiation time on the subject tissue can be done appropriately [1].

Most studies of heat transfer analysis in biological tissue used bioheat equation. Pennes's bioheat equation, introduced by Harry H. Pennes on 1948 [2], where the model based on the heat diffusion equation, is a frequency used for analysis of heat transfer in biological tissues. Nevertheless, mathematic model prediction of biological tissue based on Pennes's equation is quite good for micro vessels, however, in the presences of large vessels, more complicated models are recommended.

The studies of high temperatures tissue ablation using a modified bioheat equation during heating have been proposed by many researchers. Okajima et.al. [3] derived the dimensionless steady-state solutions of bioheat transfer equation to discuss the bioheat transfer characteristics common to all organs or tissues. Chua and Chou [4] have developed a bioheat model to study the freeze–thaw thermal process of cryosurgery.

Our research group has numerically investigated the temperature increase in human tissue subjected to EM fields in many problems [5-7]. Wessapan et al. [5-6] utilized a 2D finite element method (FEM) to obtain the specific absorption rate (SAR) and temperature increase in the human body exposed to leaked EM waves. Keangin et al. carried out a numerical simulation of liver cancer treated using a mathematical model that considered the coupled model of EM wave propagation, heat transfer, and mechanical deformation in the biological tissue in the couple's way [7].

Recently, transport models of biological tissue have been rapidly developed and have been used extensively in studies of dermatology implications during exposed to laser irradiation and prediction of therapeutic responses to laser irradiation.

Lee and Lu, 2014 [8] carried out numerical analysis of heat transfer in three-dimensional skin tissue model with an embedded vascular system of actual histology structure. Pual et al., 2014 [9] studied the cooling effects of large blood vessels on temperature distribution in tissues during laser irradiation based on Beer–Lambert law. Chen et al. 2014 [10] presented the numerical calculation solution of the finite element method of skin model after laser irradiation with four wavelengths of 532 nm, 694 nm, 755 nm, and 800 nm. Singh et al., 2015 [11] demonstrated the numerical simulation of two dimensional axisymmetric cylindrical skin model with irradiation of continuous wave laser beam based on Pennes's heat transfer equation for minimizing undesired thermal damage. Bhowmik et al., 2015 [12] represented ablating breast tumor during focused ultrasound and laser heating model with bioheat transfer analysis.

However previous studies have mainly focused on the modeling and the influence of the specific parameters, such as, wavelength. They have been a few work to investigate the systematic studies of the effects of operating parameters such as laser wavelength, laser irradiation intensity, type of tissues and irradiation time on the heat transfer in the layered skin, although it directly affects the therapeutic heat transfer effect during treatment. In practical situation, these effects lead to enhance the heat and transfer process of absorption within the target tissue, which can cause changes in temperature within tissues. Therefore in order to provide adequate information on the appropriate level of laser transition from laser instrument, it is essential to consider all of the previously mentioned parameter in analysis.

In this study, the temperature distribution during laser induced thermotherapy is investigated with a developed 3 layered skin model. Finite element method (FEM) is applied for modeling of numerical simulations to analyze the temperature changes in layer of skin tissues which employs the energy absorption of the laser irradiation described by the Beer-Lambert's law and the Pennes's bioheat model for the spatial transient temperature distribution. The objective of this research is to propose modeling of the laser-tissue interaction. The obtained results can optimize the effective parameters in order to understand optimal laser dosage to prevent the damage. Furthermore, effects of operating parameters, namely, laser wavelength, laser intensity, type of tissues and irradiation time on the heat transfer during the laser induced thermotherapy in the layered skin are systematically investigated.

2. Formulation of the Problem

According to the real biological structure, skin is divided into three layers: epidermis, dermis and subcutaneous tissue [13]. When the skin tissue exposed to laser irradiation, the temperature gradient within the outer skin, epidermis and dermis layers, plays an important role in heat conduction mode. This study investigates the effects of operating parameters on the heat transfer in the layer of skin during subjected to laser irradiation. Due to ethical consideration, exposing the human to laser irradiation for experimental purposes is limited. It is more convenient to develop a realistic human skin model through the numerical simulation.

