Thermal Diffusion and Specular Reflection, Monte Carlo-based Study on Human Skin via Pulsed Fiber Laser Energy

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[1]ABSTRACT

The aim of traditional Chinese medicine (TCM) in acupuncture is sometimes to restore and regulate energy balance by stimulating specific points along the specific meridians traced on the human body via different techniques such as mechanical pressure, moxibustion and others. Hence, physicians have struggled to improve treatment for common diseases such as migraine and headaches. Heat stimulation and some pharmacological effects from moxa have been attributed to the therapeutic efficacy of such techniques. As heat can diffuse through the tissue, skins temperature will rise in the surrounding tissue. In this work, heat diffusion on a simple, 5-layer model of human skin is presented. Based on this, and by using Monte Carlo techniques, a photon or a photon package is launched into the tissue for mimicking the propagation of such photons at two different wavelengths through the tissue. The method generally describes the scholastic nature of radiation interactions. Most of the laser energy is deposited within a volume which cross-sectional area is the size of the beam itself. As could be seen, in the epidermis layer of the model, the heat does not go deep and nearly all the heat diffusion occurs on the edges of the beam, causing losses. Heat dissipation occurs faster and goes down to 2°C in the adipose tissue since there is low water content in this region. On the contrary, there is a fast heat increase in the muscle layer, up to 6°C at the most superficial layer. Since melanin is the most important epidermal chromophore, it can be noted that light shows strong absorption via melanin, at 690nm laser wavelength. In the papillary dermis the heat decreases and spreads out to the surrounding tissue. Once it reaches the adipose tissue, the heat is not absorbed enough; therefore, it is transmitted into the muscle, where the temperature rise is higher and reaches nearly 40 °C. Finally, photo-dynamics in a simple 5-layer skin model were explored at two laser wavelengths: 690nm and 1069nm, where no thermal damage would be expected, given the energy level of the employed pulses. Such pulsed laser energy levels remain to be tested in living tissue.

Key words: Thermal diffusion, Monte Carlo, Photodynamic therapy

1. INTRODUCTION

One of the main objectives of Traditional Chinese medicine (TCM), among others, is to help on restoring and regulating the energy balance of the human body by stimulating specific spots along the invisible but recognized lines in human anatomy called meridians. This has been done via different techniques such as: mechanical pressure, moxibustion, and the insertion of needles for helping the treatment of a series of diseases. Moxibustion therapy utilizes heat generated by the combustion of moxa in order to fulfill the treatment. According to the Chinese medical theory, 361 acupuncture spots are recognized along 14 meridians connecting the body. Those 14 meridians are associated with specific organs and serve as pathways for the flow of the so-called vital energy or "Qui"; Qui should maintain the balance with Yin, Yang and Xue (blood) (*Seung-Ho, 2009*).

Adverse events for acupuncture treatment reported in China are hepatitis and bacterial infections, these are caused by the reuse of metal needles in some of these therapeutic procedures, could lead to skin infections in patients, imposing some rejection from the general public and new patients (*Deng et al, 2013*). Furthermore, pediatric population does not permit the use of needles for their treatment. In recent years, the need for non-invasive therapies has increased. At the beginning of the new millennium, laser-needle therapy had started with more applications in health sciences

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(*Junyi et al, 2015; Onur et al, 2014*). In particular, laser-needle therapy stimulates acupuncture points using mainly monochromatic light to help with the healing process of certain illnesses like pain and inflammation among others and to try and restore body balance (*Hoy et al, 2010*).

