研 究 速 報
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MEASUREMENT OF THERMOPHYSICAL PROPERTIES OF BIOLOGICAL SYSTEMS—PART 2

生物体における熱的物性値の測定 第2報

—Result of Measurement—

(測定結果)

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1. Apparatuses and Procedures

(1) Instruments for the temperature measurement

Figure 1 shows an instrument to measure the heat flow to or from an object tissue. It is a solid copper cylinder of 99.92% purity and the size is 5 mm in diameter and 62 mm in length.

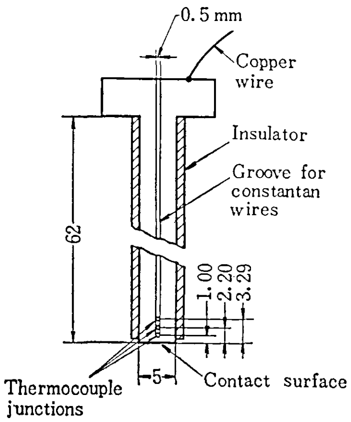

Fig. 1 Schematic diagram of the thermal property measuring device

It is easily seen from Eq. (14) in the preceding report[1] that the change in temperature is greater as the diameter of the bar is smaller. In addition, the properties of narrower area can be measured. Meanwhile, as the length of the period in which the semi-infinite media approximation holds is proportional to the square of the diameter, the first measurement should be done within a very short initial period. Thus, the existence of a certain optimum may be anticipated. Among the reasons why the authors chose the diameter as 5 mm, the restriction due to technical difficulty in manufacturing the bar, especially, in arranging thermocouples inside was involved.

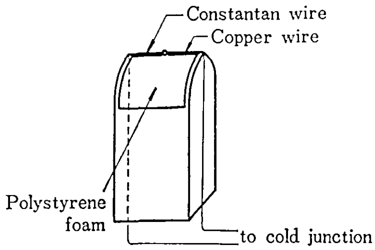

Fig. 2 Device for the surface temperature measurement

For the measurement of the surface temperature of the tissue, a device shown in Fig. 2 was used.

(2) Procedures

At first, the surface temperature of the object tissue is measured with the device shown in Fig. 2. Then, one end of the measuring bar shown in Fig. 1 is brought into contact with the surface. The e.m.f. of the thermocouples are recorded with an osoillograph (Galvanograph, Sanei Sokki Inc.). The change in the output is read at every 1.2 seconds, converted to the temperature, non-dimensionalized and then the thermal conductivity is calculated following the method described in the previous report. The initial temperature difference between two materials, ΔT, was taken as 10～20°C in order to obtain sufficient variation in the e.m.f. Ideally, ΔT within 1～5°C may be desirable, but it was not possible with the present recorder.

As to the contact resistance between the copper bar and the tissue, Umehara[2] has concluded that

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it could be ignored provided the contact pressure exceeds 0.2 kg/cm^2 and the tissue is soft enough. Therefore, the authors did not give any special consideration upon this effect.

2. Results of Measurements

(1) Preliminary measurements on materials whose thermophysical properties are known

In order to assure if this method would work satisfactorily, tests were done using materials whose thermophysical properties were known in advance. The materials used were Teflon, soda glass and rubber.

Table 1 Result of Preliminary Measurement

Materials	b kcal/m^{2}h$^{1/2}$°C	k kcal/mh°C	Temperature °C
Teflon	12.0	0.25	25.7
	10.7～11.3	0.22	
Soda glass	17.2	0.70	32.8
	17.3	0.64	
Rubber	13.5	0.41	33.6
		0.41	9.6

(Figures in the lower columns for each material show reference values. For Teflon they are the values obtained by ASTM method, for soda glass they are quoted from "Den'netsu kogaku shiryo (Heat Transfer Data Book), 2nd edition, (1969), JSME", and for rubber they are the results of the absolute measurements.)

The results are summarized in Table 1. It may be concluded that the present contact method is effective in measuring the thermal conductivity and diffusivity within the accuracy of about 20%.

Before proceeding to the measurement on living tissues, the authors gave consideration upon the effect of the length of the initial period, t_i, with which the square root of the dimensionless parameter, $\sqrt{\alpha}$, was decided. It was found out that k did not vary so much with t_i^* $(=\alpha t_i/R^2)$ in case of Teflon and rubber, while for glass k was seen to decrease as t_i^* was increased. Main cause of this may lie in insufficient thickness of the glass plate, since the principle of the present method is founded on the assumption of semi-infinite medium. As to Teflon and rubber, whose thermal conductivities are lower, this effect might still be masked.

(2) Results of measurements on living tissues and other objects

As the results of the preliminary measurements as described above, it is assured that the present method is useful in measuring the thermal conductivity and diffusivity within the accuracy of 20%.

Table 2 Results of Measurements (I)

Measured Materials	b $\frac{\text{kcal}}{\text{m}^2\text{h}^{1/2}\text{°C}}$	k $\frac{\text{kcal}}{\text{mh°C}}$	T_{10} °C	T_{20} °C
Forehead	21.3	0.47	33.0	8.3
Cheek	18.3	0.42	30.2	8.5
Nose	17.0	0.42	24.0	8.4
Ear	22.2	0.46	20.8	8.9
Ear (frostbitten part)	23.8	0.57	23.1	12.1
Jaw	17.2	0.43	33.0	9.0
Arm	19.5	0.46	32.1	11.9
Hand (back)	19.3	0.51	21.4	9.2
Hand (palm)	18.1	0.44	30.9	11.9
Hand (scabbed part)	11.6	0.32	28.9	12.1
Foot (back)	19.3	0.51	21.4	9.2
Foot (sole)	14.5	0.35	23.1	12.1

Table 2 shows the results of measurements of the thermal conductivity k and another quantity $b(=\sqrt{c\gamma k})$ of human skin of various parts of the body of one person.

