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A three-temperature model of selective photothermolysis for laser treatment of port wine stain containing large malformed blood vessels

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HIGHLIGHTS

- A three-temperature model is proposed for the laser treatment of port wine stain (PWS).
- Average sized and large malformed blood vessels in porous medium (tissue) are considered.
- Thermal responses of PWS to near-infrared and visible laser irradiations are compared.
- Large-sized or deeply buried blood vessels exhibit a poor response to 585 nm laser.
- Near-infrared (1064 nm) laser can treat Large-sized or deeply buried blood vessels better.

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ABSTRACT

As congenital vascular malformations, port wine stain (PWS) is composed of ectatic venular capillary blood vessels buried within healthy dermis. In clinic, pulsed dye laser (PDL) in visible band (e.g. 585 nm) together with cryogen spray cooling (CSC) have become the golden standard for treatment of PWS. However, due to the limited energy deposition of the PDL in blood, large blood vessels are likely to survive from the laser irradiation. As a result, complete clearance of the lesions is rarely achieved. Assuming the local thermal non-equilibrium in skin tissue during the laser surgery, a three-temperature model is proposed to treat the PWS tissue as a porous media composed of a non-absorbing dermal matrix buried with the blood as well as the large malformed blood vessels. Three energy equations are constructed and solved coupling for the temperature of the blood in average-sized PWS vessels, non-absorbing dermal tissues and large malformed blood vessels, respectively. Subsequently, the thermal responses of human skin to visible (585 nm) and near-infrared (1064 nm) laser irradiations with various pulse durations in conjunction with cryogen spray cooling are investigated by the new model, and Arrhenius integral is used to analyze the thermal damage. The simulations show that the short pulse duration of 1.5 ms results in a higher selective heating of blood over epidermis, which will lead to a desired clinic outcome than the longer pulse duration. Due to a much deeper light penetration depth, laser irradiation with 1064 nm in wavelength is superior to that with 585 nm in treating patients with cutaneous hyper-vascular malformation. Complete coagulations are predicted in large-sized and deeply extending blood vessels by 1064 nm laser.

1. Introduction

As congenital vascular malformations, port wine stain (PWS) birthmarks occur in approximately 0.3% of the newborns [1]. PWS is composed of ectatic venular capillary blood vessels with diameters ranging from 10 to 300 μm buried within healthy dermal tissue [2]. Laser treatment of port wine stains (Laser PWS) is based on the principle of selective photothermolysis developed by Anderson and Parrish [3]. According to the theory, PWS blood vessels can be selectively damaged by the thermal response due to their preferential absorption of laser energy with the chosen wavelength. In comparison, normal skin tissues are minimally affected. However, due to unwanted absorption of laser energy,

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Nomenclature

A	array to score light energy absorption
a	specific interfacial area (m^{-1})
c	specific heat (J/kg K)
C	correction factor for tissue optical properties in homogeneous layers
d	diameter (m)
E	incident laser fluence (J/m^2)
F	light fluence distribution within tissue (J/m^2)
g	anisotropy index
h	heat transfer coefficient ($w/m^2 \cdot K$)
k	thermal conductivity ($w/m \cdot K$)
K_{bd}	the ratio of the thermal conductivities of the blood to the dermal tissues
N	photon number
Nu	non-dimensional heat transfer coefficient
Q	volumetric heat generation due to laser energy absorption (J/m^3)
x	radial coordinate (m)
s	free path length of the photon (m)
T	temperature (°C)
$\overline{T}$	volume-averaged temperature (°C)
t	time (s)
V	volume (m^3)
z	axial coordinate (m)

Greek symbols

α	thermal diffusivity (m^2/s)
ε	volumetric fraction of the chromophore
μ_a	absorption coefficient (m^{-1})
μ_s	scattering coefficient (m^{-1})
μ_t	attenuation coefficient (m^{-1})
τ	normalized time
ξ	random number

Subscripts and superscripts

a	absorption
air	air
b	blood
bd	interface between the blood vessel and the dermis
c	cryogen
d	dermis
e	epidermis
epi/PWS	interface between epidermis and PWS layer
k	bottom surface of the computation domain
large-b	large blood vessel
m	melanin
p	pulse
pm	porous medium
PWS	the PWS layer
REV	representative elementary volume
s	scattering
t	attenuation
*	normalized

melanin in epidermis could lead to thermal damage to skin surface, which can be effectively prevented by cryogen spray cooling (CSC) introduced by Nelson et al. [4].

Pulsed dye laser (PDL) with wavelength in visible brand in conjunction with the CSC technique now has become the golden standard for treating PWS. However, clinical studies indicate that complete blanching of the lesions is not commonly achieved (less than 20%). The possible reasons may be the limited light penetration depth in large-sized or deeply-buried blood vessels [5]. Light in near-infrared wavelengths will be absorbed less by epidermal melanin and penetrate deeper into skin dermis than visible wavelengths [6]. Therefore, laser irradiation with near-infrared wavelengths may improve the therapeutic outcome of cutaneous hyper-vascular malformations with large-sized or deeply-buried blood vessels.

Some theoretical models have been developed to simulate laser treatment of PWS [5,7,8]. In most existing models, the complex skin anatomy is treated as a simple multi-layered structure, based on which the Multi-Layer Monte Carlo method (MLMC) [9] is used to simulate light propagation within tissues and thus quantify light energy deposition [10–12]. Energy deposition can then be input into the bio-heat transfer equation as an energy source term. Solutions of the bio-heat equation yield temperature change of the skin tissues, from which thermal damage can be quantified with thermal injury model [13].

However, it is difficult to describe the complex anatomic structures of PWS by the multi-layered structure. Various models for laser treatment of PWS have been developed and can be roughly divided into two categories, the homogeneous model and the discrete blood-vessel model. The former refers to models in which the skin tissue with PWS is treated as a homogeneous mixture of uniformly distributed blood and surrounding dermal tissue with a given blood volumetric fraction. Detailed anatomic structure of the blood vessels was not taken into account [10]. The homogeneous model fails to distinguish the temperature between the blood and the surrounding dermal tissue as they were assumed in the same temperature. In the case for laser PWS, such a local thermodynamic equilibrium assumption makes the homogeneous model undesirable to simulate the selective photothermolysis.

Afterward, the discrete blood-vessel model is developed to treat PWS blood vessels as straight cylindrical tubes which are parallel to the skin surface and buried in dermis [7,8,11,12]. Early discrete models considered as either a single blood vessel [11] or a blood vessel array regularly arranged within the dermis [12]. Multiple blood vessels randomly arranged within the dermis have also been taken into consideration [14]. Most simulations only considered PWS blood vessel with constant diameter. The thermal responses of PWS lesions with vessels of various diameters are seldom investigated. To construct more realistic simulation, PWS model with complex structures was attempted by Pfefer et al. [15] according to geometric configurations of PWS blood vessels obtained through biopsy. Unfortunately, the imaging modalities that can map PWS blood vessels noninvasively are not currently available, making this three-dimensional model impractical to use.

In the authors' previous work [16], a local thermodynamic non-equilibrium two-temperature model for simulating the thermal response of PWS to laser irradiation was constructed. In the model, PWS skin was treated as a porous medium composed of a tissue matrix buried with highly-absorbing chromophores (blood confined within the vessels). Two energy equations, one for the blood and the other for the dermal tissue, were developed based on the local thermal non-equilibrium theory of porous media. As an approximation, the geometric configuration of the