A REVISED METHOD TO PREDICT SKIN'S THERMAL RESISTANCE

by

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Human body can adjust heat loss by vasoconstriction, vasodilatation, and other methods. The purpose of this research is to investigate whether the thermal resistance of skin reflects vasoconstriction and vasodilatation. For this aim, the ambient temperature was controlled as 18.1, 21.6, 24.9, 27, and 30.5 ℃, respectively. In each temperature, the skin temperature and heat flux in the forearm were recorded. Based on tested data, the thermal resistance was calculated by a common method. The results showed that the thermal resistance at low temperature was less than that at high temperature, which was contrary to the rule of vasoconstriction and vasodilatation. So a new formula for thermal resistance was presented based on skin diffusion, sweat evaporation, and mass transformation. The results showed that the new method could predict vasoconstriction and vasodilatation. The revised equation is a useful index for physiological thermoregulation.

Key words: *human skin, thermal resistance, thermoregulation*

Introduction

Human has an elaborate and highly effective thermoregulatory system to maintain the constant temperature of body. This system depends on the ability to move heat from the body core to surface via the blood flow [1]. The common methods of thermoregulation are vasoconstriction, vasodilatation, muscle metabolism by shivering, and skin moisture excretion by sweating [2, 3]. In quiet condition, 60~70% of the circulatory blood is stored in vein [4]. So the vein is called as capacitance vessel. Some organs and tissues can store lots of venous blood when vasodilatation, and release venous blood when vasoconstriction. Although the thermal conductivity of fat is bad, the heat convection of blood can strengthen the thermal transfer of skin. So the skin thermal resistance shall reflect vasoconstriction and vasodilatation.

For most materials, the thermal resistance is equal to temperature difference divided by heat flux. This method was applied to evaporator wick [5], nanoscale thin films [6, 7], nanofluid in a tube [8, 9], and so on. Brajkovic *et al.* [10] used this method to study cheek thermal resistance during exposure to cold wind. They proved that cheek thermal resistance decreased as ambient temperature decreased from 0 to –10 °C. Osczevski [11] measured the

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cheek thermal resistance in resting subjects. He found that cheek thermal resistance increased linearly from 0.02 to 0.07 °Cm^2/W as cheek skin temperature decreased from 33 to 10 °C. That means the early researches have opposite trend. So the method to calculate skin thermal resistance should be proved.

Human has the ability to adapt to environment. In clod environment, skin can close pore, and constrict vessels to weaken convective heat transfer of blood. So the thermal resistance of skin shall increase when the ambient temperature decreases. In order to prove that idea, the experiment in 18.1, 21.6, 24.9, 27, and 30.5 °C were carried out.

Mathematic models

Thermal resistance equation before revised

The skin thermal resistance can not be tested directly. It is obtained by the following method. According to Fourier's law, the thermal conductivity can be obtained by [12, 13]:

$$\lambda = -\frac{q}{\frac{\mathrm{d}t}{\mathrm{d}x}} \tag{1}$$

where λ is the thermal conductivity, q – heat flux, and $\mathrm{d}t/\mathrm{d}x$ – the temperature gradient.

Because the skin layer is very thin, the differential formula can be replaced approximately by difference formula. So the thermal resistance can be written as:

$$R = \frac{\Delta x}{\lambda} = \frac{-\Delta t}{q} = \frac{t_{\text{in}} - t_{\text{skin}}}{q} \tag{2}$$

where R is the thermal resistance, Δx – the thickness between inside and outside skin, Δt – the temperature difference between inside and outside skin, t_{skin} – the surface temperature of skin, and t_{in} – the temperature inside skin (it is about 37 °C).

