第 36 卷第 6 期
2017 年 12 月

红 外 与 毫 米 波 学 报
J. Infrared Millim. Waves

Vol. 36, No. 6
December,2017

文章编号: 1001 - 9014(2017)06 - 0665 - 08

DOI:10. 11972/j. issn. 1001 - 9014. 2017. 06. 006

An infrared heat transfer in biological tissue

LI Chen-Jing[1], XU Xue-Mei[1], CHANG Xiao-Rong[2]

(1. School of Physics and Electronics, Central South University, Changsha 410083, China;
2. College of Acupuncture & Moxibustion and Tui-na, Hunan University of Chinese Medicine, Changsha 410208, China)

Abstract: Combined with the fundamental theorems of thermodynamics and the heat radiation theory, Pennes bio-heat equation is improved, which can describe the thermal process in tissue subject to heat stimulation of moxibustion more vividly. Applying the Green function method, we derive the analytical solution of the equation and establish a straightforward way to quantitatively interpret the temperature behavior of living tissues, such as healthy tissue, tumor tissue, non-acupoint tissue and acupoint tissue, as a result of moxibustion. The concept of temperature attenuation coefficient (TAC) is proposed to measure the energy absorption at different depth of tissue. The coherence between the simulation and experiment about surface temperature demonstrates the flexibility and availability of the solution. The oscillation energy flow has a mild stimulus to the biological tissues, which is an advantageous physical exciter for organization to achieve its good functions. Our results reveal that the heat with high frequency is mainly absorbed by the surface layer, while that of low frequency can deeply penetrate into the living biological parts. Significantly, the diseases can be treated by moxibustion heat through the role of deep penetration.

Key words: moxibustion, heat flux, pennes equation, temperature attenuation coefficient
PACS: 87. 10. Ed, 87. 19. Pp

生物组织内红外热传递

李晨静[1], 许雪梅[1], 常小荣[2]
(1. 中南大学 物理与电子学院,湖南 长沙 410083;
2. 湖南中医药大学 针灸推拿学院,湖南 长沙 410208)

摘要:结合热力学基本定律和热辐射理论,改进了 Pennes 生物热传导方程,描述艾灸生物组织内的热量传递过程。采用 Green 函数法推导了其解析解,建立了定量解释艾灸不同生物组织如健康组织、肿瘤组织的温度变化行为的方法。提出温度衰减系数的概念来衡量组织内不同深度处的能量吸收情况。艾灸时皮肤表面温度的变化趋势与仿真结果的一致性验证了方法的有效性。振荡的能量流对于组织是温和的刺激,这是生物组织实现良好功能的物理兴奋剂。结果表明,高频能量主要被皮肤表层吸收,而低频能量可以深入到生物组织内部。重要的是,疾病可以通过艾灸热的深透作用来治疗。

关 键 词:艾灸;热流密度;Pennes 方程;温度衰减系数

中图分类号:TK124, R245-0 **文献标识码**:A

Introduction

Moxibustion has been applied to prevention and treatment of many diseases[1-2]. Although the scholars have reached a consensus on the therapeutic effect of moxibustion, their understanding of the mechanism of moxibustion is still inconsistent. The characteristics of moxibustion determine that its efficacy is inclined to warm and nourish. The warmth is implemented through thermal radiation essentially[3-4]. Despite the progress in research on the biophysical specificity of thermal radia-

Received date: 2017- 05- 11, **revised date**: 2017- 09- 16 **收稿日期**:2017- 05- 11, **修回日期**:2017- 09- 16
Foundation items: Supported by the Subproject of 973 Program of China (738010018), National Natural Science Foundation of China (61502538, 61501525), the Nature Science Foundation for Young Scientists of Hunan Province, China (2015JJ3157), and the Graduate Scientific Research Foundation of Central South University (2017zzts474)
Biography: LI Chen-Jing (1993-), female, Master. Research fields focus on moxibustion thermal mechanism and signal processing. E-mail: 1971045757@qq. com

tion on the surface of the body[5-6], the available methods are still at the infrared thermography level. Most importantly, the mechanism of thermal conduction in the different depth of the living tissue is unknown. Moreover, the knowledge of tissue thermal conduction properties is extremely important for the explanation and the quantification of the moxibustion therapeutic research, as well as for both the prediction of thermal energy distribution and absorbed energy for Chinese traditional medicine theory of acupoints. Therefore, we focus on establishing the heat conduction model in the living tissue and figuring out temperature-dependent thermal action occurred in shallow and deep tissues. Several bioheat transfer equations have been developed by former researchers[7-11]. Among them, the Pennes equation is most widely used. The paper is committed to the analytical solution[12] of Pennes equation, which is derived by means of the Green's function method[13-14]. It will satisfy the present request that the obtained solutions should be capable of solving the bioheat problems with moxibustion heating or time-dependent boundary conditions.

In this paper, the expression of heat flux density for thermal radiation from moxa to the skin is proposed. It serves as surface heat flux under the second boundary condition. After improving and solving the Pennes equation by Green's function in detail, we present the initial temperature of four tissues, such as non-acupuncture point, acupuncture point, healthy skin and tumor skin, and then analyze temperature distribution of them subject to moxibustion. Moreover, we measure the transient temperature on the surface of acupuncture points Laogong (PC8), Shenmen (HT7) and Hegu (LI4). The comparative results indicate the rationality of the simulation method. Furthermore, the energy absorption at different depth of tissue was estimated qualitatively by the concept of TAC that we put forward. At last the conclusion is given that the moxibustion obtains therapeutic effectiveness through heat infiltration.

