Ding JF, Chu X, Chang XR, *et al*. Mechanism study of the transmission of moxibustion heat in human acupoint tissues. J Acupunct Tuina Sci, 2019, 17(1): 24-30
DOI: https://doi.org/10.1007/s11726-019-1089-8

Special Topic for 973 Program

Mechanism study of the transmission of moxibustion heat in human acupoint tissues

灸热在人体穴位组织中传导机理研究

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Abstract
Objective: To discuss the topical action characteristics of the biological transmission of moxibustion heat via temperature collection and numerical modeling.
Methods: Temperature of moxibustion was measured at multiple points at a distance of 3 cm to obtain the moxibustion temperature field nephograms by the high-accuracy temperature measure array. Finite element analysis was used to imitate the three-dimensional dynamic distribution of temperature in acupoint tissues.
Results: Through numerical analysis, the one-dimensional, two-dimensional and three-dimensional distributions of temperature in human acupoint tissues at 5 min of moxibustion were established. The result showed that moxibustion heat mainly transmitted from the surface of the tissue to the internal, and the influence of moxibustion heat decreased with the depth of the tissue. The analysis of the nephograms of acupoint tissue temperature at 5, 10, 15 and 20 min of moxibustion showed that with the increase of the moxibustion time, the temperature in acupoint tissues constantly rose, and the transmission depth of moxibustion heat also further expanded inside acupoint.
Conclusion: By establishing the three-dimensional dynamic model of heat transmission inside acupoint tissues with the biological parameters of human tissues and the temperature values obtained, this study used finite element analysis software ANSYS 14.0 and discovered the rules in the transmission of heat in body tissues during moxibustion, and the features in moxibustion heat transmission (from the proximal to the distant) and heat penetration (from the surface to the internal). This study provides theoretical and experimental support for the application of moxibustion in clinical practice.
Keywords: Moxibustion Therapy; Moxa Stick Moxibustion; Point, Zusanli (ST 36); Finite Element Analysis; Temperature; Thermal Conductivity; Temperature Field; Healthy Volunteers

【摘要】目的：通过温度采集技术和数值建模方法探讨艾灸生物传热的局部作用特点。**方法：**采用高精度温度测量阵列，实现对 3 cm 灸距下艾灸温度的多点测量并获取艾灸温度场云图。运用有限元分析方法模拟出穴位组织温度三维动态分布模型。**结果：**通过数值分析，建立了人体穴位组织在施灸 5 min 时温度分布的一维、二维及三维模型。结果表明灸热主要沿着组织表面至内部进行传导，随着组织深度的增加灸热的影响也越来越小。通过对5、10、15 和 20 min 不同时刻内穴位组织中温度场分析，表明随着施灸时间的增长，穴位组织的温度不断增加，灸热在穴位的传递深度进一步扩大。**结论：**运用有限元分析软件 ANSYS 14.0，结合人体组织的生物参数及实际测量的温度数值，建立了穴位组织温度场传播过程的三维动态模型，发现艾灸过程中热量在组织中的传播规律，揭示了艾灸传热(从近到远)、透热(由浅入深)的作用特点，为临床灸法的运用提供了理论和实验支持。
【关键词】灸法；艾条灸；穴，足三里；有限元分析；温度；导热性；温度场；健康志愿者
【中图分类号】R2-03 **【文献标志码】**A

Moxibustion is a health protection or treatment method with moxa leaves or wools as main materials ignited over acupoint or the affected area[1]. It is a significant component of acupuncture-moxibustion and one of the external therapies with most distinctive features of traditional Chinese medicine (TCM). The process for moxibustion to induce change in tissue temperature is in fact the transmission of heat, which can be generally described as: the source of moxibustion heat-heat transmission medium-human acupoint[2-5].

Detecting the change in topical temperature during moxibustion is essential to the study of moxibustion mechanism. With the development of modern electronic thermometry technique, many scholars have used this technique to measure the topical temperature during moxibustion[6-7]. Liu CY, *et al*[8] used digital

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dermal thermometry to observe the effect of moxibustion on patient's dermal temperature and concluded the relation between topical dermal temperature and time length of moxibustion. Dai GB, *et al*[9] used high-accuracy platinum resistance thermometry PT1000 to detect changes in moxibustion temperature with the length of time at different distances. Wang XY, *et al*[10] described the increasing process of human acupoint temperature and the distribution of temperature with infrared imager. However, current thermometry techniques are often limited to the measure of a single spot, and few methods can be adopted to detect the temperature field during moxibustion.

