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Measurement of Thermal Effusivity of Human Skin Using the Photoacoustic Method

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Abstract In order to understand heat transfer in the human body, information regarding the thermophysical properties of biological materials is required. It is preferable that these properties are evaluated by *in vivo* measurements. The photoacoustic method is a non-contact, non-destructive method of measuring the thermophysical properties of various materials. In this study, the photoacoustic method was applied to human skin, and an open-type cell for on-site measurements was used instead of the previously used closed-type cell. Measurements of the thermophysical properties of human skin were carried out, and reasonable values of the thermal effusivity of the skin were obtained. Differences between different body parts and individual variations in thermal effusivity were investigated.

Keywords Human engineering · *In vivo* measurement technique · Non-destructive method · On-site measurement · Skin structure · Thermophysical properties

1 Introduction

The human skin is a contact point of the body with the surrounding environment, and it is necessary to understand the thermal properties of the skin in various fields such as medicine and environmental engineering. It is preferable to measure the properties of the skin *in vivo* to ensure accuracy. In addition, because the thermal properties of the skin differ among individuals, among different skin regions, and among different states, it is preferable to undertake on-site measurements rather than establishing a constant value. Thus, a reliable, fast, and non-destructive measuring method is required.

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Previous researchers used different measurement techniques to determine the thermal effusivity of the skin. Two studies estimated it from the change in skin temperature when the skin was exposed to materials with known thermophysical properties [1,2]. Other studies used the change in ambient temperature [3] or light irradiated to the skin painted black [4] to determine the change in skin temperature. In this study, we used the photoacoustic method to measure the thermal effusivity of the skin *in vivo* when it is exposed to thermal contacts.

2 Measurement Theory

If intermittent light at varying intensities is periodically irradiated onto the surface of a specimen, the surface layer of the specimen will instantaneously absorb this light and be heated. The surface-temperature changes correspond to the cycle of intermittent light irradiated onto the specimen surface by diffusion of the generated heat. The expansion and contraction of the surrounding gas and a pressure change in the sealed specimen cell corresponding to the cycle of intermittent light are produced. In the photoacoustic method, pressure changes are detected with a microphone. Thermophysical properties such as thermal diffusivity are related to the thermal diffusion process. For this reason, information on the thermophysical properties of the specimen is included in the phase lag of the detected signal.

In this study, as shown in Fig. 1, one-dimensional heat and radiation transfer were assumed. This measurement principle is summarized in the Rosencwaig–Gersho (RG) theory [5]. The light absorbed by the specimen is instantaneously changed into heat, and the heat is diffused into the specimen, backing material, and surrounding gas. The thermal diffusion equations for the gas, specimen, and backing material are shown below.

$$0 \le x < l_{\mathrm{g}} \quad \text{(gas)}$$

$$\left(\frac{\partial^2}{\partial x^2} - \frac{1}{\alpha_{\mathrm{g}}}\frac{\partial}{\partial t}\right) T_{\mathrm{g}}(x,t) = 0 \tag{1}$$

$$-l_{\mathrm{s}} \le x < 0 \quad \text{(specimen)}$$

$$\left(\frac{\partial^2}{\partial x^2} - \frac{1}{\alpha_{\mathrm{s}}}\frac{\partial}{\partial t}\right) T_{\mathrm{s}}(x,t) = -A\exp(Kx)\{1-\exp(j\omega t)\} \tag{2}$$

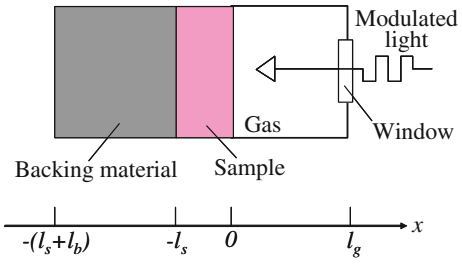

Fig. 1 One-dimensional model of the photoacoustic cell

$$-(l_s + l_b) \le x < -l_s \quad \text{(backing material)}$$
$$\left(\frac{\partial^2}{\partial x^2} - \frac{1}{\alpha_b}\frac{\partial}{\partial t}\right) T_b(x,t) = 0 \tag{3}$$

where $K, \omega, l_i, T_i, \alpha_i$, and k_i are the absorption coefficient, angular frequency of modulated light, thickness, temperature, thermal diffusivity, and thermal conductivity, respectively. Subscripts $i = $ b, s, and g indicate the backing material, specimen, and gas, respectively. It is expressed as $A = KI_0\eta/(2k_s)$, where η indicates the efficiency of changing light into heat by the transition to a lower level without emitting light in the specimen, which absorbs light of wavelength λ; η is assumed to be $\eta = 1$ at room temperature. I_0 indicates the intensity of the incident light. The right side of Eq. 2 represents the generation paragraph of heat by the laser light.