1 Methods

Judging by the energy conservation law, the energy transduction in biological body comes from the energy release of moxa combustion. Therefore, it is necessary for the paper to describe properly the basic physical characteristics of moxa burning. The specific mode of energy transmission is also discussed in order to use the mathematical model to present impartially the moxibustion heat transfer regularity in bio-tissue. Thus the model is studied from the perspective of heat radiation.

2 Moxibustion thermal radiation theory

Stefan-Boltzmann law shows that the radiation power per unit area per unit time, scilicet radiation heat flux density of the black body, is proportional to the fourth power of the temperature[15]. However, the black body is an idealized model, and the ability of all the actual objects' emitting thermal radiation is lower than that of the black body at the same temperature. Thus a parameter called the emissivity ε is defined to measure the difference between the actual object and the black body[16].

The total radiation heat flux emitted by moxibustion combustion can be obtained as:

$$E_a = \varepsilon_a \sigma T_a^4 \quad , \quad (1)$$

where ε_a, T_a are respectively the radiation emissivity and the surface temperature of burning moxa, $\sigma = 5.67 \times 10^{-8}$ W/(m^4·K^4).

Here the irradiation is introduced to represent the radiant heat flux that the surface received from all directions of the space, thus the irradiation of the skin is equal to the portion of the radiation reaching the surface of the skin within the specified range, ignoring the influence of the air and the environment. According to Lambert cosine law, the radiation reaches the point S on the skin is written as:

$$G = \frac{E_a A_a}{\pi H^2} \quad , \quad (2)$$

where A_a means the surface area of the moxa combustion radiation. The distance from the moxa burning center point to the surface of the skin is denoted as H.

However only part of the radiation that gets to the surface of the skin is able to be absorbed. α_s is the absorptivity, which represents the absorbed fraction of the external irradiation. By Kirchhoff's law, the total hemisphere absorptivity of the skin is equal to its hemisphere emissivity, that is $\alpha_s = \varepsilon_s$. Therefore, the heat flux absorbed by the skin during moxibustion can be rewritten as[16]

$$q_0 = \frac{\phi_{abs}}{A_s} = \alpha_s G = \varepsilon_s G \quad . \quad (3)$$

In the moxibustion combustion process, the heat flux which is actually acting on the tissue is changing at any time, increasing and decreasing[17]. It is presumed that the heat flux of moxibustion has a periodic change, and that this periodicity is reflected in the temperature sudden change[16]. Therefore the periodic fluctuation of temperature can be described by the harmonic wave.

$$T_a = 400 + 300\cos\left(\frac{2\pi}{280}t\right) \quad . \quad (4)$$

Substituting Eqs. 1-2 and 4 into Eq. 3, we derive the final heat flux as

$$q_0(t) = \frac{\varepsilon_s \varepsilon_a \sigma A_a \cdot \left[400 + 300\cos\left(\frac{2\pi}{280}t\right)\right]^4}{\pi H^2} \quad . \quad (5)$$

Thus q_0 is time-dependent, this is conducive to study the volatility of heat conduction in biological tissue.

3 Biological heat transfer model

Moxa combustion radiation leads to energy production in body, which is equivalent to the additional spatial heat source in biological heat transfer equation. However, in moxibustion the interaction relationship between biological tissues and the energy waves is unclear. Here we do not consider the thermal term caused by attenuation of radiative electromagnetic wave in tissues. The moxa thermal radiation can be attributed to the boundary conditions (B. C.) of the biological tissue. It is surface heat flux under the second boundary condition upon Fourier law. During the moxibustion thermal process, the second BC at the skin surface can be generalized as:

$$-k\frac{\partial T}{\partial x} = q_0(t), x = 0 \quad . \quad (6)$$

Based on the above conditions, the generalized Pennes equation is given as:

$$\rho c\frac{\partial T(x,t)}{\partial t} = \nabla[k\nabla T(x,t)] + \omega_b\rho_b c_b(T_{art} - T) + Q_m \quad , \quad (7)$$

where, ρ, c, k are the density, the specific heat, and the thermal conductivity of the tissue, respectively, ρ_b, c_b denote density and specific heat of blood respectively. ω_b is the blood perfusion rate respectively. T_{art} is the arterial temperature which is treated as a constant, and T represents the tissue temperature. Q_m is the rate of metabolic heat generation per unit volume of tissue.

The initial temperature field for the basal state of biological bodies can be obtained through solving the following equations.

$$\begin{cases} k\frac{d^2T_0(x)}{dx^2} + \omega_b\rho_b c_b[T_{art} - T_0(x)] + Q_m = 0 \\ T_0(x) = T_c, x = L \\ -k\frac{dT_0(x)}{dx}h_0[T_e - T_0(x)], x = 0 \end{cases} \quad , (8)$$

where, $T_0(x)$ is steady-state temperature fields prior to moxibustion, T_c is the body core temperature and often regarded as a constant, h_0 is the apparent heat convection coefficient between the skin surface and the surrounding air under physiologically basal state, and T_e represents the surrounding air temperature. Here, the skin surface is defined at $x=0$ while the body core at $x=L$.