Revised thermal resistance equation

In fact, latent heat loss happens between skin and air, while the heat flow meter only measures the sensible heat flux. The latent heat loss for human body includes water vapor diffusion and sweat evaporation. The former is one part of insensible perspiration, not controlled by thermoregulatory. The latter is sensible perspiration and controlled by thermoregulatory. Besides, the water moving from skin inside to outside also carries some heat capacity. Based on the reasons above, the thermal equilibrium formula of skin layer can be written as:

$$q + E_{\text{diff}} + E_{rsw} = \frac{t_{\text{in}} - t_{\text{skin}}}{R} + \dot{m}c(t_{\text{in}} - t_{\text{skin}}) \tag{3}$$

According to eq. (3), a revised thermal resistance can be written as:

$$R = \frac{t_{\text{in}} - t_{\text{skin}}}{q + E_{\text{diff}} + E_{rsw} - \dot{m}c(t_{\text{in}} - t_{\text{skin}})} \tag{4}$$

where E_{diff} is the heat loss by skin diffusion, E_{rsw} – the heat loss by sweat evaporation, $\dot{m}$ – the mass flow rate per area, and c – the specific heat capacity of water, about $4.2 \cdot 10^3$ J/kg°C.

According to literature [14, 15], E_{diff} and E_{rsw} can be expressed:

$$E_{\mathrm{diff}} = 3.045(0.256t_{\mathrm{skin}} - 3.37 - P_a) \tag{5}$$

$$E_{rsw} = \omega 16.7 h_{\mathrm{c}} (0.256t_{\mathrm{skin}} - 3.37 - P_a) \tag{6}$$

where P_a is the vapor pressure in ambient air, ω – the skin wetness, and h_{c} – the convective heat transfer coefficient affected by air speed. For forced convection, $h_{\mathrm{c}} = 8.3\upsilon^{0.5}$ [16].

During this experiment, the sweat in the forearm did not flow or drop, and all the water from the skin changed into vapor. The heat loss by diffusion and sweat evaporation could be equivalent to the vaporization heat of $\dot{m}$ water:

$$E_{\mathrm{diff}} + E_{rsw} = \dot{m}r \tag{7}$$

$$\dot{m} = \frac{E_{\mathrm{diff}} + E_{rsw}}{r} \tag{8}$$

where r = 2450 kJ/kg is the latent heat of vaporization.

Experiment

Climatic chamber

The climatic chamber is located at the School of Apparel and Art Design, Xi'an Polytechnic University. The model of refrigeration equipment is ATH-E4C-60, and the net dimension is 4.4 × 2.4 × 2.25 m. The air temperature can be controlled between –40 °C and 50 °C, and the relative humidity can be controlled between 30% and 95%. The maximal wind speed was 5 m/s. The chamber also can simulate rainfall, and the maximum rainfall is 75 mm/h.

Subject characteristics

For each set ambient temperature, 8 male subjects are recruited. A total of 40 subjects participated in this study. The subjects are all graduates between 23 and 27 years old. The height is 1.77 ± 0.07 m, and the weight is 71.1 ± 10.9 kg. Prior to commencing with the experiment, the subjects wear the required clothing of men's briefs (0.04 clo), ankle-length athletic socks (0.02 clo), shoes (0.02 clo), long-sleeve shirt (0.27 clo), and thin straight trousers (0.15 clo) [17]. During the experiment, the subject simulates light activity, such as reading or chatting.

Subjects who might suffer from skin allergy, fever and other disorders or might be using skin medicinal products that are known to interfere with the evaluation of skin physiology are excluded. The subjects are prohibited from applying lotions, sunscreens, skin-care products, or pharmaceutical products of therapeutic effects at the measurement points during the experiment. They are also prohibited from performing strenuous exercise, and drinking coffee or alcoholic drinks in 24 hours prior to testing. The subjects are briefed on the course of this experiment.

Instruments

The photos of skin surface are taken by an inverted metallurgical microscope MA200 which can scale up to 100, 200, and 500 times.

Skin temperature and heat flux were widely tested to reveal thermal sensation [18-20]. If the skin temperature and the heat flux were measured, the thermal resistance could be calculated by eq. (2) [10, 11]. In this experiment, both the skin temperature and heat flux are tested by the multi-channel heat flow meter (HFM-215N) with low heat flow sensors (KM1). The KM1 is designed to be high sensitivity and high precision on a living body. Its outside diameter is 30 × 15 mm, and the thickness is 1.7 mm. The heat flow measurement range is 11.6-3480 W/m^2, and the temperature range is –40-150 °C. The accuracy is ±2%.

The air speed inside the chamber is tested using a hot-wire anemometer. The reading accuracy of the anemometer is ±3%, with a resolution of 0.01 m/s.