3. Methods and Model

The study focuses attention on the differences in heat transfer characteristics of the skin induced by laser beam from medical instrument in different the therapeutic situations. Finite element method (FEM) is applied for modeling of numerical simulations to analyze the temperature changes in layered skin which employs the energy absorption of the laser irradiation described by the Beer-Lambert's law and the Pennes's bioheat equation for the spatial- temporal temperature distribution.

3.1 Physical Model

A 2D asymmetrical model of the layered skin, which refers to the physical model in the previous research is developed [14]. Fig. 1(a) and (b) show the 3D and 2D asymmetrical plane of the skin model used in this study, respectively.

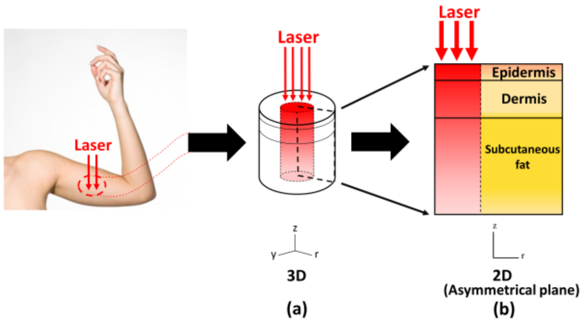

Fig. 1 The skin model, (a) 3D skin model with laser irradiation, (b) 2D skin model with laser irradiation

3.2 Equations for Heat Transfer Analysis

The temperature distribution within the layered skin is obtained by solving the Pennes's bio-heat equation [2]. The transient bioheat equation effectively describes how heat transfer occurs within the layered skin, and the equation can be written as

$$\rho C\frac{\partial T}{\partial t}=\nabla\cdot(k\nabla T)+\rho_b C_b\omega_b(T_b-T)+Q_{met}+Q_{Laser} \tag{1}$$

where ρ is the tissue density (kg/m^3), C is the heat capacity of tissue (J/kg K), k is thermal conductivity of tissue (W/m K), T is the tissue temperature (° C), T_b is the temperature of blood (° C), ρ_b is the density of blood (kg/m^3), C_b is the specific heat capacity of blood (J/ kg K), ω_b is the blood perfusion rate (1/s), Q_{met} is the metabolism heat generation (W/m^3) and Q_{Laser} is the external heat source term related to laser irradiation (W/m^3). Heat transfer coefficient, h and ambient temperature, T_{am} are specified, respectively as 10W/m^{2}k and 25˚C.

3.3 Boundary Condition

According to an axisymmetrical plane, as shown in Fig. 1b. The physical domain and the boundary conditions are indicated in Fig.2

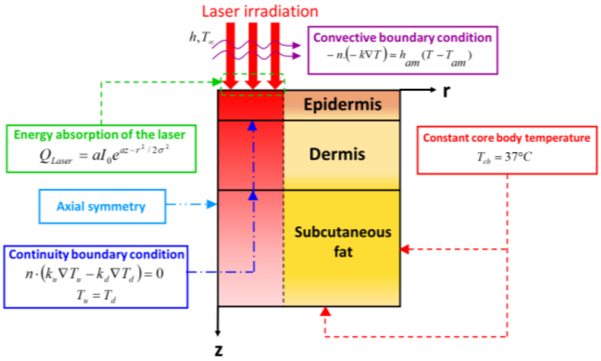

Fig. 2 Physical domain and boundary conditions

Consider the laser beam irradiation, the boundary condition will be applied on the boundary of the model in the direction of the laser beam in order to simplify the solution. Therefore, the laser intensity along tissue depth (z) is described by the Beer-Lambert's law as follows,

$$I(z) = I_0 e^{-az} \tag{2}$$

The energy absorption of the laser irradiation can be expressed as follows,

$$Q_{Laser} = aI_0 e^{az - r^2/2\sigma^2} \tag{3}$$

where I is the laser irradiation intensity (W/m^2), I_0 is the irradiation intensity at the skin surface (W/m^2), a is the absorptivity of the tissue (1/m), and z is the depth of tissue and σ is the width of the irradiated area (mm).