Considering that the biological body tends to keep its core temperature to be stable, the body core temperature can be regarded as a constant.

$$T = T_c, x = L \quad . \quad (9)$$

Using the following transformation[12]

$$T(x,t) = T_0(x) + S(x,t)\exp(-\frac{\omega_b\rho_b c_b}{\rho c}t) \quad . \quad (10)$$

The Pennes equation can be changed into homogeneous equation

$$\frac{\partial S}{\partial t} = \alpha\frac{\partial^2 S}{\partial x^2} \quad , \quad (11)$$

where $\alpha = k/\rho c$ is the thermal diffusivity of tissue.

The corresponding boundary and initial conditions are then re-expressed as:

$$\begin{aligned} -k\frac{\partial S}{\partial t} &= g(t), x = 0 \\ S &= 0, x = L \\ S(x,t) &= 0, t = 0 \end{aligned} \quad , \quad (12)$$

where

$$g(t) = [k\frac{dT_0(x)}{dx}\bigg|_{x=0} + q(t)]\exp(\frac{\omega_b\rho_b c_b}{\rho c}t)H(t) \quad . \quad (13)$$

and $H(t) = \begin{cases} 0, t<0 \\ 1, t>0 \end{cases}$ is the Heaviside function.

Using Green function method, $S(x,t)$ can be solved from the combined Eq. 11 and Eq. 12. The corresponding expression for Green function is obtained as

$$G(x,t;\xi,\tau) = \frac{2}{L}\sum_{m=1}^{\infty} e^{-\alpha\beta_m^2(t-\tau)}\cos(\beta_m x)\cos(\beta_m\xi)H(t-\tau) \quad , \quad (14)$$

where, $\beta_m = \frac{2m-1}{2L}\pi, m = 1,2,3,\cdots$.

Then, the solution to equation (11) can be obtained as

$$S(x,t) = \frac{\alpha}{k}\int_0^t G(x,t;\xi,\tau)\big|_{\xi=0} g(\tau)d\tau \quad . \quad (15)$$

The final solution for $T(x,t)$ is therefore constructed in the form of

$$T(x,t) = T_0(x) + S(x,t)\exp(-\frac{\omega_b\rho_b c_b}{\rho c}t) \quad . \quad (16)$$

For the present analysis, the parameter change with temperature is not considered. Typical values for healthy skin tissue properties and other parameters are applied as given in Ref. 18: $\rho = 1\,000$ kg/m^3, $c = 3\,980$ J/kg·℃, $c_b = 4\,200$ J/kg·℃, $\rho_b = 1\,050$ kg/m^3, $T_{art} = T_c = 37$℃. The apparent heat convection coefficient due to natural convection and radiation is taken as $h_0 = 10$ W/m^2·℃, while the surrounding fluid temperature is chosen as $T_f = 25$℃[19].

4 Results and discussion

Here, four different cases of heat transfer in skin tissue were researched. The four cases cover non-acupuncture point, non-acupoint with tumor, acupoint and acupoint with tumor. Due to a shortage of experimental measurements of these parameters, the following assumptions are made for healthy tissue and highly vascularized tumor situated under-neath the skin, according to previous research and experience[19-20]. The four tissues have been defined with homogeneous heat conductivity blood perfusion, and metabolic heat generation, but of different values, the corresponding parameters are shown in Table 1. 0.005 m $< x < 0.015$ m is prearranged as the tumor domain.

Table 1 The essential parameters of several tissues
表 1 四种组织的基本参数

Tissue	k/(W/m℃)	ω_b(ml/s/ml)	Q_m/(W/m^3)
Non-acupoint	0.42	0.0005	840
Acupoint	0.45	0.0005	2100
Non-acupoint with tumor	0.42	0.001	4200(0.005 m<x<0.015 m) 840 (others)
Acupoint with tumor	0.45	0.001	4800(0.005 m<x<0.015 m) 2100(others)

In the absence of moxibustion thermal, the solution to Eq. 8, *i. e.*, the initial temperature field for the basal state of biological bodies is:

$$T_0(x) = T_{art} + \frac{Q_m}{\omega_b\rho_b c_b} + \frac{\left(T_c - T_{art} - \frac{Q_m}{\omega_b\rho_b c_b}\right)\left[\sqrt{\gamma}\cosh(\sqrt{\gamma}x) + \frac{h_0}{k}\sinh(\sqrt{\gamma}x)\right]}{\sqrt{\gamma}\cosh(\sqrt{\gamma}L) + \frac{h_0}{k}\sinh(\sqrt{\gamma}L)}$$

$$+\frac{\frac{h_0}{k}\left(T_e - T_{art} - \frac{Q_m}{\omega_b\rho_b c_b}\right)\cdot \sinh[\sqrt{\gamma}(L-x)]}{\sqrt{\gamma}\cosh(\sqrt{\gamma}L) + \frac{h_0}{k}\sinh(\sqrt{\gamma}L)} \quad , \quad (17)$$

where, $\gamma = \omega_b\rho_b c_b/k$.