The ambient temperature and RH are tested using a self-recording thermohygrometer. The temperature accuracy of the thermohygrometer is ±0.5 °C, the RH accuracy is ±3% (at 25 °C), the temperature resolution is 0.1 °C, and the RH resolution is 0.1%.

Experimental procedure

In order to study the effects of vasodilatation and vasoconstriction on skin thermal resistance, the subjects shall experience thermal comfort, a little cold and a little hot. So the ambient temperature is controlled as 18.1, 21.6, 24.9, 27, and 30.5 °C for each subject. The relative humidity and air speed are constant, and they are 40% and 0.3 m/s, respectively. Under each ambient temperature, the subject's skin temperature and heat flux in the forearm are recorded. In order to quantify subject's thermal sensation, the ASHRAE thermal sensation scale, see [17], is used, as shown in tab. 1. When the measurement at one exposure temperature is finished, the exposure temperature is set to the next temperature value. During the experiment, the subjects are blinded to the exposed environment.

Table 1. Define of thermal sensation

3	2	1	0	–1	–2	–3
Hot	Warm	Slightly warm	Neutral	Slightly cool	Cool	Cold

Results and analysis

Skin characteristics

Human skin consists of epidermis, dermis and subcutaneous tissue. It is the largest organ of human body. It has the functions of protection, perspiration, feeling hot, cold, or pressure. Skin surface looks flat and smooth by eyes, but it is like hills after amplified.

When magnified 100 times, the skin surface appears the regular shape. It's like a pie chart, as shown in fig. 1(a). Each intersection point links 2 deep grooves and 4-5 shallow grooves. The deep grooves can be watched by eyes, but the shallow grooves can be watched only by the microscope. These shallows are useful to dredge sweat.

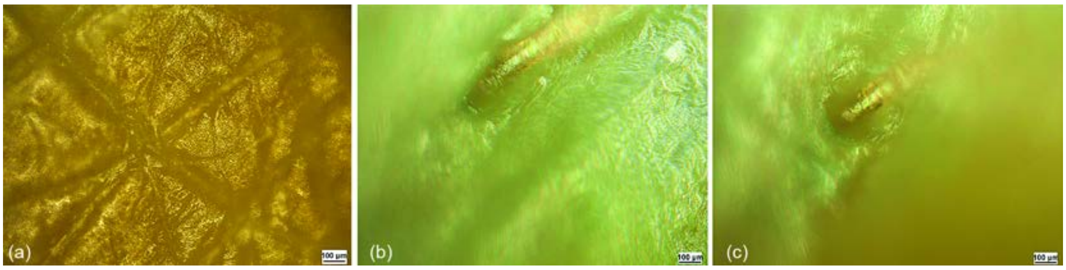

Figure 1. Skin characteristics magnified 100 and 500 times; (a) skin surface (100 times), (b) pore closed (500 times), (c) pore open (500 times)

When magnified 500 times, the structure of the pore in cold and hot environment is captured. In fig. 1(b), the pores are closed. The cuticle tightly wraps the fine hair, and the scales of the fine hair are clear. The moisture diffusion in the pore is cut off. While in warm or hot environment, the pores are open. There is a hole between cuticle and fine hair, as shown in fig. 1(c). The moisture diffusion and perspiration are not limited. Since the characteristics of the skin differ in the cold and hot environment, the capacity of heat transmission must be different.

Skin temperature and thermal sensation

Skin temperature plays the fundamental role in regulating the heat exchange by convection, radiation, and evaporation. It is an effective physiological parameter to predict human thermal sensation. Human mean skin temperature may change in 25-39 °C, and 33-34 °C is the neutral temperature for a sedentary human. Figure 2 presents the local skin temperature of the forearm. It shows that as ambient temperature increases from 18.1, 21.6, 24.9, 27.0 to 30.5 °C, the mean skin temperature of forearm increases from 28.9, 30.4, 30.9, 31.2 to 32.4 °C. The ambient temperature increases by 12.4 °C, and the skin temperature increases by 3.6 °C. When the temperature difference between the skin and air decreases, the convective heat loss will decrease and thermal sensation will increase.