3.4 Calculation Procedure

In this study, bioheat equation and related boundary conditions are numerically simulated by using FEM with COMSOL^{TM} Multiphysics software.

The 2D axissymmetrical model is discretized using triangular elements. Convergence test of the wavelength 532 nm, intensity 1.5 W/mm^2 are carried out to identify the suitable number of elements required. The convergence curve resulting from the convergence test is shown in Fig.3. This convergence test leads to the grid with approximately 40,000 elements. It is reasonable to confirm that, at this element number, the accuracy of the simulation results is independent from the number of elements.

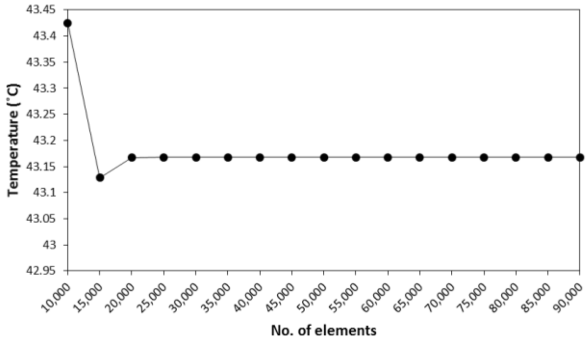

Fig. 3 Grid convergence curve of the model

4. Results and Discussion

In this study, the effects of laser irradiation wavelength, irradiation time and laser intensity on the temperature distribution in the layered skin during laser induced thermotherapy are systematically investigated. Numerically, the wavelengths of 532 nm, 755 nm and 800 nm, which are referred to actual clinical treatment, are selected and assuming the output of the laser beam is continuous. Further, the laser irradiation intensities of 1 W/mm^2, 1.5 W/mm^2, 2 W/mm^2 are selected. It is supposed that the laser beam is circular and laser irradiates the skin perpendicularly. Considering layered skin tissue, the thickness of epidermis, dermis and subcutaneous fat are set as 0.05 mm, 1.95 mm and 10 mm, respectively, and the radius of the domain is 10 mm.

For the simulation, the absorption coefficients of different wavelengths in epidermis of the upper inner arm is directly taken from Tseng et al., 2009 [15]. Nevertheless, for all these laser wavelengths, the absorption coefficients of dermis and subcutaneous tissues are from Aguilar et al., 2002 [16], as 0.24 (1/mm) and 0.24 (1/mm), respectively. The thermal properties and skin thickness are obtained from Chen et al., 2014 [17] and metabolic heat generation is obtained from Bhowmik et al., 2015 [12].

4.1 Verification of the Model

In order to verify the accuracy of the present numerical model, the modified case of the simulated results is then validated against the numerical results with the same geometric model obtained by He et al., 2004 [18]. The axially symmetrical of two layers skin tissue with cancerous tumor is used in the validation case. In the validation case, the laser irradiation is exposed to the skin with intensity of 1.4 W/mm2. The results of the selected test case are illustrated in Fig. 4 for temperature distribution in the skin with cancerous tumor. A good agreement of the temperature profile with elapsed times between the presented study and that of He et al., 2004 [18] is clearly shown.

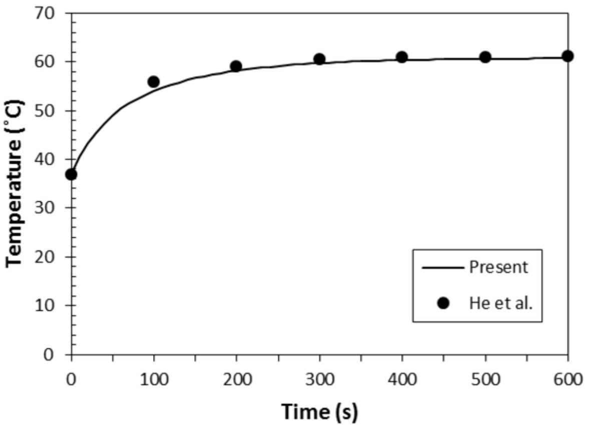

Fig. 4 Comparison of the calculated temperature profile between presented study and work of He et al., 2004 [18]

4.2 Temperature distribution

As explained in previous section, during laser induced thermotherapy, it is necessary to control the temperature increase as well as hot spot zone. This high temperature could lead to undesired thermal damage in the surrounding healthy tissues. The temperature increase during laser induced thermotherapy mainly depends on irradiation time, laser intensity and wavelength exposed to the laser beam. Following discussion will refer to all of these two parameters.