The initial temperatures of the four tissues at $x = 1$ cm are listed in Table 2. The data reveals that the temperature of tissue with tumor is generally higher than the healthy tissue, and the non-acupoint has lower temperature than acupoint. The trend matches well with the results in reference[21].

Table 2 The initial steady-state temperature of four tissues

表2 四种组织的初始稳态温度

Tissue	Non-acupoint	Acupoint	Non-acupoint with tumor	Acupoint with tumor
T_0/℃	36.4816	36.9383	36.9521	36.9521

Figures 1(a) and 1(b) respectively show the transient temperatures of healthy non-acupoint tissue and non-acupoint tumor tissue at six different locations of the skin in moxibustion process. Obviously, in both cases, the highest temperature increase occurs at the surface while smaller temperature increase occurs inside the tissue due to the decay of the heat effect of moxibustion. We also remark that as the time becomes long enough, and the temperature approaches a steady-state value. One can still find that the maximum amplitudes of the temperature oscillation($x = 0$) is due to the periodic fluctuation of temperature of the moxa burning. As the depth increases, the amplitude of the oscillation decreases accordingly. Particularly, Fig. 1 (b) shows the temperature curves of $x = 0.5$ cm, $x = 1.0$ cm and $x = 1.5$ cm tend to be stable more quickly than that in Fig. 1 (a), and the temperature steady-state value is lower. Which suggests that the temperature of the tumor is not higher than that of the normal skin because of the high blood perfusion. For the acupoint tissue and acupoint tumor tissue, the corresponding thermal responses can also be studied using the same way.

Here, the transient temperatures of four kinds of tissues at $x = 0.5$ cm are compared, the results are shown in Fig. 2. Apparently, the temperature of acupuncture point is higher than that of non-acupuncture point at the same time, then comes the acupuncture point with tumor as the third, and non-acupuncture point with tumor the lowest. The transient temperatures of four kinds of tissues at $x = 1$ cm also have such regularities. It is a benefit that this difference between healthy tissue and tumor tissue can be used for diagnostics of the physiological stage of the biological body.

Figure 3 depicts the temperature distributions of biological bodies (non-acupuncture point) owing to the effect of moxibustion, Fig. 3(a) describes the case in that moxa combustion temperature is a constant value, and the distance from the moxa burning center point to the surface of the skin was set as 3 cm. Figure 3(b) shows another case in that moxa combustion temperature is the harmonic wave. Obviously, in both cases, the tissue temperature at the early stage of moxibustion decreases from the body core to the skin surface. However, it

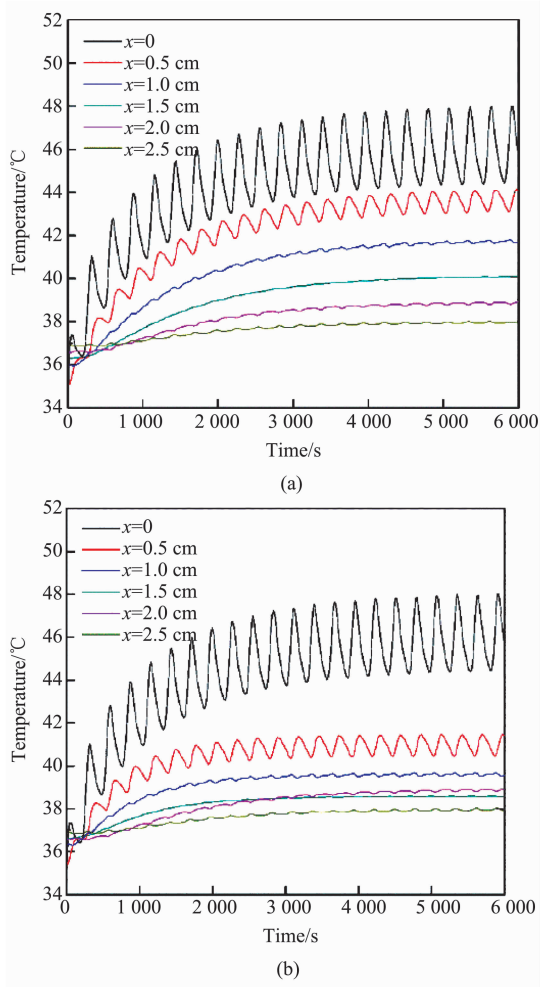

Fig. 1 The transient temperatures of (a) healthy non-acupoint tissue, and (b) non-acupoint tumor tissue at six different locations of the skin, respectively

图1 (a)健康非穴位组织皮肤不同深度处的温度随艾灸时间的变化,(b)非穴位肿瘤组织皮肤不同深度处的温度随艾灸时间的变化

will be improved gradually due to the moxibustion thermal stimulation. Moreover, there is an intercross for temperature curves at different times in Fig. 3(b), which exhibits the temperature oscillation inside the tissue when the tissue is subjected to the moxibustion with harmonic wave. Temperature changes are concentrated in the shallow layer of the skin, which illustrates that the skin provides well protection for the living body[22].

