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Finite Difference Method Simulation on Effect of Blood Perfusion on Temperature Distribution of Female Human Skin

Bioheat transfer is a combination of heat transfer and biology process comprising of transfer of heat from human living tissue to the environment. This study aims to estimate the temperature distribution of female human's skin. In this study, effect of varied blood perfusions of 1.5, 2.0, 2.5 and 3.0 kg/s.m³ on bioheat transfer of female human skin, which was modeled into four layers, was simulated. To address this issue, one-dimensional unsteady state finite difference method was applied in this study. Result of this study informed that the finite difference method can be used to solve the bioheat transfer equation and to estimate temperature distribution of different skin layers of female human. In this study, blood perfusion affects temperature distribution in the four layers of unstable women's skin. The highest blood perfusion of 3 kg/s.m³ resulted in more homogeny temperature distribution of different skin layers. This circumstance occurred since higher blood perfusion increases heat transfer between blood and skin layers.

Keywords: Bio-Heat Transfer, One-Dimensional Unsteady Finite Difference Method, Female Human's Skin, Blood Perfusion.

1. INTRODUCTION

Bioengineering is a combination of two science, i.e. engineering and biomedical that can apply various kinds of science and technologies to address medical challenges also to and improve the health conditions for particular groups of people. Of many engineering sciences that can be applied to address challenges in the medical field is the heat transfer. Heat transfer involves exchange of heat energy due to temperature differences which also occur in humans. Bioheat transfer involves heat exchange from human living tissue to the environment. This process includes blood flow, organ systems and the thermal response of body tissues to the environment [1].

As the outermost and largest tissue, skin is directly affected by heat transfer with ambient air. Accounted for about 15% of the total body weight of an adult human, there are 3 layers of human skin, i.e. epidermis, dermis and fat-filled tissue [2]. In bioheat transfer, skin is considered as a solid object experiencing conduction and convection heat transfer. Heat loss through skin occurs since heat is circulated through the blood vessels which transfer heat to all human living tissues. Of many factors, blood perfusion, therefore, influences the heat transfer process from human skin to the environment. Blood perfusion is very important for normal tissue physiology. Blood perfusion is also responsible for the transport of oxygen, nutrients, and waste products which are also a major part of the body's temperature regulation system [3]. Female human has a thinner skin layer compared to male human. Oltulu *et al.* [4] investigated six parts of human body, i.e. chest, scalp, stomach, back, palms, and soles of the feet and concluded that the chest has the thickest layer of skin, i.e. 0.0004626 m. Meanwhile, the scalp has the thinnest layer of skin tissue, i.e. 0.0002108 m.

Luitel *et al.* [5] concluded that variation of environment temperature and heat transfer coefficients have a significant effect on temperature distribution in a human body towards the skin surface. Wu *et al.* [6] studied human skin blood flow regulation at varied local skin temperature perturbations and revealed that skin blood flow response can be quantitatively characterized with a vasomotor response model. Gurung *et al.* [7] concluded that skin blood flow regulation can be affected by the intensity of thermal perturbation. As the skin blood flow response in this study was mainly regulated by the small nerve fibers, further studies based on our proposed methodology may provide a non-invasive and quantitative solutions to support a diagnosis of small

fiber neuropathy. Temperature distribution in the human dermal part during physical exercises was also mathematically modeled. In this study, they showed the model for temperature variation is simulated under various physical and physiological conditions using the finite element method (FEM) modeling. Sweat evaporation has a significant effect on the living tissues' temperature variation as compared to ambient temperature during various exercises. A study of sweating effect on males' and females' body temperature variation was conducted by Shrestha *et al.* [8]. In this study, they revealed that sweating is an important mechanism for maintaining proper temperature which prevents overheating in the human body. Gurung and Acharya [9] modeled metabolic rate and thermoregulation in three layered human skin during carpentering, swimming and marathon. In addition, Wahyudi *et al.* [10] proposed no significant change in tissue temperature due to sweating and environment temperature variations when applied the FDM on the mathematical model of bioheat transfer. Luitel *et al.* [11] conducted a numerical study of a transient bio-heat transfer model and concluded that temperature at skin surface significantly decreases as heat transfer coefficient increases.

The bio-heat transfer, including temperature distribution in muscle, tumor, fat, dermis and subcutaneous tissue were studied by many researchers by applying numerical analysis and analysis of various blood parameters. Kengne *et al.* [12] analyzed the biological heat transfer equation with variable thermal conductivity by applying the Laplace transform method. It was concluded that the temperature of the network is significantly obtained from the variable parameter of thermal conductivity. The bio-thermal equation was used to investigate the thermal damage of skin tissue during hyperthermia [13-15]. Similarly, Sarkar *et al.* [16] proposed an analytical solution of the hyperbolic bio-thermal equation under a strongly moving heat source and an exact solution of the Arrhenius equation in the Laplace transform domain. The hyperbolic bio-thermal model was simplified to the parabolic bio-thermal model when thermal relaxation time was zero. In addition, Hobiny *et al.* [17] studied temperature change and thermal damage to spherical tissues during hyperthermia using the fractional derivative to simplify the parabolic and hyperbolic biological heating model.