With further study of the biological features of moxibustion, some researchers start to employ bio-heat transfer method and finite element analysis to study moxibustion therapy. Noh SH, *et al*[11] used Pennes to describe the temperature distribution in dermal tissues stimulated by moxibustion heat. They also observed the differences in the change of dermal temperature and blood perfusion between one moxa cone and three moxa cones. With the help of a software, Li Y, *et al*[12] analyzed the transmission of moxibustion heat in pig muscles in vitro, and established a single-dimensional model of the temperature field. Cheng K, *et al*[13] described the two-dimensional heat transfer process in human body tissues during warm needling with infrared thermometry and numerical modeling method. Xiao M, *et al*[14] imitated the temperature fields of conventional warm needling and electronic warm needling by ANSYS and then obtained the two-dimensional heat transfer processes of the two warm needling methods in human body tissues. But, so far, no researcher has ever imitated the temperature field inside acupoint tissues under moxibustion heat in a three-dimensional way.

To address the above issues, this study mainly targeted the measure of moxibustion temperature field and the establishment of temperature field in human acupoint tissues. Firstly, a moxibustion temperature collection platform was developed by multisensor array thermometry technique and high-precision digital temperature transmitter DS18B20. This platform allowed multi-spot measuring of moxibustion temperature at a distance of 3 cm and the obtaining of moxibustion temperature field nephograms. Secondly, based on finite element analysis and the data of moxibustion temperature field, ANSYS 14.0 was used to set up a three-dimensional dynamic model of the temperature in human acupoint tissues under moxibustion at 3 cm, for better studying the heat transfer mechanism of moxibustion in human acupoint tissues.

1 Moxibustion Temperature Collection Platform and Experiment

1.1 Establishment of moxibustion temperature collection platform

The moxibustion temperature collection platform consisted of three parts (Figure 1). The first part included moxibustion holder and moxa stick. This part made it easier to adjust the moxibustion distance and replace moxa stick. The second part was moxibustion thermometer which consisted of temperature collection array and measurement-control circuit. The temperature collection array was composed of 64 DS18B20 high-accuracy digital temperature sensors, with a measure range of –55-125 ℃, accuracy of ±0.5 ℃ and a collection cycle of 1.5 s. The measurement-control circuit used 89C52 single-chip microcomputer to modulate the temperature sensor array and sent the data of temperature to the master computer via serial interfaces. The third part was the data processing system, i.e. the computer, which kept and processed the collected data through serial interfaces and single-chip computers.

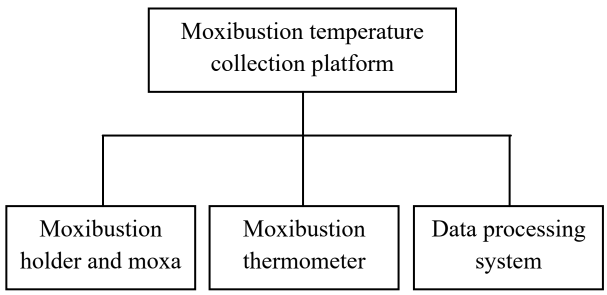

Figure 1. General design of moxibustion temperature collection platform

1.2 Experiment design

Relevant studies showed that moxibustion at 3 cm could avoid burning skin while producing thermal effect, and the induced changes in temperature-related brain regions basically conformed to the heat transfer route in human body, which all indicated that 3 cm should be the best moxibustion distance for human body[15-18]. To make it more clinically significant, the model established in this study chose 3 cm as the moxibustion distance to collect and measure the temperature field during moxibustion.

The first step of the study was to control the temperature in the laboratory at (26±1) ℃.

The second step was to adjust the moxibustion holder to set the distance between the moxa stick (Lishizhen Qiai Mugwort Group, China) and the temperature sensor at 3 cm.

The third step was to adjust the distance between moxa stick and the sensor array to be 3 cm and keep the center of moxa stick and the sensor at the same level. The moxa stick was then ignited and the temperature during moxibustion was recorded every 1.5 s automatically. The measure lasted 5 min each time.