Furthermore, when tissue is laser radiated the local temperature increases because light absorbed by the tissue is mainly converted into heat. The heat can diffuse through the tissue, causing a temperature rise in the surrounding area. The temperature rise in the tissue during the irradiation depends basically on its properties such as: absorption coefficient, anisotropy, effective scattering coefficient and thickness; and the laser parameters such as: wavelength, fluence, repetition rate, beam radius, pulse duration, pulse energy, and thermal relaxation time influence the biological action of laser application 6. (*Jae-Young et al, 2015*). Besides, corporal body temperature higher than $44\,^{\circ}C$ for $60\,seconds$ denaturalize proteins inducing necrosis of tissue (*K. Dörschel and Müller, 1996*). The thermal damage caused by continuous wave (CW) laser beam could be lower than the damage caused by pulsed laser beams, since a CW laser does not impose high thermal deposition on the skin, and the thermal relaxation time (TRT) is long enough, which allows for the temperature rise to decrease either partially or totally. From the very first pulse energetic action, the temperature can be risen up to 40°C, depending on the aforementioned parameters for both tissue and laser. This increase in temperature could lead to mild pain in compared to the feeling of De Qi. It is believed that De Qi may be an important variable in the studies of the mechanism and efficacy of acupuncture treatment, it is known that De Qi experienced by patients is often described as ma (numbness or tingling), zhang (fullness, distention, or pressure), suan (aching or soreness), and zhong (heaviness) and is felt by the acupuncturists (needle grasping) as tense, tight, and full, according to traditional Chinese medicine.

Nevertheless, it can be observed that if a pulsed laser is employed, the thermal damage can increase. Tissue temperature rises from radiation of the very first pulse, so after the second pulsed is incident into the skin, the temperature rises quickly, and the TRT only decreases to 37% of the total rise, depending of pulse energy, pulse duration and heat diffusion in the skin.

Acupuncture therapy via laser pulses shows certain advantages when is compared to another alternative medicine such as moxibustion (also known as moxa), electroacupuncture or traditional acupuncture (*Vertrees et al, 2007*). Moxa therapy utilizes heat generated by the combustion of moxa in order to give analgesia to the patient. When indirect moxa is employed, the temperature rise lies between $40° - 45°\,C$ in a period of $120\ seconds$, giving patients possible burns during the treatment (*Stux and Pomeranz, 1998*).

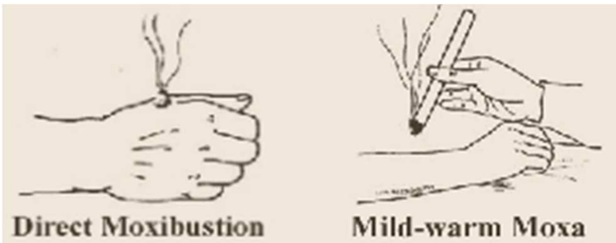

Figure 1. *Moxibustion process alternatives.*

It has been observed that when the heat source is placed near the painful area or into the acupuncture points, an immediate effect is that the segments that operate in cell 7 are maximized. At the same time, the cells 11 and 14 were activated as well. When the heat source is placed far from the aching region, the midbrain and the hypothalamus-pituitary complex were activated (cells 11 and 14). Such cells produce analgesia around the body, whereas the analgesic in the local zone is produced by cell 7 (*Lee and Myeong, 2010*).

On the other hand, the usage of laser therapy would reduce the treatment time. While the acupuncture points are stimulated with the heat from a laser beam, the temperature rises until it reaches the muscle in a few seconds period, thus representing an arguably more comfortable and safe therapy for patients.

Nevertheless, a critical situation could appear after the temperature rises up to more than $43\,°C$ as the denaturation of proteins might start around the acupuncture point. During denaturation, the aforementioned temperature rise is high enough to increase the kinetic energy of the molecules such that they overcome the bonds responsible for stabilizing the protein structure and irreversible lesions could occur.

1.1. Monte Carlo Method

Monte Carlo method or experiment is a broad class of computational algorithms on which repeated random sampling procedures provide numerical results with which complex phenomena are explained. In Physics, this method is useful in simulating fluids, cellular interactions and structures, solids and even kinetic models of gases. This technique is also employed for modelling light propagation in tissue. The method generally describes the stochastic nature of propagation and radiation interactions. In this technique, a photon or photon package is launched into the tissue in order to mimic the movements of these photons through the tissue, based on the probability density functions for step size between scattering events and for the angle of deflection at each scattering event. The main simulated parameters in this case are the absorption coefficient, scattering coefficient and the anisotropy factor.

The absorption coefficient and the scattering coefficient represent the photon absorption probability per unit of infinitesimal path-length. The anisotropy factor is the angular distribution of scattering and represents the average amount of scattering in a medium. The most commonly used model of human tissue for simulation is the simple, multilayer model. In this work, a simple 5-layer model was employed, as shown in Figure 2. In this model, the first layer is the epidermis, followed by the papillary dermis, reticular dermis, hypodermis and muscle layer. Each layer is considered to have homogeneous properties as well as optical properties.