The heat-transfer mechanism of moxibustion is so complicated that the heating pattern[23-24] of moxibustion is very difficult to be determined. Here we define a temperature attenuation coefficient η to measure the energy absorption principle of tissue in the moxibustion. It can be then obtained as:

$$\eta = -(1/x)\ln(I/I_0) \quad , \quad (18)$$

where, I_0, I are the component of the skin temperature and the component of the temperature at depth x, respectively associated with heat flux density, and we take the average value of temperature from 0 s to 4000 s. As can be seen in Fig. 4, for healthy tissues, the attenuation co-

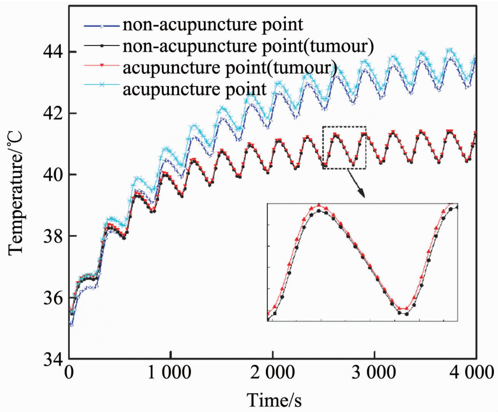

Fig. 2 Transient temperature of four different tissues at the depth $x = 0.5$ cm

图 2 非穴位健康组织、非穴位肿瘤组织、穴位肿瘤组织以及穴位健康组织皮下 0.5cm 处的温度随艾灸时间的变化趋势对比

efficient increases rapidly in the entire depth range with the increasing depth. However, the coefficient changes fast when $x < 0.6$ cm. Then, the coefficient grows more smoothly while $0.6 \text{ cm} < x < 2.5$ cm. Eventually, the change rises quickly again. This result indirectly demonstrates that the tissues of different depths respond differently to the stimulation of moxibustion. The heat radiation absorbed by shallow tissue of the skin may be relatively larger than that by deep tissues. For tissue with tumor, the attenuation coefficient of tumor region is greater than that of healthy skin under the same conditions. The oscillation energy flow in the living tissue and is equivalent to a mild stimulus but not a strong one in biological tissue, which is significantly beneficial for organization achieving its good functions. Our simulation results also indicate that the heat with high frequency is mainly absorbed by the surface layer, while that of the low frequency can penetrate deeply into the living biological parts.

We applied an infrared thermal imager (Fluke Ti400) to obtain the temperature field distribution of the ignited moxa sticks (Fig. 5). Three years moxa sticks from Nan Yang (1:5), 1.7 cm in diameter and 10 cm in length were used in our experiment. The temperatures of different parts have various values. The lighter the color, the higher the temperature. The maximum temperature position lay in the center of the ignited moxa stick, which can reach from 508℃ (after half of 1 minutes) to 757 ℃ (after 5 minutes). And the temperature of the ignited stick was rising as an oscillating mode. Then we also got the temperature distribution of the palm after 2 minutes moxibustion (Fig. 6).

According to traditional Chinese medicine theory and International Standard Nomenclature, several acupuncture points such as Laogong (PC8), Shenmen (HT7) and Hegu (LI4) were selected and then the transient temperatures on the surface of these acupuncture points were measured.

Four healthy volunteers (two males, two females) were recruited. Their ages ranged from 20 years to 24 years (mean (22 ±2) years) old. The inclusion criteria

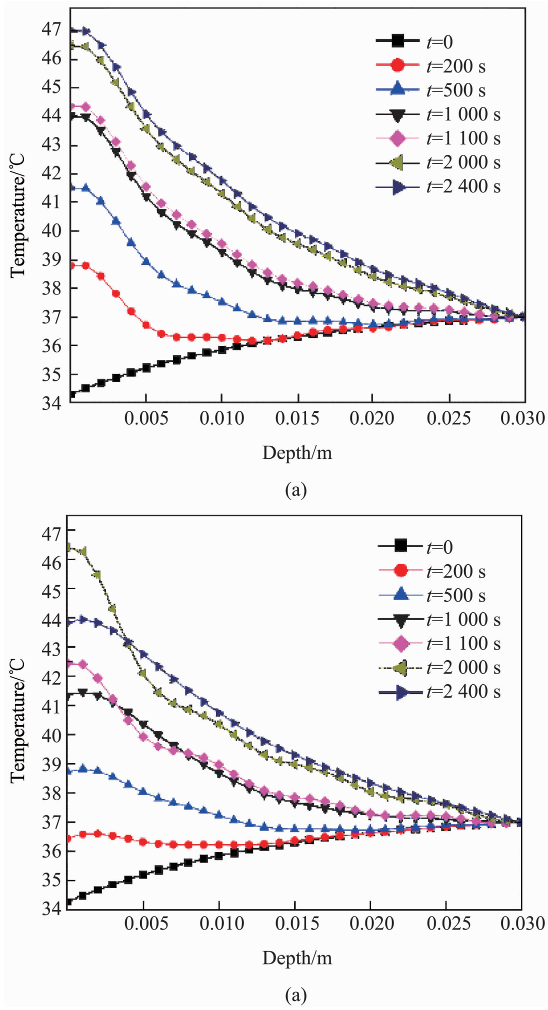

Fig. 3 Temperature distribution at different times ($k = 0.42$ W/m · ℃, $Q_m = 840$ W/m^3, $\omega_b = 0.0005$ ml/s/ml). (a) $T_m = 550$℃, (b) $T_m = 400 + 300 \cos(2\pi/280)$ (℃)

图 3 艾灸不同时刻的温度分布,其中,$k = 0.42$ W/m · ℃, $Q_m = 840$ W/m^3, $\omega_b = 0.0005$ ml/s/ml. (a) $T_m = 550$℃, (b) $T_m = 400 + 300 \cos(2\pi/280)$ (℃)

were normal body temperature. All participants were informed of the nature of the experiment.