A general solution can be calculated if the proper boundary conditions are applied to these thermal diffusion equations. When these equations are solved by the boundary conditions on each boundary side, based on the continuous temperature and heat flux, the wave-like temperature distribution and wave progression during rapid attenuation from the laser heating side to the inside of the specimen are obtained. The depth for the wave to enter the specimen can be estimated according to the thermal diffusivity length $\mu_i = \sqrt{\alpha_i/\pi f}$ where f is the modulated frequency. If the thickness of the specimen is thinner than the length, the temperature wave in the specimen undergoes transformation at the boundary, with a discontinuity of thermophysical properties. Therefore, the phase of the temperature change on the heated surface of the specimen differs from the phase of the intensity change of the irradiated laser light. The surrounding gas is heated by the temperature change on the specimen surface, and the attenuating temperature wave progresses inside the gas, as well as into the specimen. As a result, a photoacoustic signal that contains information on the thermophysical properties of both the specimen and backing material is generated, because the surrounding gas periodically expands and shrinks like a piston.

The difference in the phase between the photoacoustic signal and the irradiated light is shown as a function of two parameters, ξ and b;

$$\phi = F(f : \xi, b) \tag{4}$$

where

$$\xi = \frac{l_s}{\sqrt{\alpha_s}} \tag{5}$$
$$b = \frac{k_b\sqrt{\alpha_s}}{k_s\sqrt{\alpha_b}} \tag{6}$$

ξ and b are the theoretically expected values of the phase lag, which mostly correspond to the measured results at multiple frequencies by the least-squares method that applies a Taylor differentiation linear correction. The thermal diffusivity and thermal conductivity of the specimen can be calculated using Eqs. 5 and 6.

Although the information on the thermophysical properties of the specimen influences the amplitude of the photoacoustic signal, this change is smaller than that of

the phase. The phase, which is sensitive to the thermophysical properties, is targeted in this study. The phase has the advantage of not depending on the strength of the irradiated light.

When the experimental apparatus is arranged as shown in Fig. 1, it is necessary to seal the specimen in the device, and the cutout and processing become indispensable to assess the skin of the measured object. Thus, the specimen should be measured on the backing material side (Fig. 1) to avoid these procedures, and the material with known thermophysical properties will be used on the specimen side. As a result, restrictions on the size of the specimen are lost, preprocessing is not necessary, and thus, the measured object can be expanded. Because the value of ζ shown in Eq. 4 becomes known by this replacement, only the value of b has to be obtained. However, neither the thermal diffusivity nor the thermal conductivity is independently obtained in this case, and only the thermal effusivity $k_\mathrm{b}/\sqrt{\alpha_\mathrm{b}}$ defined by the following Eq. 8 is obtained.

By placing a thin metallic plate onto the skin and pressing the cell with the gas space onto this plate, sealing-up of the apparatus was secured in this study. In the actual measurement, a thin plate of titanium of 105 μm thickness was used for the specimen. This composition has the following advantages. In general, it is assumed that the scattering of light in the skin layer is strong around the visible to near-infrared region, and if the light is irradiated directly onto the skin, the analytical model becomes extremely complex, as the light continues scattering internally. Only the heat penetrates into the specimen when the light is not applied directly to the skin but onto a thin plate of metal, as in this study. Although the skin is divided into two or more layers histologically, these layers do not show any differences in thermophysical properties, and it is thought that the skin layer is thermally uniform.

