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Radiative heating of superficial human tissues with the use of water-filtered infrared-A radiation: A computational modeling

Leonid A. Dombrovsky [a,*], Victoria Timchenko [b], Chinmay Pathak [b], Helmut Piazena [c], Werner Müller [d], Michael Jackson [e]

[a] Joint Institute for High Temperatures, Krasnokazarmennaya 17A, NCHMT, Moscow 111116, Russia
[b] School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney 2052, Australia
[c] Medical Photobiology Group, Charité – Universitätsmedizin Berlin, Berlin, Germany
[d] Dr. h.c. Erwin Braun Foundation Basel, Switzerland
[e] Prince of Wales Clinical School, University of New South Wales, Sydney 2052, Australia

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ABSTRACT

A computational model of both the absorbed radiation and transient temperature fields in multilayer superficial human tissues in the case of an external water-filtered infrared-A irradiation is developed. A novel simplified model for radiative transfer is based on local 1-D solutions taking into account the oblique incidence of radiation at the periphery of the heated region. The computational study of a model problem at typical geometrical, optical, and thermal parameters confirms the acceptable accuracy of the 1-D solution for the temperature field formed in human tissues during thermal treatment with periodic infrared irradiation. The effects of uncertainties in spectral absorption coefficients and thermal conductivity of biological tissues on thermal treatment parameters are analyzed. It is shown that the temperature response to periodic water-filtered infrared-A heating can be used to estimate optical properties of human tissues. The calculations show that the decrease in convective heat transfer with the heating of air in the gap between the radiation source and the body surface has to be taken into account.

1. Introduction

In clinical applications, water-filtered infrared-A (wIRA) irradiation is generated by passing the full spectrum of radiation of a halogen bulb through a cuvette, containing water, to reduce the undesired irradiation within the spectral range characterized by high values of the absorption coefficient of water. After water filtering, the spectrum of the transmitted radiation is within the therapeutically desired window ($0.78 < \lambda < 1.4\ \mu$m) and therefore can produce a therapeutically usable volumetric heating of the tissue. In addition, the ability of wIRA to penetrate deeply into tissues stimulates the basic energy processes in the mitochondria of cells within the exposed area and results in direct stimuli on cells and cellular structures [1].

Due to the increase of the tissue temperature as well as the improvement of both the energy supply per time (increase of metabolic rate) and the oxygen supply, wIRA has shown good clinical effects on wounds and wound infections [2] as well as in applications of photodynamic therapy [3]. Thermography guided water-filtered infrared-A hyperthermia has been successfully used for local recurrent breast cancer with promising clinical results [4].

Despite the various applications of wIRA irradiation in medicine the methodological description in studies of cellular responses after wIRA exposure in single cells and skin is insufficient or absent [5]. This includes information about the experimental setups for wIRA exposure (e.g., wIRA emitter, water filter thickness, other filter sets, the resulting spectral irradiance of the unit); the method of cooling or temperature regulation of the sample during irradiation (i.e., air or water cooling, temperature measurement of the sample); environmental conditions; room temperature and humidity; the absorption spectra of the media used and cell culture materials; or the thermography employed in the experimental setup. In addition, computational modeling of wIRA applied to hyperthermia of superficial tumors has been very limited.

Therefore, in this paper we focus on the development of a model for radiative heating of superficial human tissues with the use of water-filtered infrared-A radiation. At the first step of modeling, the normal (healthy) skin tissues are considered. There are two methodological differences in modeling of wIRA irradiation as compared with the models developed in previous studies of laser-induced hyperthermia [6–11]:

* Corresponding author. Tel.: +7 499 250 3264; fax: +7 495 362 5590.
E-mail address: ldombr@yandex.ru (L.A. Dombrovsky).