All experiments were performed under controlled environmental conditions: dark environment, temperature (25 ± 1)℃ with minimal air flow, relative humidity 35% ~ 60%, quiet and shielded from electromagnetic fields. A set of highly sensitive temperature measurement system was fabricated based on temperature sensor (PT100).

In this set of experiments, the distance from the moxa burning center point to the surface of the skin was set as 3 cm. The moxa stick was ignited and then placed against the acupuncture points. The temperature sensor was attached to the point. The temperature data was displayed on the PC in real time. In the burning process, the moxa stick length would change, so we pushed the moxa forward every minute to maintain the distance between the moxa tip and the skin as 3cm. The ashes was also removed every minute. The burning of each moxa

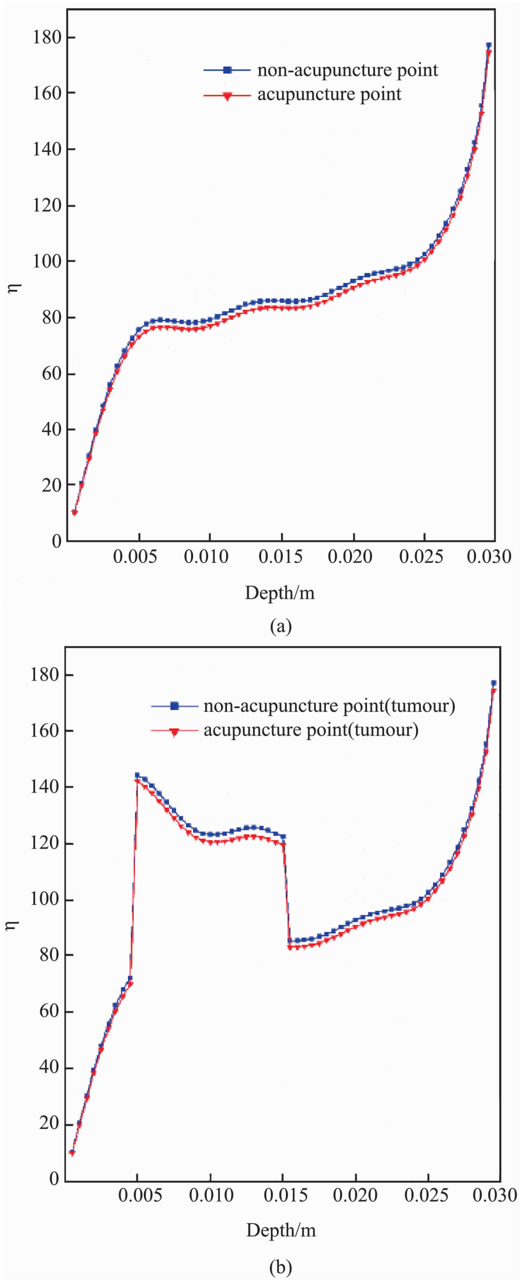

Fig. 4 Temperature attenuation coefficient of four different tissues. (a) Healthy tissue, and (b) tumor tissue

图 4 四种不同组织的温度衰减系数随深度的变化情况. (a)健康组织,(b)肿瘤组织

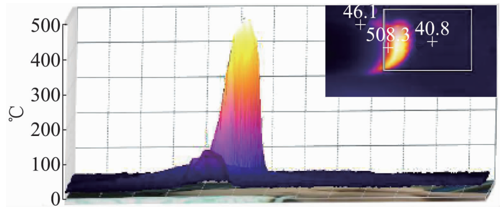

Fig. 5 The experiment result of the distribution of temperature field of the whole burning moxa stick. The insert figure represents the section temperature distribution

图 5 艾条燃烧表面截面的温度分布三维图,其中右上插图为截面热像温度分布图

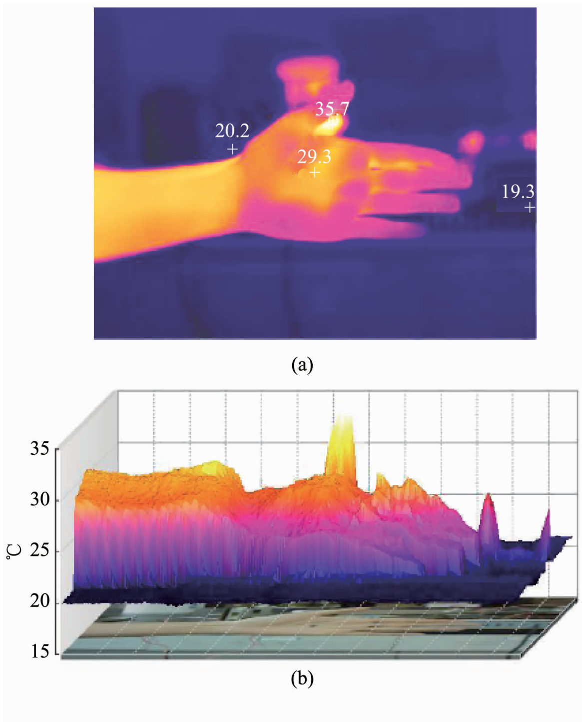

Fig. 6 (a) The experiment result of the distribution of temperature field of the whole palm, (b) the temperature field spectrum of the whole palm

图 6 (a)艾灸时整个手掌的热像图,(b)手掌对应的温度场分布三维图

stick lasted about 30 minutes, the experiment was repeated five times under the same experimental conditions.