The fourth step was to detect the initial temperature at Zusanli (ST 36) of human body. Twenty healthy student volunteers from Central South University were recruited (10 males and 10 females). Inclusion criteria: ages 18-25 years old; healthy, without a history of hereditary disease, contagious disease, trauma or surgery; had regular diet and sleep, with no habit of staying up late, drinking alcohol, smoking, drinking strong tea or coffee. The subjects were informed of the content and objective of the trial before the study started, and they all signed the informed consent form.

The temperature data of ignited moxa stick collected at 3 cm by the temperature collection platform were made into a temperature nephogram (Figure 2). In the diagram, X and Z axes represented the locations of the 64 temperature sensors, and Y-axis represented temperature. According to the nephogram, the average value of the temperature field at the center of the ignited moxa stick (T_w) was 45.2 ℃. The initial temperature of Zusanli (ST 36) measured among the 20 volunteers ranged from 26.4 ℃ to 30.1 ℃, and the average (T_f) was 28.1 ℃.

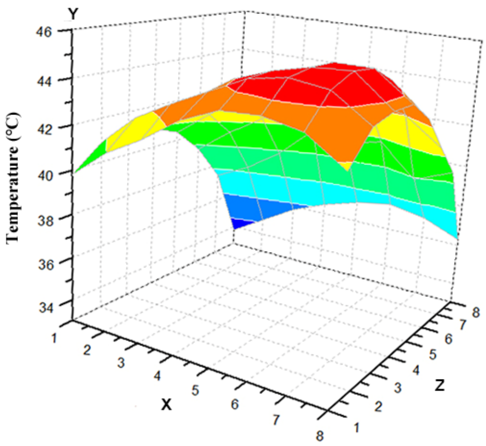

Figure 2. Moxibustion temperature nephogram at a distance of 3 cm

2 Numerical Imitation of Heat Transmission in Human Acupoint Tissues

2.1 Theory of heat transmission of mild moxibustion

The heat transfer during mild moxibustion consists of two parts: heat transfer between moxibustion and acupoint through air and heat transfer in body tissues. At a certain distance, when the duration of moxibustion increases, the temperature field inside human acupoint tissues will also change. That is why we adopted transient state analysis in the imitation. According to Fourier's law, the heat conduction formula for human acupoint tissues should be $q^{*}=-K_{nn}(\partial T/\partial n)$. Here, q^{*} represents heat flux; K_{nn} represents heat transfer coefficient; $\partial T/\partial n$ stands for temperature gradient of the heat transfer direction; minus sign indicates that heat transfers from higher temperature towards the lower. Three-dimensional Cartesian coordinate system has simplified this formula to be: $q^{*}=-[K_X(\partial T/\partial x)+K_Y(\partial T/\partial y)+K_Z(\partial T/\partial z)]$. According to Newton's law of cooling, the heat convection formula for moxibustion is $q^{*}=-h_f(T_f-T_w)$. In this formula, h_f represents convective heat transfer coefficient; T_f stands for the initial temperature of skin; T_w represents the temperature in the temperature field at the source of moxibustion heat.

2.2 ANSYS model

Finite element analysis software ANSYS 14.0 was used to imitate the process of heat transfer between moxibustion and the temperature field of acupoint tissues. The details are prescribed as follows.

The first step was to establish a reasonable model of human acupoint tissues. Relevant studies showed that the sensitization range of Zusanli (ST 36) was about 2 cun, and its safe puncturing depth was 1-2 cun (1 cun=2.5 cm)[19]. Hence, Thermal Solid was selected as the model unit for human acupoint tissues, with parameter set at Quad 8 node 70, to build up a cuboid of 5 cm×5 cm×3 cm for analysis (Figure 3).