Fig.5 shows result of the skin temperature changes (at the position of z=0, r=0) with elapsed times at the different laser intensities with wavelengths of 532 nm, 755 nm and 800 nm, respectively. It can see that laser with wavelength of 532 nm has highest maximum temperature for all of intensity level. More intensities provide faster temperature increases as well as heat up.

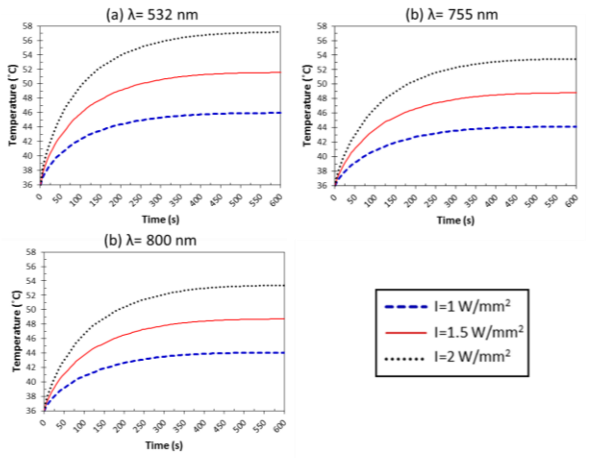

Fig. 5 The temperature changes (at the position of z=0, r=0) with elapsed times at the different laser intensities (1 W/mm^2, 1.5 W/mm^2 and 2 W/mm^2) and wavelengths of (a) 532 nm, (b) 755 nm and (c) 800 nm, respectively.

However, at the time progresses (Fig. 6), the wavelength of 532 nm still has the highest maximum temperature for all three intensities when compared with the wavelength of 755 nm and 800 nm. Moreover, the hot spot area with wavelength of 532 nm is wider and has higher temperature at the skin surface. This is because the effect of absorption coefficient of epidermis layer. When provide more irradiation time up to 600 s, even intensities increase to 1.5 W/mm^2 and 2 W/mm^2, the maximum temperature with wavelength of 755 nm and 800 nm are still occurred deep inside the skin layer as illustrated in Figs.6 (b) and (c), which is in contrast with case of short wavelength where the upper surface or skin surface is always highest temperature than deep inside. This is because the effect of thermal conductivity plays an important role in the conductance of the laser energy absorbed and the irradiation time is long enough for allowing heat diffusion into the deeper layer. This phenomenon has not been discussed in details before in previous work.

Fig.7 shows the temperature distribution in the layered skin along the radial direction (r-axis and z=0)