2. MODELLING

In order to contribute to therapy in combination with acupuncture procedures, a simple, yet novel fiber laser design has been proposed for generating similar effects when compared to traditional acupuncture and, in some way, helping to minimize secondary effects. The output spectrum of the Yb^{3+}-doped fiber laser was between 1069 and $1071\,nm$. This output spectrum was proposed since a therapeutic window lies within such wavelength range and water is the chromophore with the highest absorption. This wavelength penetrates deeply into the tissue because of lower scattering and absorption coefficients; therefore, they have little effect on tissue properties. In spite of the deep penetration of this wavelength range, there is a possibility that laser light does not reach the muscle layer of the skin, and not stimulate analgesia. In order to confirm the possibility for laser light not reaching the muscle layer of the skin, new simulations are proposed in this work.

Initially, in order to simulate heat diffusion into the tissue we used Monte Carlo methods for the simulations described here, where the photons are launched at the origin ($x = 0$, $y = 0$, $z = 0$) with a trajectory at ninety degrees with respect to the tissue surface ($\mu_x = 0$, $\mu_y = 0$, $\mu_z = 1$). The results are then saved into cylindrical coordinates as $Q(r, z)$ in units of photon weight, then converted into units of energy per volume: J/cm^3.

The model divides the skin into 5 layers as follows: epidermis, papillary dermis, reticular dermis, hypodermis and muscle. For each layer, the optical properties: absorption coefficient (μ_a $[cm^{-1}]$), scattering coefficient (μ_s $[cm^{-1}]$), anisotropy ($g[dimensionless]$) and thickness ($d[cm]$) need to be calculated in order to produce some prediction of the photons dynamics within the skin.

Figure 2 shows the proposed multi-layer model, employed in this work. From the figure, the model starts at zero depth for the epidermis and at $0.6\ cm$ at them layer.

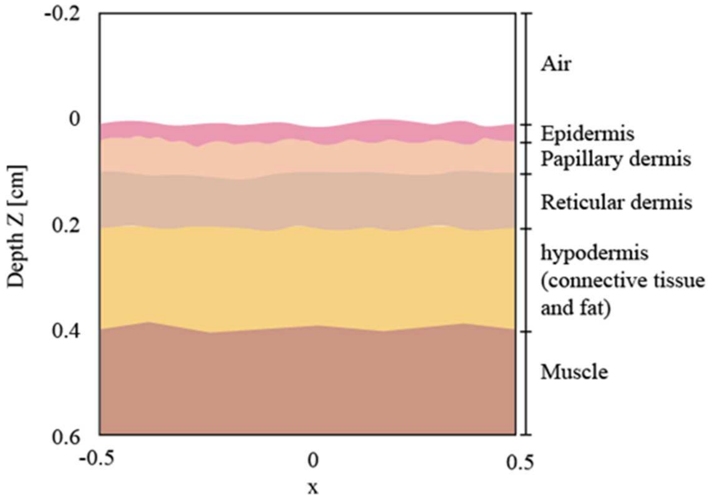

Figure 2. *Multi-Layered skin model.*

In order to calculate the basic optical properties of the epidermis, the total optical absorption coefficient of the epidermis (mua.epi) which depends on the baseline skin absorption value and on the dominant melanin absorption, was first calculated. Hemoglobin and melanin are the main chromophores of human skin in the visible range. Hemoglobin is found in the microvascular network of the dermis, typically $50 \pm 500\,mm$ below the skin surface. On the other hand, melanin is located in the epidermis, which occupies the top $50 \pm 100\,mm$. Human skin is characterized by variable concentration in Melanin, giving skin colour tone from Caucasian to black African (*Ahn et al, 2010; George et al 2001*).