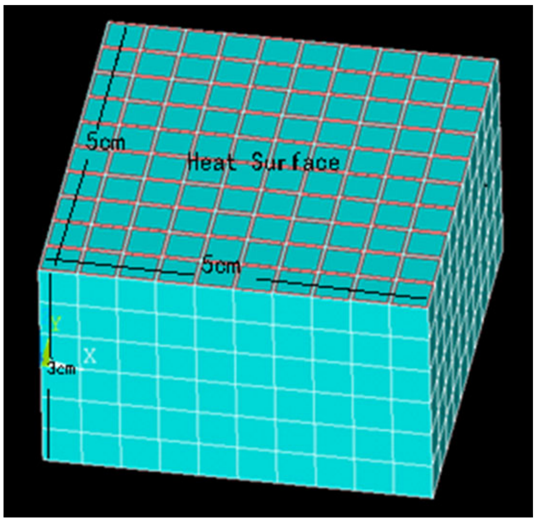

Figure 3. ANSYS model of human acupoint tissues

The second step was to determine the thermophysical parameters. Since the predominant acupoint tissues are muscles, the thermophysical parameters of human acupoint tissues were determined based on relevant literatures[11]. Section: muscles; heat transfer coefficient (K_{nn}): 0.41 W/(m^2·K);

tissue density (ρ): 1 050 kg/m^3; and specific heat (C): 2 800 J/m^3.

The third step was to determine the superficial heat transfer load of acupoint tissues (the top side in Figure 3). T_w (temperature in the temperature field of moxibustion at 3 cm), T_f (the initial skin temperature) and h_f(the convective heat transfer coefficient between human acupoint and air) were taken as the boundary conditions for analogue computation to imitate the distribution of temperature field inside human acupoint tissues[20]. Initial temperature (T_f): 28.1 ℃; field temperature (T_w): 45.2 ℃; and heat transfer coefficient (h_f) : 20 W/(m^2·K).

2.3 Finite element analysis of human acupoint temperature field

2.3.1 Imitation of acupoint tissue temperature field during 5-minute moxibustion

The numerical modeling was conducted by software with heat loading time as 5 min. The numerical modeling realized the construction of single-dimensional, two-dimensional and three-dimensional models of temperature distribution in human acupoint tissues during 5-minute moxibustion (Figure 4-Figure 6). Figure 4 shows how the curve of acupoint tissue temperature changed with the depth of tissues (0-3 cm). When the depth of tissue increased, the acupoint temperature decreased, and the highest temperature T_{max}=32.7124 ℃. The temperature decreased most rapidly when the depth of tissue was 0-0.6 cm; the temperature decreased relatively slowly when the depth of tissue was 0.6-1.0 cm; the temperature basically remained the same when the depth of tissue was 1.0-3.0 cm. Figure 5 is the two-dimensional vertical nephogram of temperature distribution in acupoint tissues. In this diagram, different colors represent different temperature values. It shows that with the increase of the vertical depth, the color changed from red to blue, suggesting that the acupoint temperature declined with the increase of vertical depth. Figure 6 shows the three-dimensional temperature distribution nephogram of acupoint tissues, revealing that the temperature increased significantly in superficial-layer tissues while it increased insignificantly in relatively deeper-layer tissues.

Analyses of the single-dimensional, two-dimensional and three-dimensional temperature models during 5-minute moxibustion indicated: moxibustion heat mainly transferred from superficial tissues to deeper tissues, and the influence of moxibustion heat decreased with the depth of tissue; the temperature in deep layer tissues basically remained the same till 5 min.