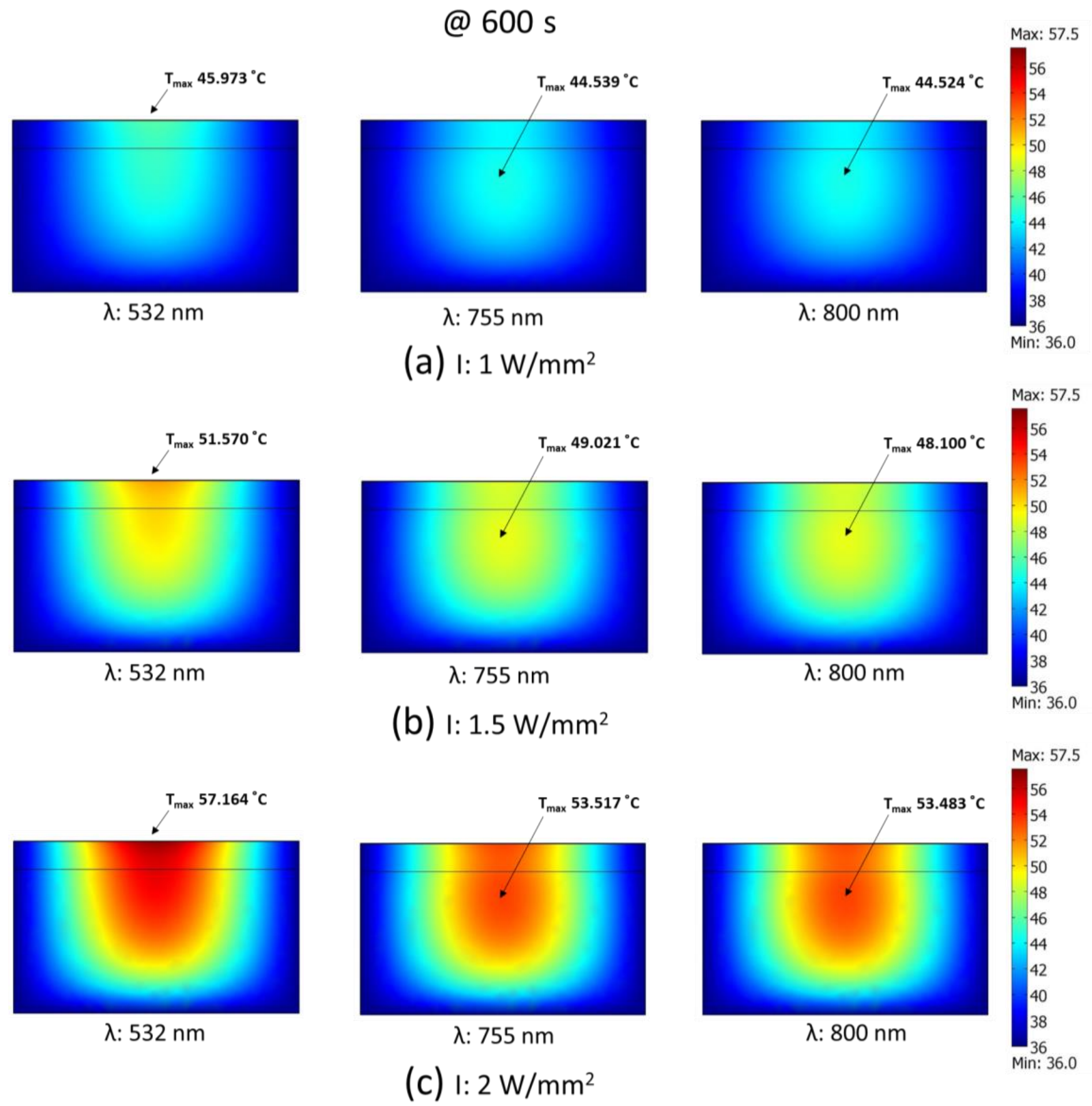

Fig. 6 The temperature distribution in skin after irradiation with three different wavelengths, where irradiation duration of 600s, the wavelengths are 532 nm, 755 nm and 800 nm. (a)-(c) correspond to intensities of 1 W/mm^2, 1.5 W/mm^2 and 2 W/mm^2, respectively.

and longitudinal direction (z-axis and r=0) for 600 s, at wavelengths of 532 nm, 755 nm and 800 nm, exposed to laser irradiation intensities of 1 W/mm^2, 1.5 W/mm^2 and 2 W/ mm^2, respectively. From figure shows that the short wavelength (532 nm) displays a highest center temperature and largest area for the remarked same temperature, especially at the center of leading edge which closed to the laser irradiated beam. This means that the epidermis absorbed more energy and then converts it into heat for case of short wavelength than other two wavelengths (755 nm and 800 nm). This is due to the effect of optical properties, i.e., absorption coefficient of epidermis layer which its value vary with wavelength, and also the effect of thermal parameters of tissues in each layer are much different. Further, from this simulated results seem that the temperature increase at the irradiation center region is highest and its decrease from the irradiation region to the surrounding healthy tissues (for both of radius and longitudinal directions) for all wavelengths and laser intensity, after applied laser irradiation. The latter arises from the fact that heat from the hot spot zone in center region will diffuse to cold region in surrounding tissues, particularly, longitudinal temperature distribution affects heat diffusion through the different layers in tissues. It is remarkable that, the high temperature area decreases with increasing the wavelength and the temperature at irradiation center region decreases with increasing the wavelength. The temperature gradient along the longitudinal direction is greater than that of radial direction. This is because of the upper surface of skin (z=0) is considered as convective boundary condition which will continuously convey heat along radial direction to surrounding. It can be observed that the temperature distribution in both directions are not different for these two wavelengths (755 nm and 800 nm). The increasing of laser intensity level leads to more energy absorption and causes a highest temperature distribution in all wavelengths.