The baseline absorption can be calculated via the following equation:

$$mua.baseline = (7.84 \cdot 10^8) \cdot \left(\lambda^{(-3.255)}\right) \ [cm^{-1}] \quad (1)$$

The absorption of epidermis by the melanin absorption follows the equation:

$$mua.mel = (6.6 \cdot 10^{11}) \cdot \left(\lambda^{(-3.33)}\right) \; [cm^{-1}] \qquad (2)$$

The whole epidermal absorption coefficient, mua.epi, combines the baseline skin and the melanin absorption as follows:

$$mua.epi = (f.mel)(mua.mel) + (1f.mel)\;(mua.baseline)\;[cm^{-1}] \qquad (3)$$

Where f.mel is the number of melanosomes per unit volume in the skin. The absorption coefficient of the dermis (mua.der) can be calculated via equation 4. The absorption coefficient μ_a is a combination of the blood and water absorption.

$$mua.der = B\left(S \cdot \mu_{a.oxy} + (1 - S) \cdot \mu_{a.deoxy} + W \cdot \mu_{a.water}\right)\;[cm^{-1}] \qquad (4)$$

Where:

$B =$ 0.002 [average volume fraction of whole blood in skin (dimensionless)].
$S =$ 0.075 [tissue oxygen saturation].
$W =$ 0.65 [average volume fraction of water in tissue (dimensionless)]

$$\mu_{awater} = 0.13\;cm^{-1}$$
$$\mu_{aoxy} = 3.73\;cm^{-1}\;(\lambda = 1069\;nm)$$
$$\mu_{adeoxy} = 0.057\;cm^{-1}\;(\lambda = 1069\;nm)$$

The reduced scattering coefficient μ_s is a combination of Rayleigh and Mie scattering which allows the calculation of the reduced scattering coefficient as shown in the following equation:

$$\mu_{s\;500nm} = \left(f\left(\frac{\lambda}{500\;nm}\right)\right) + (1 - f)\left(\frac{\lambda}{500\;nm}\right) \qquad (5)$$

3. SIMULATION RESULT

The simulation was performed as follows: The input file containing the optical properties (see Table 1 and Table 2) of the multi-layer tissue was generated first. A set of codes written in C, were employed in order to simulate the light propagation in a tissue. Such programs are based on Monte Carlo methods. The results from such a simulation generate an output file which was used to estimate the optical properties of the skin, by extracting such properties from the output file, via a second code in Matlab. The Matlab script that uses the optical properties of the tissue was then employed to compute the convolution of the Azr with the different laser light wavelengths. All the optical properties were calculated using the aforementioned Matlab code. The optical properties for the first simulation, at a wavelength of $\lambda = 1069\;nm$, are shown below.

Table 1. *Optical properties of multi-layered tissue at λ=1069 nm*

Layer Optical properties	Epidermis	Papillary dermis	Reticular dermis	Fat	Muscle
N	1.38	1.38	1.38	1.38	1.38
μ_a (cm^{-1})	0.08	0.10	0.08	0.06	0.12
μ_s (cm^{-1})	32.99	32.99	32.99	32.99	32.99
g (dimensionless)	0.90	0.90	0.90	0.90	0.90
d (cm)	0.06	0.02	0.18	0.18	6.00

After the optical properties were calculated, such values were saved into a file that represents the input file for the Monte Carlo simulations, where photon absorption, fluence, reflectance and transmittance are the physical quantities to be simulated.

The absorbed photon probability density (cm^{-3}) can be seen in Figure 3. Figure 3a) represents the photon probability of absorption in each layer. Figure 3b) shows the photon fluence in each layer. Those figures are the impulse response of Monte Carlo for a narrow photon beam incident at 90º on the surface of the multi-layered tissue.

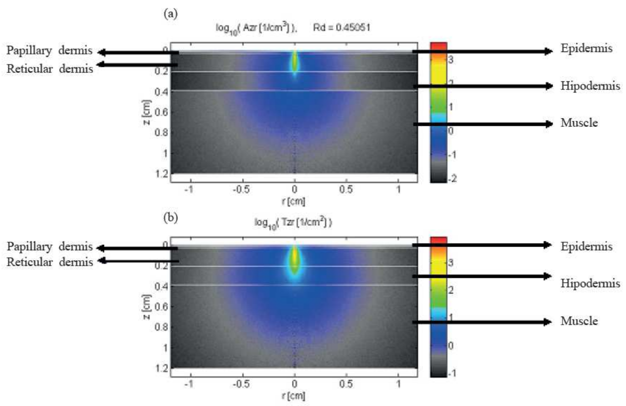

Figure 3. *a) Photon probability of absorption by each layer. b) Photon fluence.*

Specular reflectance (Rd) and absorbed photon probability density (Azr[cm^{-3}]) of the tissue are shown in Figure 4 a). The way a photon is propagated inside the tissue and how the photon penetrates the layers after the specular reflection is transmitted is illustrated in this figure. It is considered that most of the photons that are absorbed by the tissue are converted into heat.