2. METHODOLOGY

This study is to determine the effect of blood perfusion on the temperature distribution that occurs in the skin tissue of a female human. Finite difference method (FDM) application in heat transfer at unsteady conditions and involving varied blood perfusion has never been previously used to investigate heat transfer in the human body. In this study, human skin was divided into 4 layers, i.e. epidermis, dermis, muscle and fat (Figure 1). All these layers were assumed to have constant heat conductivity values. The bioheat transfer equation was expected to predict the one-dimensional unsteady temperature distribution of female human's skin layer as a function of skin thermal conductivity, blood perfusion, metabolic heat, ambient temperature, convection heat coefficient of ambient air and other heat sources.

Figure. 1. Four layers of female human skin used in this work

The temperature difference between the skin surface and body core was determined and used as a boundary condition for the FDM. The FDM simulation applied also the modified Pennes' equation as one-dimensional mathematical model. The unsteady a one-dimensional Pennes' equation describing blood perfusion within the tissue temperature distribution was used to analyze the bioheat transfer. In general, the Pennes' equation depends on specific heat (c) of skin tissues, thermal conductivity (k) of skin tissues, blood perfusion rate per unit volume (ω_b), blood density (ρ_b), the temperature at the investigated point ($T(x)$), arterial temperature (T_a) which is considered constant in this study, blood specific heat (C_b) and generation of metabolic heat (Q_m) (eq. 1) [18].

$$\rho c \frac{dT(x)}{dt} = k \frac{d^2T(x)}{dx^2} + \omega_b \rho_b C_b [T_a - T(x)] + Q_m \quad (1)$$

This study used four varied blood perfusion (ω_b) values in unsteady condition, i.e. 1.0, 1.5, 2.0, 2.5 kg/s.m³.

2.1 The Finite Difference Method of The Unsteady One-Dimensional Bioheat Transfer Equation

Domain Determination

Figure 2. The FDM model for number of human skin layer

Domain determination to be simulated using the FDM should describe the model into nodes and elements. The settlement area in this study is one-dimensional with a line along 0 - 0.0323103 meters by searching Δx (Figure 2) and the space between nodes (Δx) depends on total thickness of layer (L) and number of nodes (M) (eq. 2).

$$\Delta x = \frac{L}{M-1} \quad (2)$$

Since the total thickness of the modeled layer is 0.0322 m and the number of nodes was 11, the space between nodes in this study was then 0.00322 m.

Boundary Condition

In unsteady one-dimensional discretization of skin layers, thicknesses are considered along the x-axis and convection heat losses occurred when human skin surface is exposed to the environment. The energy balance approach is a function of thermal conductivity of female human skin (k), the temperature difference between surface and body core of skin (T_∞), ambient air convection heat coefficient (h), and human skin surface temperature (T_s) (eq. 3) [19].

$$-K \left. \frac{dT(x)}{dx} \right|_{x=0} = h[T_\infty - T_s(x=L)] \quad (3)$$

The heat transfer in human skin tissue that occurs from the core of the body to the skin tissue (fat boundary layer) was negligible in this study. The heat flux that occurs along the x-direction was therefore also negligible. Thus, the boundary conditions were assumed as shown in eq. 4.

$$\left. \frac{dT(x=0)}{dx} \right|_{x=0} = 0 \quad (4)$$

The next step was to determine the boundary and initial condition used in the study (Table 1).

Table 1: Initial and boundary condition used in this study

Condition	Time	Temperature
Initial condition	$t = 0$ s	309.85 K (body core temperature)
Boundary condition	$t > 0$ s	$T(L,t)$: 297.15 K (skin surface temperature) $T(0,t)$: 309.85 K (body core temperature)

2.2 FDM Simulation of the Unsteady One-Dimensional Bioheat Transfer Equation

Temperature of female human skin applied the core model of the FDM simulation for one-dimensional unsteady bioheat transfer as depicted in eq. 5.

$$kA \frac{T_{m-1}^i - T_m^i}{\Delta x} + kA \frac{T_{m+1}^i - T_m^i}{\Delta x} + \omega_b C_b A x (T_a - T_m^i) + Q_m A \Delta x = \rho A \Delta x C_p \frac{T_m^{i+1} - T_m^i}{\Delta t} \quad (5)$$

