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Research paper

Modeling skin cooling using optical windows and cryogens during laser induced hyperthermia in a multilayer vascularized tissue

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HIGHLIGHTS

- Skin surface cooled laser induced hyperthermia is studied.
- A multi-layer 2-D cylindrical tissue geometry is considered.
- Both Pennes and Weinbaum–Jiji bioheat models are considered.
- Laser transport in the tissue is modeled using discrete ordinate method.
- Results for 4 optical windows and 2 cryogens for skin cooling are presented.

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ABSTRACT

This article deals with the spatial and the temporal evolution of tissue temperature during skin surface cooled laser induced hyperthermia. Three different skin surface cooling methodologies viz., optical window contact cooling, cryogenic spray cooling and cryogen cooled optical window contact cooling are considered. Sapphire, yttrium aluminum garnet, lithium tantalate, and magnesium oxide doped lithium niobate are the considered optical windows. The cryogens considered are liquid CO_2 and R1234yf. Heat transfer in the multilayer skin tissue embedded with thermally significant blood vessels pairs is modeled using the Pennes and Weinbaum–Jiji bioheat equations. Weinbaum–Jiji bioheat equation is used for the vascularized tissue. Laser transport in the tissue is modeled using the radiative transfer equation. Axial and radial (skin surface) temperature distributions for different combinations of optical windows and cryogens are analyzed. Liquid CO_2 cooled yttrium aluminum garnet is found to be the best surface cooling mechanism.

1. Introduction

Laser induced hyperthermia and thermal therapy are emerging as promising methods of treatment for many ailments like port-wine stain, and diseases like malignant tumors [1–3]. During such procedures, light energy gets absorbed in tissue and the absorption starts from the skin surface in case of external laser irradiation. Therefore, the maximum thermal energy produced is in the skin and the tissue layers immediately below the skin surface (dermis and subcutaneous layers). The multilayer skin tissue is composed of epidermis, the outermost layer, the intermediate dermis, and internal vascular tissue with layers of fat. The epidermis contains melanin which is characterized by high absorption of light, and is therefore most susceptible for thermal damage during laser heating of tissues [4,5]. In any externally irradiated hyperthermia procedure, principal aim is to provide treatment to target tissue while minimizing thermal damage to the skin surface. Therefore in any such procedures, which involve high temperatures, cooling the skin is desirable.

Many methods of skin cooling during laser induced hyperthermia and thermal therapy have been proposed by researchers [6,7]. Optical window surface contact cooling and cryogenic spray cooling are widely used methods for the skin surface cooling. Contact type cooling using optical windows and spray type cooling using

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Nomenclature

a	vessel radius
ρ, ρ_b	density of tissue and blood
$h_o^*(\tau)$	normalized heat transfer coefficient
k	thermal conductivity of tissue
k_{eff}	effective thermal conductivity
η_b	blood perfusion rate
Q_m	metabolic heat generation rate
T_a	arterial blood temperature
λ	wavelength
u	average blood velocity
c_p, c_{pb}	specific heat capacity of tissue and blood
$h_{cryo}(0,\tau)$	surface heat transfer coefficient
$h_{o,max}$	maximum heat transfer coefficient
$I_{c,max}$	intensity
κ_a	absorption coefficient
p	scattering phase function
n	number of vessel pairs
σ_{sf}	shape factor
σ_s	scattering coefficient
τ	non-dimensional time

cryogens has been studied by many researchers in detail [8–10]. Zenzie et al. [11] studied three different application procedures of cooling agent, viz. passive contact plate cooling, active contact plate cooling and spray cooling.