At the epidermis level, heat is absorbed and transmitted into the papillary dermis and the reticular dermis. On the contrary, the adipose tissue does not show good level of heat absorption since the water content of this layer is too low. This is mainly, because in biological tissue laser absorption occurs by water molecules, proteins, melanin and hemoglobin. It is important to keep in mind that $1069\ nm$ is a wavelength at which water absorption is high. Furthermore, heat is transmitted into the muscle layer via fat in the tissue [7].

The absorption of photons is key for some treatments in clinical medicine. Since the absorption of light via a specific chromophore at a location **r**, inside the tissue, could occur irrespective of their direction of propagation, the integral of the radiance rate $\varphi(r)$ $[cm^{-2}]$ (figure 4b), provides a good estimation of the total absorption in stereo-radian. The radiant energy fluence rate at a given point in space is proportional to the radiant power incident on a small sphere divided by the cross-sectional area of such sphere.

Furthermore, the few figures below show the diffusion of photons obtained via Monte Carlo simulations. In order to understand the heat diffusion though the five layers and to determine if the heat reaches the muscle to mimic the moxibustion action that enables stimulation via acupuncture analgesia, it is necessary to perform the convolution with the absorbed photon probability density Azr (cm^{-3}) over various beam diameters. Basically, the convolution was performed with two beam diameters. For the first one a broad beam was considered of about $1\ cm$ and the second one was as narrow as $2\ mm$.

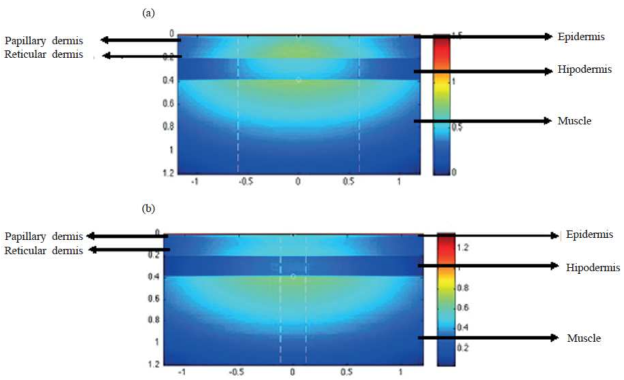

Figure 4. *a) Convolution of broad beam over Azr λ=1069nm b) Convolution of a narrow beam over Azr.*

Figure 4 a) and figure and 4 b) show the two-dimensional distribution of light as a function of depth along the central z axis within a simulated tissue, which is produced by a broad beam of flat-field irradiance. The computation involves $100{,}000$ photons and the results are stored in a cylindrical coordinate system of grid elements, previously declared in the code. The size of the grid elements is $z = 6mm\ dr = 6mm$. And the employed beam diameter was 1 cm.

When a broad beam is propagated in a turbid tissue, the scattering will confine the light down to a superficial layer close to the surface and thereby also it will attenuate the light within the tissue. Therefore, the photons are scattered in multiple directions and propagated via diffusion in the medium. The broad irradiance does not represent a significant problem because it is essentially a one-dimensional problem of light versus depth, and the tissue optics determined the illuminated zone.

Figure 4 a) shows the way the epidermis the light was absorbed and transformed into heat for which the temperature rises to around $6\ °C$. This heat is propagated into the papillary dermis; at this layer the heat was absorbed and in the reticular dermis layer, it caused almost no effect at all. On the contrary, when this heat reached adipose tissue, the heat was dissipated and the temperature decreased to almost $5\ °C$, via heat transmission into the muscle layer. However, this temperature is insufficient to stimulate the nerves to inhibit pain and activating the cellular message to the spinal cord to release neurotransmitters responsible of analgesia.