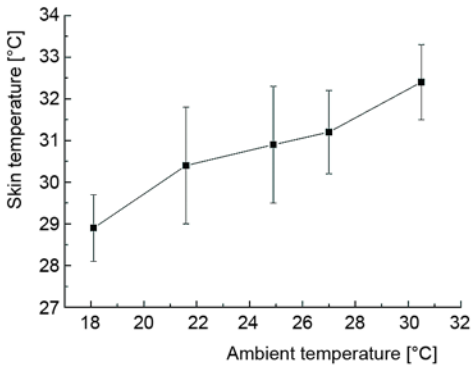

Figure 2. Skin temperature in different ambient temperatures

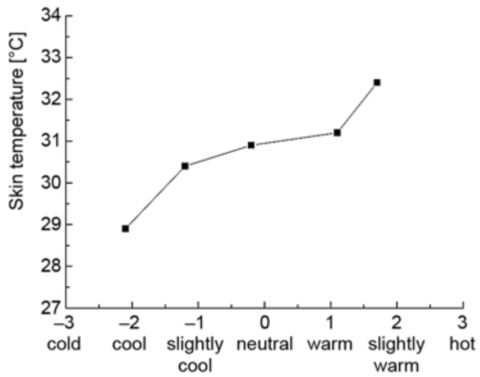

Figure 3. Skin temperature and thermal sensation

Choi and Loftness [21] investigated human skin temperature as a bio-signal to indicate overall thermal sensations. They found that the skin temperature at wrist was more interpretable data with the thermal sensation than that of any other body segments. In their results, when subjects felt slightly cool, neutral, and slightly warm, the skin temperatures at the wrist were 30.74, 30.57, and 31.70 °C, respectively. Figure 3 shows that when subjects feel slightly cool, neutral, and slightly warm, the skin temperatures at the forearm are 30.58, 30.9, and 31.20 °C, respectively. The results are accordant with the data of Choi and Loftness.

Heat flux of skin

The heat flux tested by HFM-215N is shown in fig. 4. As the ambient temperature grows, the heat flux of skin reduces. When ambient temperature is 18.1, 21.6, 24.9, 27, and 30.5 °C, the heat flux is 116.8, 113.3, 80.3, 32.3, and 11.3 W/m^2, respectively. At low temperatures, the temperature difference between skin and environment is large so that the sensi-

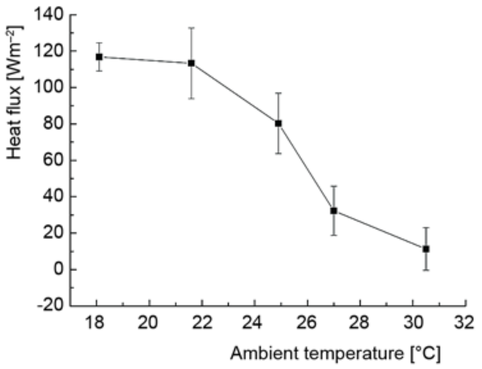

Figure 4. Heat flux in different ambient temperature

ble heat flux is great. While at high temperatures, it is opposite, the latent heat is the main heat-dissipating way, water vapour diffusion and/or sweat evaporation. However, the latent heat can not be captured by the heat flow meter.

Thermal resistance

According to eq. (2), the thermal resistance of forearm can be calculated, as shown in fig. 5. When the ambient temperature is 18.1, 21.6, 24.9, 27, or 30.5 °C, the thermal resistance is 0.070, 0.062, 0.080, 0.242 or 0.723, °Cm^2/W, respectively. The data show that the thermal resistance increases to above 10 times (from 0.070 to 0.723 °Cm^2/W). The growth of the data is a little high for living skin.

Figure 5 also shows that the thermal resistance in low ambient temperature is lower than that in high ambient temperature. The truth is that in hot environment, human body can open the pore, and increase the convective heat transfer of blood. So the thermal resistance in low ambient temperature should be greater than that in high ambient temperature. Based on the previous reasons, eq. (2) is not effective for skin. So it needs a new method to calculate thermal resistance of skin.