Optical windows are transparent material with applications in laser optics, electronics, and medicine [12]. For applications in laser induced hyperthermia and thermal therapy procedures, optical windows are used for providing a highly conducting contact cooling material which passes most of light through it [6,13]. This provides a way of simultaneously heating the tissue deep inside from the surface while preventing thermal damage to top surface of skin [14,15]. For contact cooling application, sapphire is most preferred material because of its wide range of transparency from UV to IR wavelengths, high strength and high conductivity. Optical quality crystalline aluminum oxide or sapphire is characterized by very high thermal conductivity, approximately 23 W/m K, high stability and hardness. Sapphire also has high threshold for optical damage [13]. In the present study, three new optical materials with thermal conductivity comparable or greater than sapphire are examined for suitability for contact cooling applications. The new optical window materials viz. sapphire (Al_2O_3), yttrium aluminum garnet (YAG), lithium tantalate ($LiTaO_3$), and magnesium oxide doped lithium niobate ($MgO{:}LiNbO_3$), were selected based on their ability to pass light between wavelength range of medical lasers i.e. between 500 nm and 1200 nm [16–19]. Other important properties for selection were high conductivity, low reflection loss, stability, hardness, insolubility, non-toxicity, and high threshold for optical damage. Yttrium aluminum garnet is a synthetic, hard material with wide transparency range between UV and IR. Lithium Tantalate and Magnesium Oxide doped Lithium Niobate, apart from having high thermal conductivities, also exhibits wide range of transparent window ranging from UV to IR wavelengths. A theoretical assessment of suitability of these four materials for contact cooling application is done.

Cryogenic liquids, also known as cryogens, have very low boiling point (typically less than −30 °C) [20–22]. At low temperatures, cryogens are in their liquid state. When exposed to normal temperature and pressure conditions, cryogens expand into large volume of gas. For spray cooling, the scattering from the cryogen is ignored, as desired results can be achieved by varying the laser power. The two cryogens selected in the present study are HFO-1234yf or R1234yf (Boiling point −30 °C) and liquid CO_2 (Boiling point −57 °C), and the selection criteria followed are low boiling point, low global warming potential and low toxicity [23].

2. Model and formulation

In the present study a quantitative evaluation of skin surface cooling during laser induced hyperthermia and thermal therapy is performed. Schematic of the multilayer skin tissue with deep vascularized soft tissue is shown in Fig. 1a. The tissue consists of skin layer viz. epidermis, dermis, and fatty soft tissue. The fourth (bottom) layer of tissue is a vascularized tissue with embedded large blood vessel pairs. Heat transfer in the top three layer and the fourth (bottom) layer are modeled using the blood perfusion based Pennes bioheat equation [24] and blood velocity based Weinbaum–Jiji bioheat equation, respectively. The computational geometry, shown in Fig. 2a, is a 2-D axisymmetric cylinder, with a 2-D planner solution space. The modeling of laser propagation and absorption in biological tissue is done by solving the radiative transfer equation (RTE) [25]. The 3-D control volume for solution of RTE is shown in Fig. 2b. A solver for collimated radiation modeling is developed using discrete ordinate method (DOM) [26]. The volumetric radiative source term, in the form of the divergence of radiative heat flux is incorporated in Pennes bioheat as well as Weinbaum–Jiji models. With radiative information computed using the discrete ordinate method, the bioheat energy equations are solved using the finite volume method (FVM) [27].

Laser of wavelengths of 1064 nm, irradiated on top surface of 2-D cylindrical tissues geometry is considered. To the best of our knowledge, this is the first time when a set of radiative transfer equation for laser transport and light absorption, along with Pennes bioheat equation for blood perfused tissue, and Weinbaum–Jiji bioheat equation for vascularized deep tissue is applied in conjunction. Also for numerical study of skin surface cooling, both optical window contact and cryogenic spray types, this is first attempt to model a realistic real-time scenario of laser heating of multilayer skin with deep seated tissue embedded with thermally significant blood vessels. A perfect contact between the skin and optical window is assumed for all cases of contact cooling. In practice, a near perfect contact can be achieved by applying high conductive gels on the skin.

For a 2-D axisymmetric cylindrical geometry, Pennes bioheat equation is given by,

$$\rho c_p \frac{\partial T}{\partial t} = k\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial z^2}\right] + \eta_b \rho_b c_{pb}(T_a - T) + Q_m \qquad (1)$$

where ρ_b and c_{pb} are the density and the specific heat of blood, respectively. ρ, c_p and k are the density, the specific heat, and the thermal conductivity of the tissue, respectively. With arterial blood temperature T_a,η_b is the blood perfusion rate and Q_m is the volumetric metabolic heat generation rate.

For the 2-D cylindrical geometry (Figs. 1 and 2a), the Weinbaum–Jiji (WJ) model can be expressed as,

$$\rho c \frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(r k_{eff}\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(k_{eff}\frac{\partial T}{\partial z}\right) + Q_m \qquad (2)$$

where ρ, c, k_{eff} and Q_m are the density, the specific heat, the effective thermal conductivity and the volumetric metabolic heat generation rate of the tissue, respectively. The effective thermal