After bad data points were eliminated, the transient temperatures of four volunteers were shown in Figs. 7 (a) ~ (c), and the simulation curve was also added. Obviously, in the early stage of moxibustion, the temperature of the three acupoints increases rapidly over time. As time continually increases, the temperature fluctuates within a certain range. The skin excretes sweat and the psychological characteristics of the participant may change, which will affect the experimental results, either directly or indirectly. Even so, experimental result on skin surface have the same change trend with the simulation results. This proves that the prediction about biological tissue temperature is referable for the research. As shown in Fig. 7(d), the temperature of Laogong is higher than that of Hegu and Shenmen, which may be related to the structure of organization where the acupuncture is located. In these experiments, due to the small sample quantity, significant difference is not shown in the temperatures of volunteers with different sex and age. Further studies will focus on exploring the effects of sex, age, and timing of the subjects on the skin temperature.

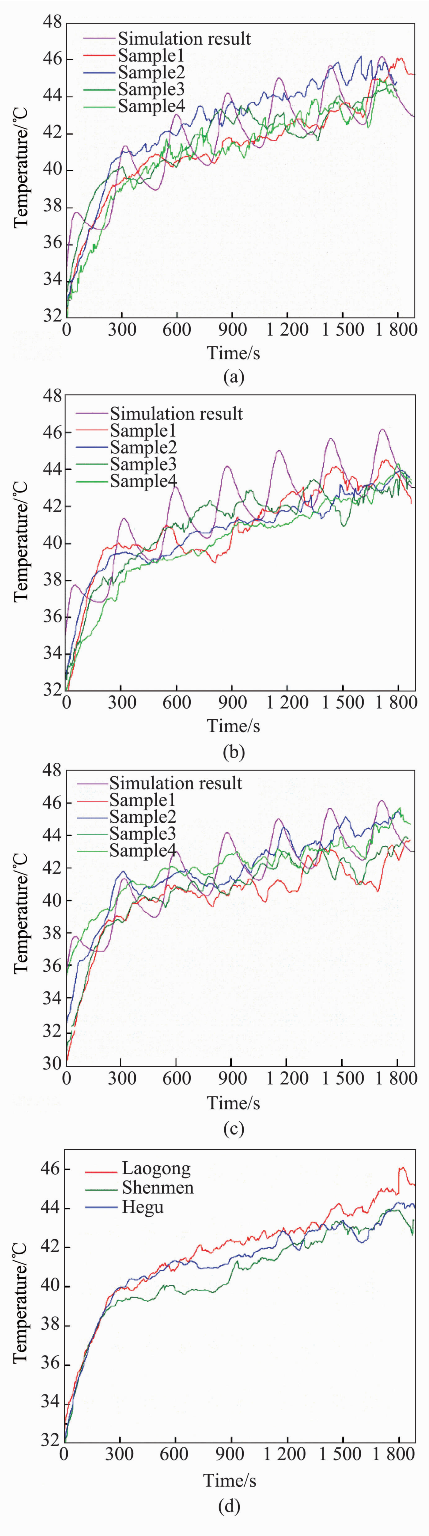

Fig. 7 (a) The transient temperature of skin acupoint Laogong subject to moxibustion, (b) the transient temperature of skin acupoint Shenmen, (c) the transient temperature of skin acupoint Hegu, (d) The average temperature change trend of the four samples

图 7 (a)艾灸时四名志愿者劳宫穴处温度随时间的变化，(b)艾灸时四名志愿者神门穴处温度随时间的变化，(c)艾灸时四名志愿者合谷穴处温度随时间的变化，(d)不同穴位处四个样本的平均温度变化趋势

5 Conclusion

In this paper, we presented the accurate expression of energy flow for the heat radiation and established the bio-heat transfer model in moxibustion. It is the first time that the heat radiation theory was applied to research of heat transfer in biological tissues under moxibustion. The temperature distribution of four tissues, such as healthy tissue, tumor tissue, which are non-acupoint tissue and acupoint tissue subject to mild moxibustion, was simulated by the Green's function method that we proposed. Moreover, we put forward new proposals for applying the temperature attenuation coefficient to analyze the energy absorption law at different depth of tissue. These characteristics were explored through numerical simulations and experimental measurements in different living tissues. The consistency between the prediction and experiment about surface temperature variation verified the effectiveness of the proposed solution. Based on the simulation results, we drew the conclusion that the fluctuation of moxibustion combustion temperature led to oscillation of the skin tissue temperature, and the amplitude of the oscillation decreased accordingly as the depth increases. Energy attenuated most rapidly in the shallow layer of the skin. On the other hand, temperature change in healthy tissues and tumor tissues also reflected the difference of heat transfer law in tissue between physiological and pathological states. It has important reference value for the estimation of tissue thermal damage and tumor diagnosis in medicine. Moxibustion thermal has three kinds of behavior in living tissues: transmission, penetration and expansion. Our study reveals heat infiltration mechanism. Moxibustion heat penetrates into deep tissue slowly, and even to the thoracic and abdominal organs. The symptoms are alleviated in the area where the thermal reaches. Few researchers have paid attention to this important physical feature and our study lays the foundation for research into the mechanisms of moxibustion.