According to eq. (4), the thermal resistance is calculated, as shown in fig. 6. When the ambient temperature is 18.1, 21.6, 24.9, 27, or 30.5 °C, the thermal resistance is 0.064, 0.054, 0.049, 0.044, or 0.036 °Cm^2/W, respectively. When ambient temperature increases by 12.4 °C, the thermal resistance increases by 0.028 °Cm^2/W. The thermal resistance of forearm in low temperature is greater than that in hot ambient temperature. So the revised method to calculate thermal resistance can reflect the truth of thermoregulation. According to [16], when human body was in the condition of maximum vasoconstriction, natural and great perspiration, his heat transfer coefficients were 8, 15, and 50 W/m^2°C, respectively. The thermal resistance is inversely proportional to the heat transfer coefficient, and the thermal resistance

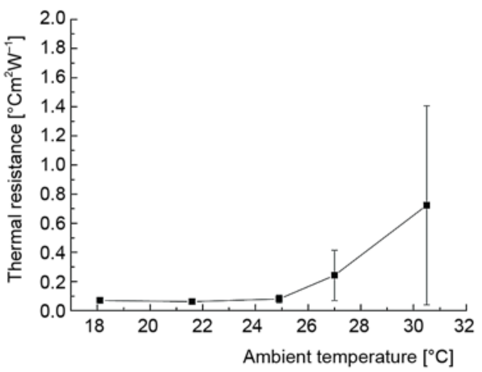

Figure 5. Thermal resistance before revised in different ambient temperature

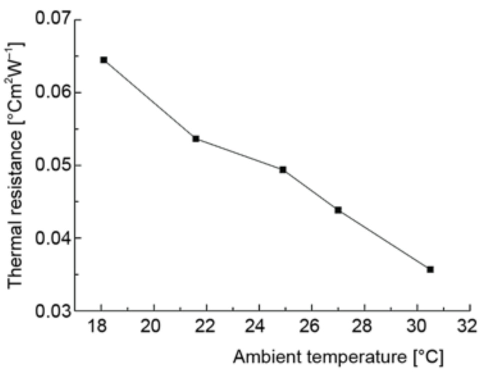

Figure 6. The revised thermal resistance in different ambient temperature

should be 0.125, 0.067, and 0.02 °Cm^2/W. From maximum vasoconstriction, natural, to great perspiration, human thermal sensation changes from cold to hot, and the thermal resistance drops. The trend is the same with the revised thermal resistance formula in this paper.

In this research, the thermal resistance in natural is about 0.049 °Cm^2/W. It is lower than that in literature [16] because of different part of body. In this paper, the tested part is forearm, while in literature [16] it is the whole body. The skin layer of forearm is thinner than that of the most other parts. It is reasonable that thermal resistance of the forearm is smaller than that of the whole body.

Conclusions

Vasoconstriction, vasodilatation, and sweating are common ways for human to keep the constant temperature of body. While it is difficult to quantitatively describe the degree of these actions, especially vasoconstriction and vasodilatation. The revised formula presented in this paper is a good index to indirectly reflect these behaviors.

The skin tissue is different from other materials. It has the function of thermoregulation, such as vasoconstriction, vasodilatation, diffusion, perspiration and shivering, which include sensible and latent heat transformation. The common method to calculate thermal resistance is ineffective for living skin. Therefore, this paper proposed a revised method based on experiment, and it is in accordance with human thermoregulation rule.

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Nomenclature

c – specific heat capacity of water, [Jkg^{-1}°C^{-1}]
E_{diff} – heat loss by skin diffusion, [Wm^{-2}]
E_{rsw} – heat loss by evaporation of sweat secretion, [Wm^{-2}]
h_{c} – convective heat transfer coefficient, [Wm^{-2}°C^{-1}]
$\dot{m}$ – mass flow rate per area, [kgs^{-1}m^{-2}]
P_a – vapor pressure, [kPa]
q – heat flux, [Wm^{-2}]
R – thermal resistance, [°Cm^{2}W^{-1}],
r – latent heat of vaporization, [kJkg^{-1}]
t_{in} – temperature inside skin, [°C]
t_{skin} – surface temperature of skin, [°C]
Δt – temperature difference between inside and outside skin, [°C]
$\mathrm{d}t/\mathrm{d}x$ – temperature gradient, [°Cm^{-1}]
Δx – thickness between inside and outside skin, [m]

Greek symbols

λ – thermal conductivity, [Wm^{-1}°C^{-1}]
ω – skin wetness, [%]

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