3 Experimental Apparatus

Figure 2 shows the experimental device. A semiconductor laser (wavelength of 809.6 nm, output of 0.6 W) was used as the source of light that irradiated the specimen. The laser light was fed into the photoacoustic cell through the optical fiber and irradiated the specimen through the window with a beam about 2 mm in diameter. Modulation from 1 Hz to 500 Hz was done in the laser diode, which uses the internal oscillation signal of the lock-in amplifier as the signal for modulation. The generated sound wave was detected with a capacitor microphone installed in the photoacoustic cell. The measured signal was sent to the lock-in amplifier, and then, the amplitude and phase were measured. Figure 3 shows the developed open-type cell. A thin plate of titanium was placed between the cell and the specimen during the measurement process, although the plate is not shown in the figure.

The photoacoustic cell sealed up the gas surrounding the specimen surface, and the signal generated by the gas was minute. An open-type cell was developed for this study and used instead of the previously used closed-type cell [6]. This cell can seal up the inside only by holding onto the specimen. Therefore, the specimen need not be processed, and it is possible to measure the skin in the *in vivo* state on-site.

Factors particular to the experimental apparatus, such as the response of the measuring instrument, the specimen surface, and the distance from the microphone, were

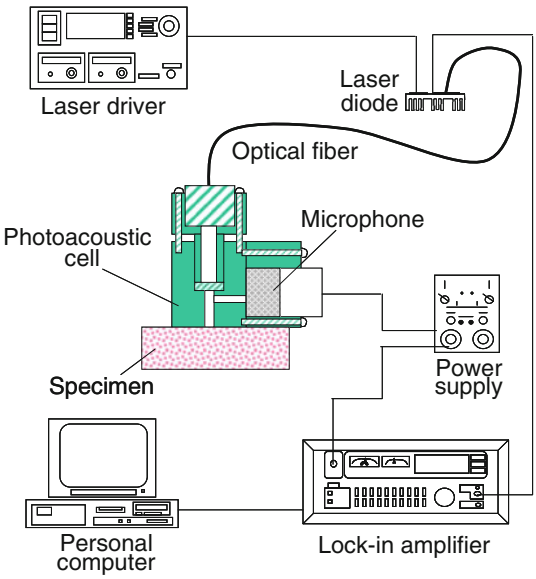

Fig. 2 Experimental apparatus for the photoacoustic method

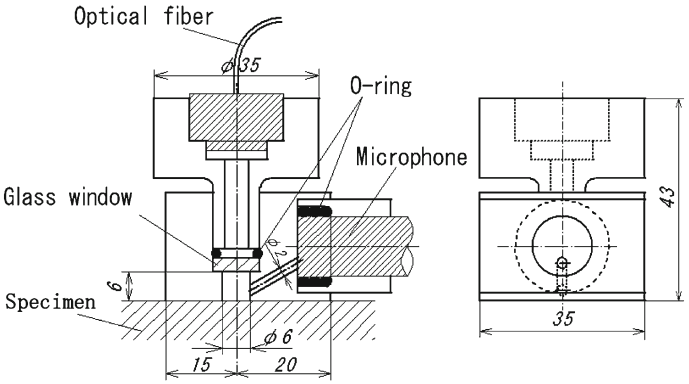

Fig. 3 Schematic diagram of the open-type cell

included in the measured phase lag. The phase lag was determined using a specimen with a constant phase lag as a reference to remove the influences of factors other than the original photoacoustic signal.

The phase lag of the photoacoustic signal obtained from a thermally thick specimen ($l \gg \mu_s, 1/K \gg \mu_s$) in optical opaque conditions ($l \gg 1/K$) does not depend on the frequency and thermophysical properties, and is assigned the exact value of 45° according to the RG theory [5]. When the phase lag obtained from such a specimen is described as ϕ_{ref}, the phase lag ϕ_{app}, particular to the experimental apparatus, is shown by the following equation.