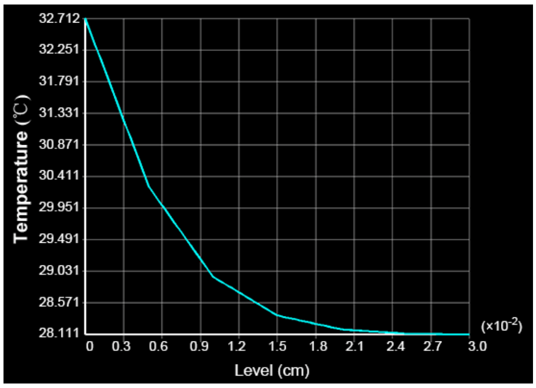

Figure 4. Temperature distribution in acupoint tissues

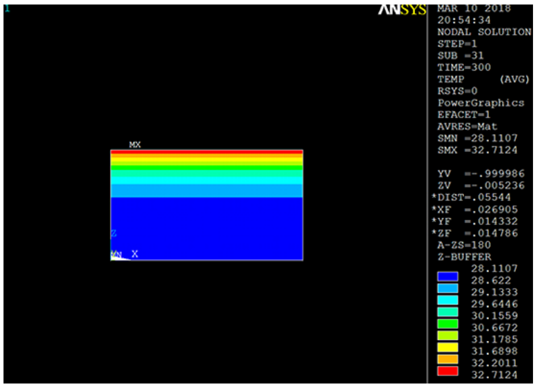

Figure 5. Two-dimensional nephogram of acupoint tissue temperature

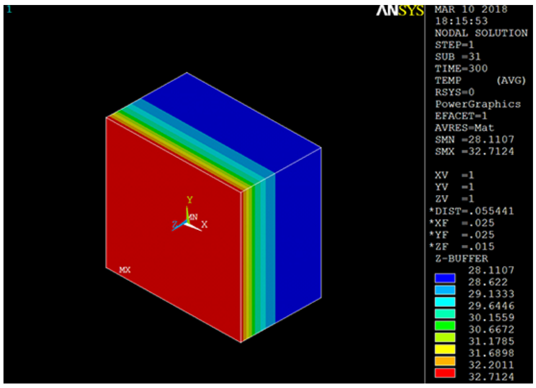

Figure 6. Three-dimensional nephogram of acupoint tissue temperature

To more directly describe the dynamic change of the temperature in different tissues with the time, three-dimensional temperature distribution nephograms during 5-minute moxibustion were established (Figure 7-Figure 11). According to Figure 7-Figure 11, the highest temperature at the five time points was 30.064 ℃, 31.088 ℃, 31.776 ℃, 32.294 ℃ and 32.712 ℃, respectively. With the extension of moxibustion time, the nephograms showed more significant changes in color. When the temperature of superficial acupoint tissues constantly increased, the color of their temperature field became darker. Meanwhile, the color of the temperature field of deeper-layer acupoint tissues almost remained the same despite the extension of moxibustion time (at 300 s, the lowest temperature of the deepest layer of tissue T_{min}=28.111 ℃, only 0.011 ℃ different from the initial temperature T_f).

Analyses of the three-dimensional temperature models of acupoint tissues within 5-minute moxibustion showed: with the extension of moxibustion time, the temperature of acupoint tissues increased constantly, the transfer of moxibustion heat further expended inside the acupoint, and the transfer was not finished at 5 min.