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Nomenclature

c	specific heat capacity
d	thickness of the computational region for radiative transfer calculations
D	radiation diffusion coefficient
E	function introduced by Eq. (8)
f	function introduced by Eq. (23)
F, G	functions introduced by Eq. (9a)
g	unknown function in Eq. (12a)
h	heat transfer coefficient
H	distance from the light source to the body surface
I	radiation intensity
J	diffuse radiation intensity
k	thermal conductivity
L	thickness of the computational region for heat transfer calculations
n	index of refraction
q	radiative flux
$\vec{r}$	spatial coordinate
r	radial coordinate
R	reflectance, radius of the region
w, W	absorbed radiation power
z	axial coordinate

Greek symbols

α	absorption coefficient
β	extinction coefficient
γ	coefficient introduced by Eq. (12c)
θ	angle measured from the normal
κ	index of absorption
λ	wavelength
μ	cosine of an angle
$\bar{\mu}$	asymmetry factor of scattering
ρ	density
σ	scattering coefficient
τ	optical thickness
$J^{\mp}, J^0$	functions introduced by Eq. (11)
ω	scattering albedo
$\vec{\Omega}$	unit vector of direction

Subscripts and superscripts

cr	critical
e	ext external
f	Fresnel's
h	heating
i	incident
int	internal
n	normal
s	surface
tr	transport
λ	spectral

- The incident radiation is not monochromatic;
- The incident radiation is not collimated, and there are various angular distributions of the radiation intensity at different points of the illuminated area (see Fig. 1).

The first of the above special features of the problem under consideration requires spectral data for all the tissues and increases the computational time. Therefore, the use of an approximate solution for radiative transfer at every wavelength is important to avoid time-consuming calculations.

The complex angular dependence of the incident radiation makes the use of traditional approximations which are developed for totally diffuse or collimated irradiation problematic. In this paper, a novel simplified approach based on the modified two-flux approximation for 1-D problem at oblique incidence is suggested. For simplicity, average angles of incidence are considered at each of several thin concentric layers of the axisymmetric computational region.

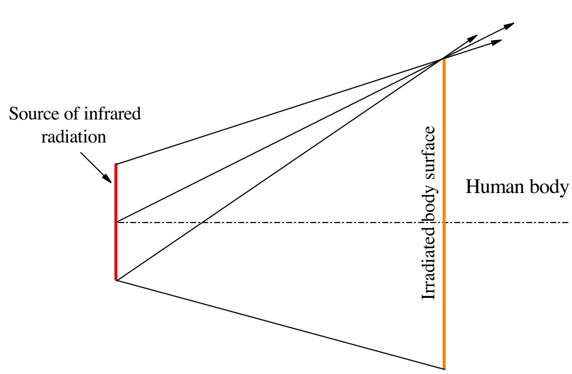

Fig. 1. Scheme of irradiation of the body surface in wIRA method.

A complete 2-D problem statement is employed to solve the transient heat transfer problem with a volumetric heat source generated mainly from the absorbed power of the external infrared radiation.

The objective of the present paper is two-fold: (1) to develop and examine an approximate method for calculating the absorbed radiation power in the case of a non-collimated near-infrared external radiation at oblique incidence and to examine the applicability of a simplified approach based on the model of local normal incidence; (2) to solve a model transient heat transfer problem at parameters close to the realistic ones for the case of a wIRA thermal treatment of superficial tissues. The applicability of the 1-D approach for the heat transfer calculation is also examined.

2. Spectral optical properties of superficial tissues

Human skin is composed of three main layers, the epidermis, dermis and subcutaneous adipose layer, or subcutaneous fat. The epidermis, which is the outermost layer, is approximately 100 μm thick and contains no blood vessels. The dermis, which is the layer just below the epidermis, can be between 1 and 4 mm thick and is the vascularised layer (contains blood vessels). Below the epidermis lies the subcutaneous fat layer, which can be between 1 and 6 mm thick and serves the purpose of attaching the upper layers of skin to the underlying bone and muscle while supplying blood vessels and nerves [12]. As a result, human skin presents a complex heterogeneous medium and the difference in optical properties of each of these layers in the wavelength range of wIRA irradiation has to be considered.

All subsequent calculations were performed by using data of spectral irradiance of the commonly used wIRA radiator, type *Hydrosun 750* (775 W, Hydrosun GmbH, Müllheim, Germany) which was equipped with filter type *BTE 595*. Spectral irradiance data shown in Fig. 2 were measured at the geometric center of