Further study based on temperature measurement experiment on the skin surface and in different depths of tissue can be implemented. Mathematical physics model will be gradually improved in line with the moxibustion process. The dynamic distribution of temperature field and its representative energy process, as well as the resulting biological effects will be further studied in the future.

References

[1] Zhou W. Acute lymphangitis treated by moxibustion with garlic in 118 cases [J]. *J Tradit Chin Med*, 2003, **23**(3):198.

[2] Deng H, Shen X. The mechanism of moxibustion: ancient theory and modern research [J]. *Evid-Based Compl Alt*, 2013, **2012**: 2379291.

[3] Yi S H. Thermal properties of direct and indirect moxibustion [J]. *Journal of acupuncture and meridian studies*, 2009, **2**(4): 273 – 279.

[4] Bai Y, Lin W. Discussion on the relationship between moxibustion and thermal stimulation [J]. *J Acupunct Moxibust*, 1991, **4**: 10 – 11.

[5] Zhao L, Shen X. *Chemical and physical characteristics of moxibustion* [M]. Current Research in Acupuncture, New York: Springer, 2013: 109 – 127.

[6] Shen X, Ding G, Wei J, *et al*. An infrared radiation study of the biophysical characteristics of traditional moxibustion[J]. *Complement Ther Med*, 2006, **14**: 213 – 219. .

[7] Pennes H H. Analysis of tissue and arterial blood temperatures in the resting human forearm [J]. *J Appl Physiol*, 1948, **1**: 93-122.
[8] Wulff W. The energy conservation equation for living tissue [J]. *IEEE Trans Bio-Med Eng*, 1974, **6**: 494-495.
[9] Klinger H G. Heat transfer in perfused biological tissued-I: general theory [J]. *Bull Math Biol*, 1974, **36**: 403-415.
[10] Arkin H, Holmes K R, Chen M M, *et al*. Thermal pulse decay method for simultaneous measurement of local thermal conductivity and blood perfusion: a theoretical analysis[J]. *J of Biomech Eng*, 1986, **108**(3): 208-214.
[11] Charny C K. An evaluation of the Weinbaum-Jiji bioheat equation for normal and hyperthermic conditions [J]. *ASME J Biomech Eng*, 1990, **112**: 80-87 .
[12] Deng Z S, Liu J. Analytical study on bioheat transfer problems with spatial or transient heating on skin surface or inside biological bodies [J]. *J of Biomech Eng*, 2002, **124**(6): 638-649.
[13] Vyas R, Rustgi M L. Green's function solution to the tissue bioheat equation [J]. *Med Phys*, 1992, **19**(5): 1319-1324.
[14] Gao B, Langer S, Corry P M. Application of the time-dependent Green's function and Fourier transforms to the solution of the bioheat equation [J]. *Int J Hyperthermia*, 1995, **11**(2):267-285.
[15] Baltes H P. Deviations from the Stefan Boltzmann law at low temperatures [J]. *Applied Physics*, 1973, **1**(1): 39-43.
[16] Xia Y L. Analysis and establishment of mathematical model of heat transfer in mild moxibustion [D]. Guangzhou: Guangzhou University of Chinese Medicine, 2008.
[17] Zhang J, Wu Y. Modern progress of mechanism of moxibustion therapy [J]. *Journal of Acupuncture and Tuina Science*, 2006, **4**(5):257-260.
[18] Arkin H, Holmes K R. Recent developments in modeling heat transfer in blood perfused tissues [J]. *IEEE Trans Biomed Eng*, 1994, **41**(2):97-107.
[19] Liu J, Xu L X. Boundary information based diagnostics on the thermal states of biological bodies [J]. *Int J Heat Mass Tran*, 2000, **43**(16): 2827-2839.
[20] Hu X L, Xu J A, Yang J, *et al*. Elicitation of infrared radiant track along meridian courses over human body surface by local heating[J]. *J Infrared Millim W*, 2002, **1**:001.
[21] Cao L, Qin Q H, Zhao N. An RBF - MFS model for analysing thermal behaviour of skin tissues [J]. *Int J Heat Mass Tran*, 2010, **53**(7):1298-1307.
[22] Ma W, Liu W, Li M. Modeling heat transfer from warm water to foot: Analytical solution and experimental validation [J]. *Int J Therm Sci*, 2015, **98**:364-373.
[23] Li J H, Liang H. *Laser Medicine-Applications of Laser in Biology and Medicine* [M]. Beijing: Science Press, 1989 .
[24] Diller K R. Modeling of Bioheat Transfer Processes at High and Low Temperatures [J]. *Adv Heat Transfer*, 1992, **22**:157-357.