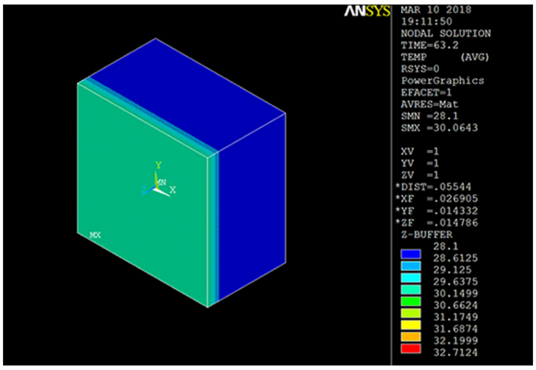

Figure 7. Three-dimensional temperature nephogram at 63 s

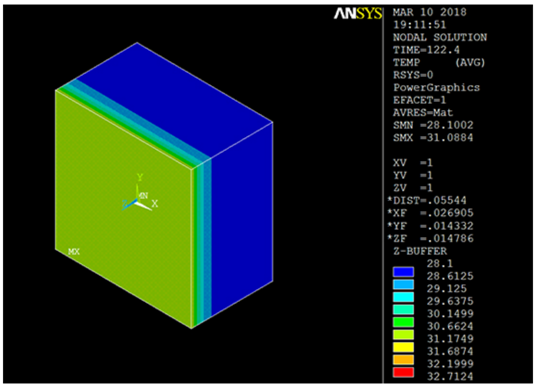

Figure 8. Three-dimensional temperature nephogram at 122 s

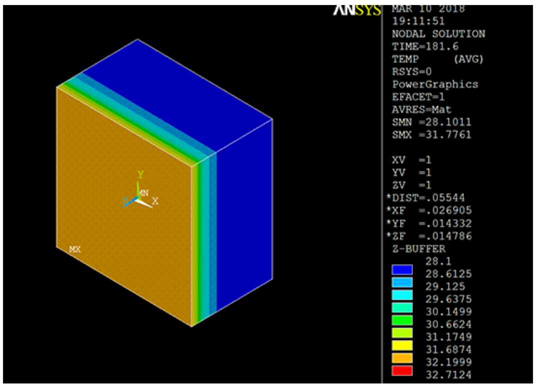

Figure 9. Three-dimensional temperature nephogram at 182 s

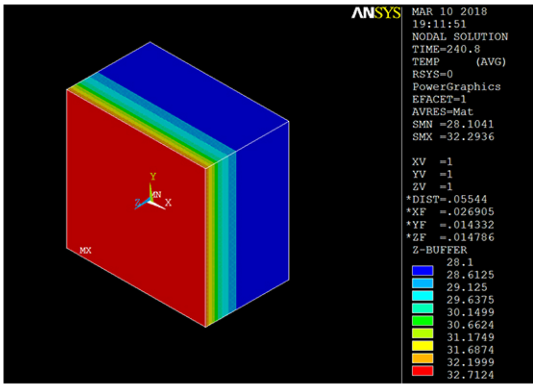

Figure 10. Three-dimensional temperature nephogram at 241 s

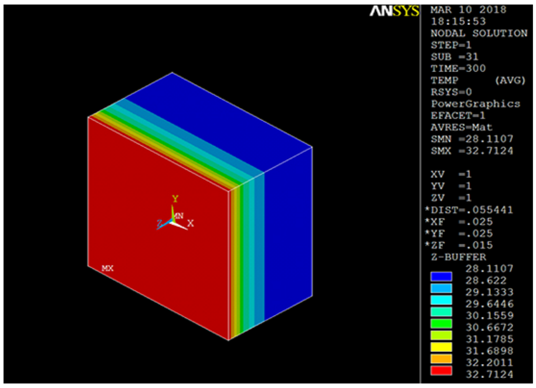

Figure 11. Three-dimensional temperature nephogram at 300 s

2.3.2 Analysis of temperature nephogram in acupoint tissues at 5, 10, 15 and 20 min of moxibustion

According to the above analyses, the heat transfer in acupoint tissues was not finished yet at 5 min. To better and deeper understand the dynamic changes in temperature of acupoint tissues with the time, three-dimensional temperature nephograms at 10, 15 and 20 min of moxibustion were established to compare with the naphogram at 5 min (Figure 12-Figure 15). According to Figure 12-Figure 15, the highest temperature of acupoint tissue (T_{max}) at the four time points was 32.712 ℃, 34.137 ℃, 35.042 ℃ and 35.715 ℃, respectively, and the lowest temperature (T_{min}) was 28.111 ℃, 28.247 ℃, 28.586 ℃ and 29.073 ℃, respectively. The results showed that with the extension of moxibustion time, the highest temperature in acupoint tissue further increased, but the rate of increase was going down; the lowest temperature in acupoint tissue further went up, and the rate of increase was going up, with more significant changes in the color of temperature field. Therefore, when the moxibustion time extended, the heat transfer inside acupoint tissues approached deeper and the temperature became higher.

Analyses of the three-dimensional temperature models of acupoint tissues at 5, 10, 15 and 20 min of moxibustion showed: acupoint tissue temperature increased significantly and the influence of moxibustion

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heat reached significantly deeper with the increase of moxibustion duration. At 20 min, the highest temperature in acupoint tissues was 35.715 ℃ and the lowest temperature was 29.073 ℃, which was 0.973 ℃ different from the initial temperature (T_f), indicating a significant change in acupoint temperature. Meanwhile, the colors of acupoint tissue temperature fields all changed, suggesting that the heat transfer inside acupoint tissues completed at 20 min.