Figure 4 b) shows the convolution of Azr over a narrow beam, when the laser radiation was delivered with a narrow beam the problem is a two dimensional one in which light can diffuse both down into the tissue and laterally to the side of the laser beam. Most of the laser energy was deposited in a volume whose cross-section is the size of the beam itself. For instance, if in the epidermis the heat diffusion was shallow, then almost all the heat remains on the edges of the beam, therefore causing losses and affecting the concentration of the heat in the central region, i.e. under the beam. The situation was present in the papillary dermis and reticular dermis. Nevertheless, in the adipose tissue the heat decreases faster down to $2°C$ since in this layer the content of water is lower. In the muscle, the heat increases to $6°C$ only at the very top of this layer as it was not efficient for activating acupoints.

The major rise in temperature occurred when the tissue was radiated with a pulsed laser and with a pulse energy of $1\,J$. In the epidermis, the temperature reached almost $7.5°C$ and the heat was transmitted to the other layers, although it decreased slowly.

In both, the epidermis-papillary and dermis–reticular, significant problems where not found since the boundary between those layers is mainly water and it has got a similar refractive index, as those are matched boundaries. On the contrary, when the heat reaches the fat layer, there is a mismatch in refractive index at the boundaries, and therefore the scattering and absorption coefficients immediately change. The heat decreases in the fat layer as it is transmitted. Due to this it can reach the muscle and increase the heat in the layer, in order to mimic the effect of moxibustion.

After the simulations, it was arguably clear that the initial laser conditions were not appropriate for producing the moxi-bustion effect.

Table 2. *Optical properties of wavelength 690 nm.*

Layer Optical properties	Epidermis	Papillary dermis	Reticular dermis	Fat	Muscle
N	1.38	1.38	1.38	1.38	1.38
μ_a (cm^{-1})	0.003	0.027	0.007	0.002	0.042
μ_s (cm^{-1})	68.16	68.16	68.16	68.16	68.16
g (dimensionless)	0.90	0.90	0.90	0.90	0.90
d (cm)	0.06	0.018	0.18	0.18	6.00

After obtaining these optical properties at 690 nm, we obtained the diffusion response from Monte Carlo simulation by using the previous mentioned Matlab code. The following figure shows the obtained response:

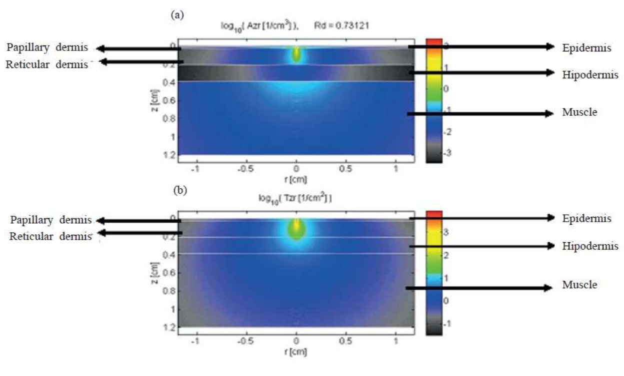

Figure 5. *a) Photon probability of absorption by each layer. b) Photon fluence.*

A new laser wavelength was chosen at $690\,nm$ in order to perform the simulation of the process. New optical properties were necessary in order to simulate the heat diffusion into the proposed kin model.

It has been observed that the absorption of photons is higher once the heat has been transmitted for laser heat energy at a wavelength of $690\,nm$ propagating through the epidermis.

The main difference between Figure 4 and Figure 5 is the incident wavelength. Figure 4 shows absorption at $1069\,nm$ compared to figure 5 on which it is at $690\,nm$. The stronger chromophore for 1069 nm is water and at $690\,nm$ it is hemoglobin. Therefore, at $1069\,nm$ the heat is absorbed mainly through adipose tissue. There, the heat is transmitted to the adipose tissue where the heat is lower and will not be transmitted to the muscle. On the other hand, when applying light at $690\,nm$ in the adipose tissue, heat is not absorbed since there is no present chromophore.

In order to observe the heat deposition in each layer it is necessary to perform the convolution. The first beam radius to make the convolution is a broad beam with 1 cm in diameter. The number of photons involved in the computation is 100000 and the size of the grid elements is $dz = 6mm$, $dr = 6mm$. The optical properties are set as the ones previously explained.

