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Research Paper

Influence of laser wavelength on the thermal responses of port wine stain lesions in light, moderate and heavy pigmented skin

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HIGHLIGHTS

- Laser surgery for port wine stain (PWS) was studied by local non-equilibrium theory.
- Wavelength selection in laser surgery under various skin pigmentation was explored.
- High pigmented skin prefers to 585 nm rather then 595 nm.
- Dual-wavelength laser (585/595 + 1064 nm) has better clinic effect than single one.
- Deep buried blood vessels can be damaged by 595/1064 nm dual-wavelength laser.

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ABSTRACT

Pulsed dye laser (PDL) in visible band (e.g. 585 or 595 nm) together with cryogen spray cooling has become the golden standard for treatment of vascular malformation such as port wine stain (PWS). However, due to the limited energy penetration depth of the PDL, deeply buried blood vessels are likely to survive from the laser irradiation. Nd:YAG laser in near infrared (1064 nm) has great potential in the laser treatment of PWS due to its deeper penetration depth. In this study, the influence of laser wavelength in treating PWS lesions with various melanin concentrations in epidermis was theoretically investigated by a two-temperature model following the local thermal non-equilibrium theory of porous media. The results showed that deeply buried blood vessels can be coagulated by dual-wavelength laser combing 585 or 595 nm with 1064 nm laser. Furthermore, the therapeutic results by dual-wavelength laser were highly related to the melanin concentration in epidermis. In the light and moderate pigmented skin, the 595/1064 nm dual-wavelength laser showed better treatment effect in treating PWS with deeply-buried blood vessels than of 585/1064 nm dual-wavelength laser. For a high pigmented skin, the 585/1064 nm dual-wavelength laser showed better treatment effect than 595/1064 nm dual-wavelength laser.

1. Introduction

As a kind of congenital vascular malformations, port wine stain (PWS) birthmarks occur in approximately 0.3% of newborn children [1]. PWS is composed of ectatic venular capillary blood vessels with diameters ranging from 30 to 300 μm buried within healthy dermal tissue [2], which may lead to increased cosmetic disfigurement and psychological distress, prompting patients and their families to seek effective treatments. 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 specific wavelength. In comparison, normal skin tissues are minimally affected. However, absorption of laser energy by melanin in epidermis could result in unwanted thermal damage to skin surface (epidermis), which can be prevented by cryogen spray cooling (CSC) introduced by Nelson et al. [4].

Nowadays, pulsed dye laser (PDL) with wavelength in visible brand of 585 nm or 595 nm in conjunction with the CSC technique have 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 reason may be the limited light penetration depth in deeply-buried blood vessels [5]. Light in near-infrared wavelength (e.g. Nd:YAG laser with 1064 nm) will be absorbed less by epidermal melanin and

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Nomenclature

A	frequency factor
a	specific interfacial area
c	specific heat
d	diameter
E	activation energy
h	heat transfer coefficient
k	thermal conductivity
K_{bd}	the ratio of the thermal conductivities of the blood and the dermal tissues
Nu	non-dimensional heat transfer coefficient
Q	volumetric heat generation due to laser energy absorption
r	radial coordinate
T	temperature
$\overline{T}$	volume-averaged temperature
t	time
V	volume
z	axial coordinate

Greek symbols

α	the thermal diffusivity
ε	volumetric fraction of the chromophore
τ	normalized time
Ω	arrhenius integral for thermal damage

Subscripts and superscripts

air	air
b	blood
basal	Basal layer of the epidermis
basal/der	interface between the basal layer and the dermal layer
bd	interface between the blood vessel and the dermis
c	cryogen
d	dermis
der/PWS	interface between the dermal layer and the PWS layer
e	epidermis
epi/basal	interface between epidermis without melanin and the basal layer
m	melanin
p	pulse
PWS	the PWS layer
REV	representative elementary volume
*	normalized

penetrate deeper into skin dermis than visible wavelengths [6]. Therefore, laser irradiation with near-infrared wavelength may improve the therapeutic effect of cutaneous hyper-vascular malformations with deeply-buried blood vessels.

Some theoretical models have been developed to simulate laser treatment of PWS [5,7,8]. Most models can be 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 vessel and surrounding dermal tissue with a given blood volumetric fraction. Since detailed anatomic structure of the blood was not taken into account [9], the homogeneous model is simple and computationally efficient. However, it fails to distinguish the temperature between the blood and the surrounding dermal tissue as they were assumed to be the same. For laser PWS, such a local thermodynamic equilibrium assumption makes the homogeneous model undesirable to simulate the selective photothermolysis.

In comparison, the discrete blood-vessel model treats PWS blood vessels as straight cylindrical tubes which are buried in dermis and parallel to the skin surface [7,8,10,11]. In early discrete models, either single blood vessel [10] or blood vessel array regularly arranged within the dermis [11] were considered. Multiple blood vessels randomly arranged within the dermis have also been taken into consideration [12]. However, the computational cost is expensive since there are hundreds of malformed blood vessels within a single laser spot. Besides, the tube-like arrangement departs a lot from the real distribution of the irregular blood vessels in PWS lesions, which may cause the inaccuracy of the discrete blood-vessel model for practical clinic applications.

In the authors' previous work [13], a local thermodynamic non-equilibrium two-temperature model for simulating the thermal response of PWS to laser irradiation was developed. In this model, the skin containing PWS lesions was treated as a porous medium composed of a normal 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 deduced based on the local thermal non-equilibrium theory of porous media. As an approximation, the geometric configuration of the blood vessels was represented by the volumetric fraction of the chromophores and a length scale, i.e., the average diameter of the blood vessels within a PWS. An approximate relation for the transient interfacial heat transfer coefficient was also proposed to quantify the heat conduction of the absorbed laser energy within blood to the surrounding dermal tissue. The validation of our two-temperature model has been verified by the good agreement with those from the discrete-blood-vessel model [12] for same cases.

In this study, the two-temperature model is implemented to investigate the effect of wavelength in treating PWS lesions. The coagulation depth of typical PDL with 585 nm and 595 nm is compared with near-infrared Nd:YAG laser (1064 nm) for various melanin concentration in epidermis: 5%, 15% and 25% for light, moderate and heavy pigmented skin. Based on the investigation, the dual-wavelength laser system with different combination of 585/595 and 1064 nm is recommended for the treatment of PWS containing deeply-buried blood vessels for different melanin concentration, because its therapeutic result was proved to be better than the pulse dye lase (585 or 595 nm) alone.

2. Mathematical model

2.1. Basic assumptions

In the two-temperature model, the skin tissue containing PWS is assumed to be a multi-layered skin geometry composed of a normal multi-layer skin matrix with the PWS blood vessels superposed on the matrix, see Fig. 1.

The multi-layer skin matrix is simplified as two parallel planar layers, which are the epidermal layer and the dermal layer without including any subcutaneous fat. Melanin in the epidermis is included by inserting a melanin-filled basal layer at the bottom of the epidermal layer. The melanin particles are assumed to be homogeneously distributed in the basal layer of the epidermis, simulating the un-tanned skin [12]. As the thermal relaxation time of melanin particles (in nanoseconds) is much shorter than the pulse duration of the laser irradiation