The FDM was then used to solve the unsteady bioheat transfer equation to acquire skin temperature distribution (eq. 6 and 7) [19]:

$$T_m^{i+1} = \frac{\alpha \Delta t [T_{m-1}^i + T_{m+1}^i]}{\Delta x^2} + T_m^i \left[1 - 2 \frac{\alpha \Delta t}{\Delta x^2} - \frac{\omega_b C_b \Delta x^2 \alpha \Delta t}{k \Delta x^2} \right] + T_a \left[\frac{\alpha \Delta t \omega_b C_b \Delta x^2}{k \Delta x^2} \right] + \frac{\alpha \Delta t [Q_m \Delta x^2]}{\Delta x^2 k} \quad (6)$$

$$T_m^{i+1} = \frac{k \Delta t [T_{m-1}^i + T_{m+1}^i]}{\rho C_p \Delta x^2} + T_m^i \left[1 - 2 \frac{k \Delta t}{\rho C_p \Delta x^2} - \frac{\omega_b C_b \Delta x^2 k \Delta t}{k \Delta x^2 \rho C_p} \right] + T_a \left[\frac{k \Delta t \omega_b C_b \Delta x^2}{k \Delta x^2 \rho C_p} \right] + \frac{k \Delta t [Q_m \Delta x^2]}{\Delta x^2 k \rho C_p} \quad (7)$$

The bioheat transfer equation was modified in this study to solve unsteady condition. In this study, skin of female human was divided into 11 nodes where the 1st node served as the boundary condition whose value was similar to female core temperature of 309.85 K. For temperature of the 2nd until the 10th node which are located in muscle and fat, eq. (8) was used to determine the difference between the calculations is the use of ρ and C_p values according to the layer.

$$T_m^{i+1} = \frac{k \Delta t [T_{m-1}^i + T_{m+1}^i]}{\rho C_p \Delta x^2} + T_m^i \left[1 - 2 \frac{k \Delta t}{\rho C_p \Delta x^2} - \frac{\omega_b C_b \Delta x^2}{\rho C_p} \right] + T_a \left[\frac{\Delta t \omega_b C_b}{\rho C_p} \right] + \frac{\Delta t [Q_m]}{\rho C_p} \quad (8)$$

Figure 3. 11 nodes of skin layer of female human in this study

The 11th node was located in the outermost layer of epidermis so that it reacted directly with the environment (Figure 3). Under this circumstance, the 11th node was influenced by convection heat transfer following eq. 9 [19].

$$h[T_{11} - T_\infty] = -k \frac{T_{11} - T_1}{L} \quad (9)$$

Time interval (Δt) in explicit finite difference method applied eq. 10 [19].

$$\Delta t \leq \frac{\Delta x^2}{2 \times \alpha (1 + \frac{h \times \Delta x}{k})} \quad (10)$$

Table 2 [2] provides data of thickness, density, thermal conductivity and specific heat to find solution for the FDM used in eq. 1 to 10. The number of skin layers used in the study were four layers, i.e fat, muscle, dermis, and epidermis as the outermost layer. Each layer has a different value of density (ρ) and heat capacity (C_p).

Table 2 Information on human skin layer for femlae human [2]

Tissues	Thickness l [m]	Density ρ [kg/m ³]	Thermal conductivity k [W/mK]	Specific heat C _p [J/kg.K]
Epidermis	0.0002	1200	0.24	3598
Dermis	0.002	1200	0.45	3300
Fat	0.01	937	0.21	3258
Muscle	0.02	1000	0.5	4000
Bone	0.008	1920	0.44	1440
Blood	-	1000	0.64	4200

3. RESULT AND DISCUSSION

Figure 4 shows the temperature distribution of 11 nodes at blood perfusion of 1.5 kg/s.m^3 for a time interval between 0 and 200 s. The temperature between the 1st and the 2nd node shows the largest difference compared to other nodes. The 1st node is the human body therefore it has the highest temperature at 36°C (309.8 K). After the 2nd node, the temperature difference between each node slightly decreases until the 9th node. After the 9th node, the temperature difference between 9th and 10th node as well as between 10th and 11th node increases again. The 11th node is the epidermis which is the outer part of the skin and has direct contact with the environment whose temperature was 30°C (303.8 K) in this study. Temperature for the 2nd until 8th node linearly decreases. Meanwhile, temperature decrease for the 9th and 10th node follows a linear path after 80 seconds since human skin is relatively thin, so the linear approach is more realistic.