5. Conclusion

The numerical simulation of the transient temperature distribution within the layered skin tissue during laser-induced thermotherapy in different treatment conditions has been performed. In the skin tissue model, the effects of laser wavelength, laser intensity, and irradiation time on heat transfer in the tissue are systematically investigated. In this study, a coupled bioheat transfer equation and laser irradiation have been solved using Finite Element Method (FEM) for a 2D asymmetrical model of the layered skin tissue. As a result, the temperature distribution and laser penetration depth depend strongly on the wavelength and laser irradiation intensity. Under the same intensity and irradiation time, the increasing wavelength of laser leads to decreases skin temperature. It is found that, the laser energy absorption is significantly higher in the shorter wavelength range (532 nm). The level of laser intensity has strongly effect to the temperature increase within the tissues where the higher intensity level provides higher temperature within the tissues.

As the result, it should be specially be careful when treatment the patient and should be reduce intensity level for reduction of unwanted thermal injury. Thus, as appropriate settings are necessary for highly effective and safe treatment. In addition, it is found that greater laser intensity results in a greater laser energy absorbed by the layered skin tissue. Moreover, this study also shows that irradiation time has also marked influence on temperature increase in the skin tissue.

The obtained results contribute to the understanding of the realistic situation and prediction of the temperature distribution in the layered skin tissue during laser-induced thermotherapy in different treatment conditions.

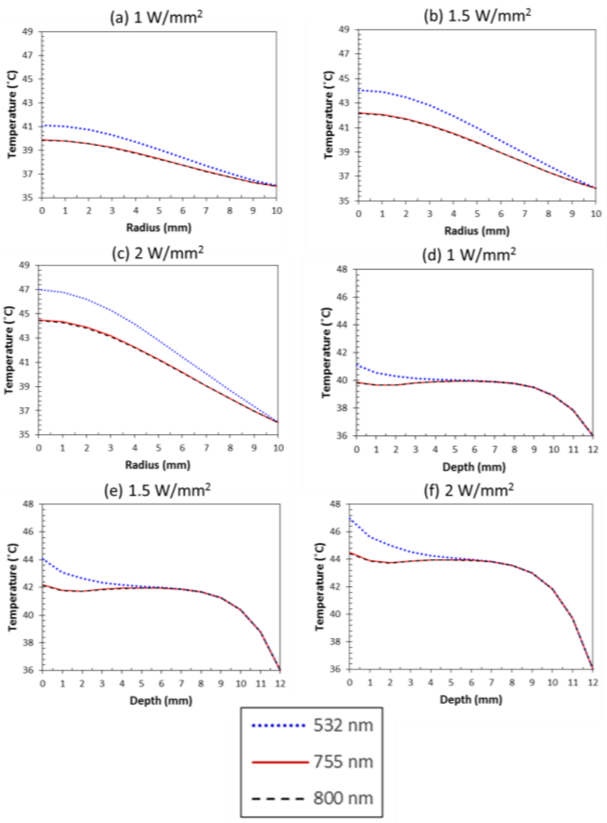

Fig. 7 The temperature distribution along the radial (a-c) and longitudinal direction (d-f) with wavelengths of 532 nm, 755 nm and 800 nm (Intensities of 1 W/mm^2, 1.5 W/mm^2 and 2 W/mm^2 and irradiation time of 600s)

6. Acknowledgement

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