$$\phi_{app} = \phi_{ref} - 45^\circ \tag{7}$$

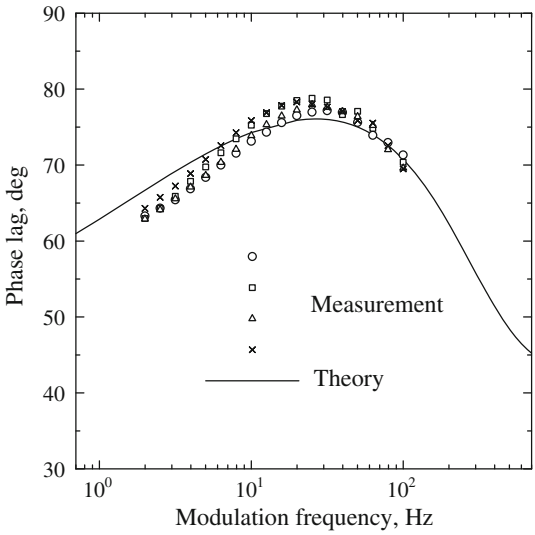

Fig. 4 Measured phase lag of natural rubber as a function of modulation frequency

The original phase lag is obtained by subtracting ϕ_{app} from the measured data of the specimen.

4 Results and Discussion

A thin titanium plate of 0.1 mm thickness was placed on the bottom of the cell onto the specimen, as shown in Fig. 1. The incident light was absorbed by the plate, and the thermal effusivity of the skin could be obtained from the known thermophysical properties of the plate. The thermal effusivity of the skin from two or more body parts was measured for six subjects.

First of all, it was verified whether the thermal effusivity of natural rubber, an elastic skin-like material, could be successfully measured by the method developed in this study. The thermal effusivity, e, is a thermophysical property defined using the density, ρ, specific heat capacity, c, and thermal conductivity, k, or using the thermal conductivity, k, and thermal diffusivity, α, as shown in

$$e = \sqrt{\rho c k} = \frac{k}{\sqrt{\alpha}} \tag{8}$$

Figure 4 shows the measured results of the phase lag of the natural rubber. The thermal diffusivity suitable for the measurement of the phase lag was obtained using the minimum mean-square method and was recorded as $(0.915 \pm 0.051) \times 10^3$ $\text{W} \cdot \text{s}^{1/2} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$. The fitting curve obtained by substituting this value is shown in Fig. 4. The statutory board (Japan Testing Center for Construction Materials) measured the physical properties of the targeted natural rubber for the verification of our measured results. The measured density, specific heat capacity, and thermal conductivity were substituted into Eq. 8, and the thermal effusivity was calculated. The

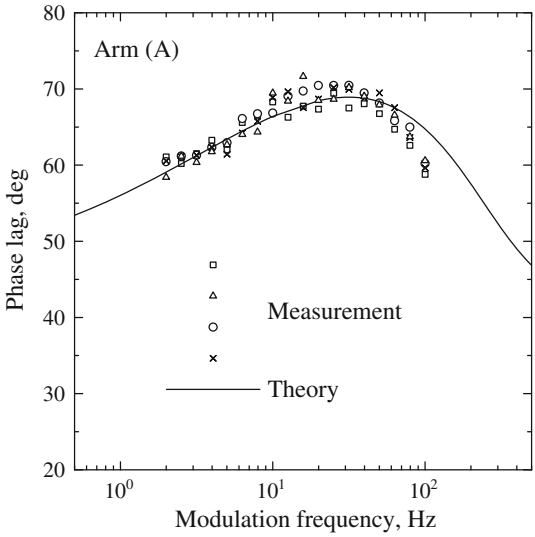

Fig. 5 Measured phase lag as a function of modulation frequency for the arm of subject A

precision of the measurement of the specific heat capacity and thermal conductivity was ±4 % and ±5 %, respectively. The thermal effusivity finally obtained was $0.842 \times 10^3\ \mathrm{W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}}$. The difference between both data sets was about 9 %, and it was thus concluded that the values obtained using the photoacoustic technique were reliable. The gap between the measured data and the theoretical curve in the low frequency region in Fig. 4 will require further examination in the future, including assessing the accuracy of the analytical model.

Figure 5 shows the measured results of the phase lag for the arm of subject A, as well as the theoretical curve obtained by substituting the mean value of the thermal effusivity, which was measured four times. It is necessary to seal up the sound space in the open-type cell apparatus. Because the acoustic pressure of the photoacoustic signal is originally slight, if sealing-up is poor, the acoustic pressure necessary for the measurement is not obtained at the position of the microphone. A pressure of about 13 kPa or more was necessary for secure sealing-up for the skin measurement. However, the measured values might have changed slightly if the pressure was raised further, and therefore, the measurement at a standard pressurized steady state with a weight was used. This change in the measured value related to an increase in pressure may be caused by the transformation of the skin and its organization.