Figure 5 shows the temperature distribution of 11 nodes at blood perfusion of 2.0 kg/s.m^3 for time interval between 0 and 200 s. Similar to the previous case, the temperature between the 1st and the 2nd node for blood perfusion of 2.0 kg/s.m^3 shows the largest difference compared to other nodes. Temperature distribution for the 2nd until the 11th node also resembles the case for blood perfusion of 1.5 kg/s.m^3 . As blood perfusion increases from 1.5 to 2.0 kg/s.m^3 , the temperature from the 2nd until the 10th node increases. For example, the temperature difference between the 1st and the 2nd node at 40 seconds for blood perfusion of 1.5 and 2.0 kg/s.m^3 are 309.85 and 308.71 K , respectively. At blood perfusion of 1.5 kg/s.m^3 and 40 seconds, temperature at the 1st and the 2nd node are 309.85 and 308.71 K , respectively (Table 3). As a comparison, the temperature at the 1st and the 2nd node at blood perfusion of 2.0 kg/s.m^3 and 40 seconds are 309.85 and 308.92 K , respectively. This is because the thickness of human skin is relatively thin, so the linear approach becomes more realistic.

Figure 4. Temperature distribution of 11 nodes for blood perfusion of 1.5 kg/s.m^3

Figure 5. Temperature distribution of 11 nodes for blood perfusion of 2.0 kg/s.m^3

Table 3. Temperature distribution from the 1st to the 11th node at 40 seconds for blood perfusion of 1.5, 2.0, 2.5 and 3.0 kg/s.m³

Blood Perfusion	Temperature after 40 seconds [K]										
	0	20	40	60	80	100	120	140	160	180	200
1.5 kg/s.m ³	309.85	309.04	308.29	308.14	307.77	307.36	307.74	307.55	307.37	307.22	307.08
2.0 kg/s.m ³	309.85	309.64	309.21	308.89	308.71	308.62	308.49	308.37	308.27	308.18	308.09

Unlike for the blood perfusion of 1.5 and 2.0 kg/s.m³, simulation for the blood perfusion of 3 and 3.5 kg/s.m³ was performed until 600 seconds. As blood perfusion increases, the temperature difference between the 1st until the 10th node becomes smaller. This is clearly depicted for blood perfusion of 3 and 3.5 kg/s.m³ (Figure 6 and 7). For the 2nd until the 10th node, the temperature of each node decreases linearly.

Figure 6. Temperature distribution of 11 nodes for blood perfusion of 2.5 kg/s.m³

Figure 7. Temperature distribution of 11 nodes for blood perfusion of 3.0 kg/s.m³

Figure 8 shows the comparison of temperature distribution which is influenced by variations in blood perfusion. This comparison was conducted in a steady condition using the Bessel equation (eq. 11) [5].

$$T = T_{\infty} + (T_a - T_{\infty}) \left[\frac{U}{v} + \frac{1}{v} \left\{ \frac{(\overline{h_c} U + \overline{N} V) I_0((\sqrt{V} r))}{\overline{h_c} I_0(\sqrt{V} r) + \sqrt{V} I_1(\sqrt{V} r)} \right\} \right] \quad (11)$$

The Bessel equation was then solved by using an analytical solution in this study. In this study, ambient air and human body temperature were simulated for 30 and 36 °C, respectively. Other data to solve the Bessel equation follows Luitel *et al.* [11] as being presented in Table 3. It is shown that temperature gradually decreases towards the endpoint. Of all varied blood perfusion rates, the blood perfusion of 1.5 kg/s.m³ shows the lowest curve, which is then followed by 2 kg/s.m³, 2.5 kg/s.m³. This occurs since low blood perfusion results in higher heat distribution distributed at each point. The blood perfusion of 3 kg/s.m³ has the highest curve value. For blood perfusion of 3 kg/s.m³, temperature between each node does not significantly vary since the speed of blood flow is the highest in this case. This circumstance results in less heat distribution at each node. Meanwhile, the temperature reaches a steady value after 150 s since the heat was already equally distributed which created more homogeny temperature distribution. It can be then concluded that the temperature gradient decreases with increasing blood perfusion rate.

Table 3: Properties of human body to solve Bessel equation [11]

Properties	Value
Thermal conductivity (k)	0.48 W/mK
Specific heat (C _p)	3850 J/kgK
Density of blood (ρ _b)	1000 kg/m ³
Metabolic heat (Q _m)	1085 W/m ³

Figure 8. Comparison of temperature distributions as function of blood perfusion of 1.5, 2.0, 2.5 and 3 kg/s/m³

4. CONCLUSIONS

The results of this study indicate that the finite difference method (FDM) can be used to solve the bioheat transfer equation one-dimensional unsteady and as an approach to estimate the temperature of the skin layers of women with a variation of blood perfusion. The study also showed that blood perfusion affects the temperature distribution in the four layers of unstable women's skin. The faster the blood transfers heat, the less significant the temperature difference will be. The lower the perfusion value of the blood, the slower it is to conduct heat, the difference in temperature is quite significant.

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