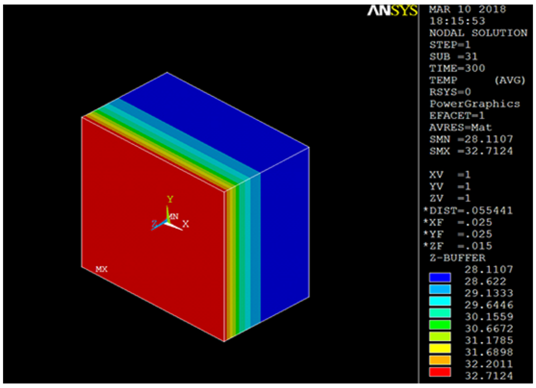

Figure 12. Three-dimensional temperature nephogram at 5 min

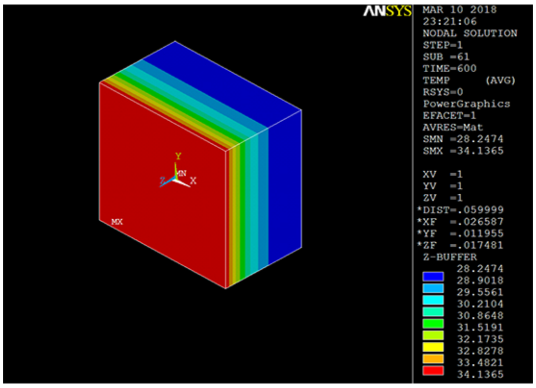

Figure 13. Three-dimensional temperature nephogram at 10 min

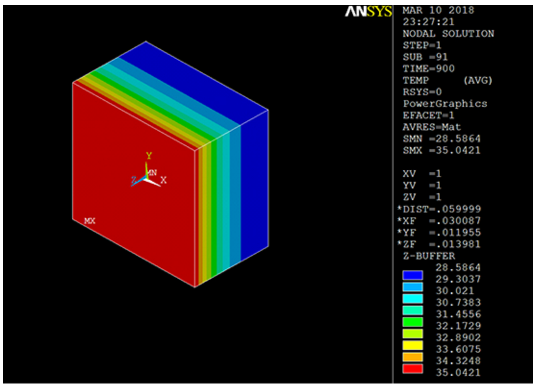

Figure 14. Three-dimensional temperature nephogram at 15 min

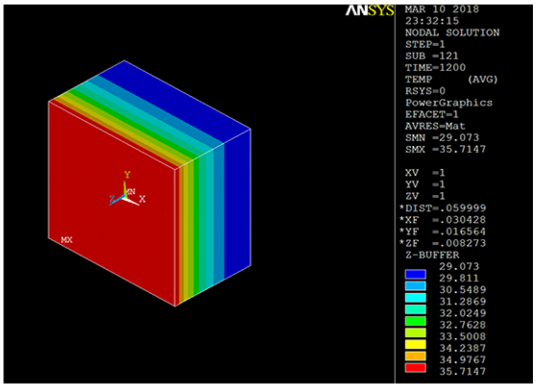

Figure 15. Three-dimensional temperature nephogram at 20 min

3 Discussion

Moxibustion has been inherited till today since a very ancient time. It has significant efficacy despite the vague action mechanism on acupoints and meridians. With finite element analysis software ANSYS 14.0, biological parameters and human body tissues and the temperature data measured, this study established three-dimensional models to show the transfer process of moxibustion heat in body tissues.

The multi-dimensional temperature distribution nephograms of human body tissues at 5 min of moxibustion showed that moxibustion heat majorly transferred from the superficial to the internal, and the influence of moxibustion heat decreased with the increased depth of tissue. This result revealed one mechanism of moxibustion heat transfer, i.e. from the proximal to the distant. Three-dimensional temperature distribution models at different time points during moxibustion also discovered that the transfer of moxibustion heat expanded in acupoint tissues with the increase of moxibustion time, which indicated the mechanism of moxibustion heat penetration, i.e. from the superficial to the internal.

Although the current study revealed the features of moxibustion heat transfer (from the proximal to the distant) and moxibustion heat penetration (from the superficial to the internal), the imitation quality could be hindered since acupoint tissues are complicated while the model adopted in this study was too simple. Therefore, the characteristics of moxibustion heat transfer still require further study.

Conflict of Interest

The authors declared that there was no potential conflict of interest in this article.

Acknowledgments

This work was supported by National Basic Research Program of China (973 Program, 国家重点基础研究发展计划项目, No. 2015CB554502); National Natural Science Foundation of China (国家自然科学基金项目, No. 61501525).

Statement of Informed Consent

Informed consent was obtained from the subjects in this study.

Received: 25 May 2018/Accepted: 27 June 2018

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