In this study, the thermal effusivity of the skin of six subjects (A–F) was measured for two body parts (arm and palm). Moreover, four body parts (back of the arm, back of the hand, finger, and heel) and two body parts (finger and heel) were added for subjects A and C, respectively. The differences in the thermal diffusivity between different body parts were verified by our results. The measured results are shown in Tables 1 and 2, including the mean value and standard deviation of the thermal effusivity obtained from 3 to 5 measurements. The thermal effusivity of the skin obtained using other methods [1–4] is shown in Table 3 as a reference.

Table 1 Thermal effusivity (in $10^3\ \mathrm{W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}}$) of the skin of several body parts of subjects A and C

Body part	A	C
Arm	1.65 ± 0.05	1.71 ± 0.05
Back of arm	1.57 ± 0.02	
Palm	1.30 ± 0.04	1.46 ± 0.01
Back of hand	1.56 ± 0.03	
Finger	1.47 ± 0.12	1.45 ± 0.04
Heel	1.19 ± 0.09	1.40 ± 0.09

Table 2 Thermal effusivity (in $10^3\ \mathrm{W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}}$) of the skin of the arm and palm of six subjects

Subject	Age	Arm	Palm
A	24	1.65 ± 0.05	1.30 ± 0.04
B	25	1.76 ± 0.04	1.38 ± 0.06
C	55	1.71 ± 0.05	1.46 ± 0.01
D	51	1.84 ± 0.08	1.42 ± 0.02
E	37	1.71 ± 0.08	1.33 ± 0.06
F	23	1.72 ± 0.01	1.38 ± 0.05

Table 3 Previously reported thermal effusivities (in $10^3\ \mathrm{W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}}$) of the skin of different body parts

	Arm	Palm	Heel
Kraning [1]	1.59		1.10
Tanasawa and Katsuta [2]	1.36	1.26	
Huang and Togawa [3]	1.54	1.74	
Vendrik and Vos [4]	1.60		

There were differences between the thermal effusivity of the skin of different body parts of subjects A and C, as shown in Table 1. The differences between the mean values of each body part was assessed by the *t* test. For both subjects A and C, the thermal effusivity of the heel and palm was lower than that of the arm, at a 5 % significance level. This tendency was also seen in the studies of Kraning [1] and Tanasawa and Katsuta [2]. Kraning [1] suggested that the difference in the thermal effusivity between the arm and heel was caused by the difference in the moisture level in the stratum corneum, with lower moisture levels associated with lower thermal effusivity. The thermal effusivity of the excised dry skin measured by Lipkin [7] was $0.982 \times 10^3\ \mathrm{W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}}$, which is considerably lower when compared with other measured data. On the other hand, the thermal effusivity of water is $1.59 \times 10^3 \mathrm{W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}}$ at 300 K. Based on this fact, it is indeed expected that lower moisture levels in the skin are associated with lower thermal effusivities.

In our study, the relationship between the thermal effusivity and moisture content was examined by measuring the moisture content of the skin of each body part. The moisture content was measured by a moisture checker (MY808-S, Scalar Company) based on the electrostatic capacity in the stratum corneum. Figure 6 shows the

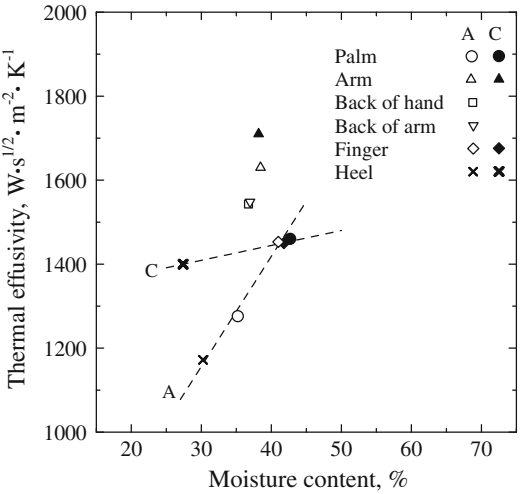

Fig. 6 Thermal effusivity of the skin of several body parts of subjects A and C versus moisture content