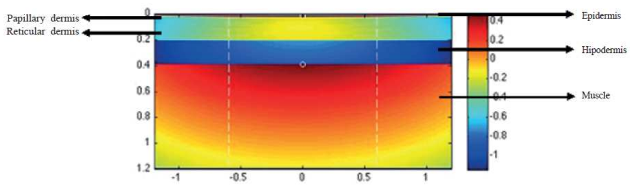

Figure 6. *Convolution of a broad beam over Azr.*

The response of the convolution between a broad beam over Azr is shown in Figure 6. It can be observed that in the epidermis, light has a strong absorption via melanin at its wavelength, since in the visible range the most important epidermal chromophore is melanin. In the papillary dermis heat goes down and spreads out to the surrounding tissue. In the adipose tissue heat is not absorbed, therefore it is totally transmitted to the muscle, where the temperature rise is high in the top layer of the tissue, reaching up to $40\,°C$. Penetration depth into the tissue at this temperature is around 2 mm. In the middle layers of the muscle the temperature is lower that at the top. In this part of the muscle the temperature goes down to $20\,°C$ and is transmitted through the bottom of the tissue.

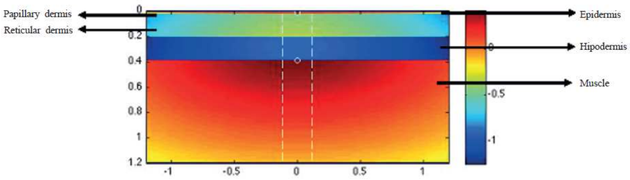

Figure 7. *Convolution of narrow beam over Azr.*

In Figure 7, the heat propagation on the epidermis is high because melanin absorbs the major part of the photons and light is converted into thermal energy.

In the epidermis the heat deposition is very high, and it is transmitted to the lower layers. When the heat reaches the reticular dermis, it propagates deeper into the skin than in the papillary dermis. As heat was conducted to the next layer (the adipose tissue) it is not absorbed, therefore it is all transmitted to the muscle. In this layer we can see that the heat deposition is high at the top of the muscle and it is spread out to the surrounding tissue; it penetrates though the tissue up to $3\,mm$. If we compare with the wider beam, the penetration depth is larger, and reaches the bottom of the muscle with a bigger increase of temperature. It is observed that with heat at this wavelength, the muscle has enough temperature to mimic the moxibustion effect. Acupuncture analgesia arises with this temperature and releases neurotransmitters to inhibit the messages of pain to the brain and body. In-vivo studies need to be performed in order to confirm effect of this laser. However, in order to explain thermal diffusion more deeply, it is necessary to observe the thermal response for when the tissue is exposed to the radiation laser with a power of $1\,J$; with this energy level we should be able to see the temperature rise in each layer.

4. Conclusion

Acupuncture and electroacupuncture requires at least $20\,minutes$ of therapy to stimulate acupoints, moxibustion could induce some minor burns in patients. Laser therapy is arguably a safer technique, since it requires less time to stimulate and generate arguably the same effect as other acupuncture therapy procedures. Our results suggest that the proposed laser energy could be able to stimulate acupoints with possible applications in TCM, but previous in vivo experiments need to be performed. Two simulations based on Monte Carlo method were performed. The first simulation was executed with a simulated energy source centered at a wavelength of $\lambda = 1069\,nm$. The optical properties of this first simulation are shown on Table 1. Overall, the results show that with these parameters the initial laser conditions we not appropriate for producing the moxibustion effect. The second simulation was executed at a wavelength of $\lambda = 690\,nm$. The optical properties of this second simulation are specified in Table 2. Pulsed laser energy at 690nm generated from an Yb^{3+}-doped fiber was employed to simulate and somehow mimic moxibustion therapy on the proposed 5-layer skin model. In contrast, laser energy at $1069nm$ Yb^{3+}-doped fiber laser was also employed for observing the dynamics in the aforementioned simple model. Finally, as observed in the results, no thermal damage was reached, which gives room for continuing investigation, possibly at the clinic level in the near future.

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