measured results. The following tendency was observed from the comparison of the mean values: the greater the moisture content of the heel, finger, and palm, the higher the thermal effusivity in both subjects A and C. However, this conclusion was not possible for subject C, considering the distribution of measured data. On the other hand, such a relationship was not seen in the arm and other body parts. Moreover, for subject C, the moisture content of the arm was lower than that of the palm, although the thermal effusivity of the arm was higher than that of the palm. It was assumed that factors other than moisture content are associated with the thermal effusivity of the arm.

We assessed whether there was significant variation between the six subjects ad the different body parts by using the *t* test (Table 2), with the significance level set at 5 %. For both subjects A and C, the thermal effusivity of the heel and palm was lower than that of the arm. Regarding the arm, significant individual variations between subject A and subjects B and D were confirmed. The greatest difference was observed between subjects A and D, and the thermal effusivity of subject D was about 12 % higher when compared to that of subject A. Regarding the palm, significant individual variation between subjects A and E and subjects C and D was confirmed. The greatest difference was between subjects A and C. These findings highlight that there is considerable individual variation in thermal effusivity in the arm and the palm. Moreover, the thermal effusivity of the palm was lower than that of the arm in all subjects.

Figure 7 shows the relationship between the moisture content and the thermal effusivity of the six subjects for the palm and arm. The higher the moisture content of the palm, the higher is its thermal effusivity. On the other hand, this tendency was not observed for the arm.

The human skin is divided by structure into two types, namely, the palma manus type such as that in the palm, sole of the foot, and finger, and the general outer-body type. Roughly speaking, the skin consists of three layers, namely, the epidermis, dermis,

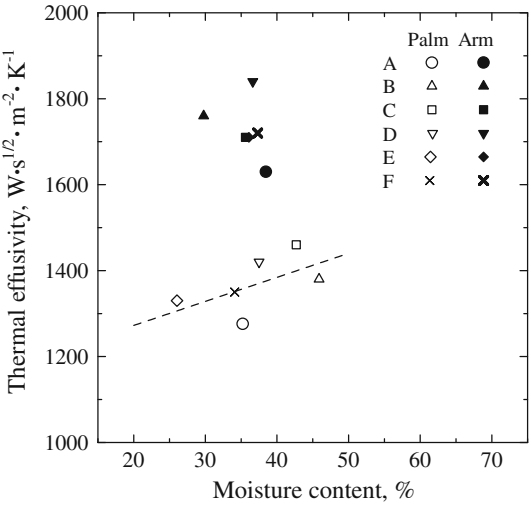

Fig. 7 Thermal effusivity of the skin of the palm and arm of six subjects versus moisture content

and subcutaneous tissue in order from the surface. In addition, the epidermis is divided into the stratum corneum, stratum lucidum, stratum granulosum, stratum spinosum, and stratum basale. Regarding the skin of the palma manus type, the entire epidermis, especially the stratum corneum, is thicker than the skin of the general outer-body type. Most of the epidermis of the body has a thickness of 70 μm to 120 μm. However, the thickness might reach 800 μm in the palm and 1400 μm in the sole of the foot. The stratum lucidum is not often seen in the epidermis of the general outer-body type skin, and the stratum granulosum also exists intermittently. This difference in the organization of human skin might influence the thermophysical properties. This possibility may be examined in future studies.

When the thermal diffusivity of the skin is adjusted to (0.5 to 2.0) $\times 10^{-7}\,\mathrm{m}^2 \cdot \mathrm{s}^{-1}$, the length of thermal diffusivity becomes 100 μm to 200 μm in the deepest body part. The thermal diffusivity stops in the epidermis or dermis. Therefore, if the thermophysical properties of human skin are uniform within this skin layer, the measurement technique described in this report is effective, and the assumptions made in this study based on the measured results are appropriate.

5 Conclusions

The conclusions drawn from this study are as follows:

(1) The thermal effusivity of human skin can be measured *in vivo* using the photoacoustic method.
(2) Differences between body parts and individual variations in thermal effusivity were observed in the measured data set.

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