It is seen that b lies within 11.6～23.8 kcal/m^2°Ch$^{1/2}$ and k is within 0.32～0.57 kcal/mh°C. These values seem quite resonable when compared with the results of Umehara[2] (b=16～21 kcal/m^2°Ch$^{1/2}$ at 36°C), Lipkin[3] (b=18～38 kcal/m^2°C h$^{1/2}$), Hatfield[4] (k=0.2～0.36 kcal/mh°C, *in vitro*), Davis[5] (k=0.36 kcal/mh°C) and Chato[6] (k=0.29～0.83 kcal/mh°C). It should be noted that the thermal properties of the living skin are affected significantly by the blood flow, though the more detailed discussion will not be done in this report.

Table 3 shows the results for the non-human tissues, most of which are dead. These values show fairly good agreement with those summarized by Chato[6].

Table 3 Results of Measurements (II)

Measured Materials	b $\frac{\text{kcal}}{\text{m}^2\text{h}^{1/2}{}^\circ\text{C}}$	k $\frac{\text{kcal}}{\text{mh}^\circ\text{C}}$	T_{10} °C	T_{20} °C
Egg (yolk)	8.4	0.25	28.2	7.4
Egg (white)	16.2	0.44	23.6	7.3
Pork (raw)	14.5	0.33	24.4	7.3
Pork (baked)	8.8	0.28	30.0	19.8
Pig (raw fat)	8.3	0.27	17.1	8.1
Pig (backed fat)	7.6	0.23	25.7	19.6
Pig (liver, raw)	14.4	0.36	24.1	9.45
Pig (liver, baked)	12.8	0.34	28.1	19.3
Fish meat (yellow-tail)	13.9	0.46	28.2	9.5
Rice-cake	5.9	0.24	26.2	19.7
Cow's milk	16.8	0.55	20.3	8.1

Calculation of the change in the temperature distribution inside the tissue reveals that the results presented in Tables 2 and 3 represent, in a sence, averaged properties up to 1 mm in depth from the surface.

As was mentioned previously, the blood flow inside the skin tissue is a very important factor which makes the thermal properties of the tissue vary significantly. Table 4 shows the results of

Table 4 Effect of Blood Flow

Conditions	b kcal/m^{2}h$^{1/2}$°C	k kcal/mh°C	Temperature °C
Ordinary	18.5	0.41	28.0
Restricted circulation	14.3	0.31	26.6
Ordinary	16.0	0.42	35.5
Enhanced circulation	20.0	0.51	34.3

measurements done under two kinds of different blood flow conditions. Namely, in one case the upper arm was bound tightly by a rubber band to prevent circulation into the hand, and, to the contrary, in another case the circulation was promoted by winding up the arm for a while or by wrapping the hand with a polyethyrene bag and keeping it immerse in 40°C water for 10 minutes.

It is seen from Table 4 that the thermal conductivity of the surface of the palm is lowered, at the maximum, by 30%, when the circulation of blood is restricted, though imperfectly; and it is increased by 20%, when the circulation is enhanced. Thus, the increase in the thermal conductivity by the blood flow reaches as high as 70% when compared to the minimum value. The data listed previously are to correspond to the ones lying somewhere between those two extremes. Considering that the blood flow in the living human body changes significantly with various external and/or internal conditions, such as the room temperature and humidity, clothing, the physical and mental condition, the physical exercise and so forth, it could easily be understood that unique determination of the thermophysical properties of the living tissues is exteremely difficult.

3. Conclusion

1) The thermal conductivity and the other thermophysical properties of living tissues were measured by means of the modified contact method within the accuracy of 20%. The values obtained were $b=16\sim22$ kcal/m$^{2\circ}$Ch$^{1/2}$ and $k=0.35\sim0.52$ kcal/mh°C, which were found reasonable when compared with the results of former researchers. However, it should be noted that these quantities are significantly affected by the blood flow, and the more detailed analysis on this effect is still left for the future study.

2) The values obtained by the present method were found to represent certain averaged quantities

over the part of the tissue up to about 1 mm in depth from the surface.

3) In order to raise the accuracy of the method, the more precise measurement of the temperature change is required. At the same time, whether the assumptions employed in deriving the fundamental equations are exactly realized on measurement should be examined. Among those assumptions, uniformity of the initial temperature inside the tissue seems doubtful, and reconsideration of its effect should be made in the future study.

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References

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正　誤　表（9月号）

ページ	段	行	種　別	正	誤
1	右	22	本　文	噴流中心速度 u_c	噴流中心速度 n_c
2	左	7	〃	$u_0, u_c = m/S$	$u_0, u_0 = m/S$
6	〃	〃	〃	ガスの沸点以上	ガスの共沸点以上
〃	〃	15	〃	Back reflection laue 法	Back reflectin lane
8	〃	6	〃	P_{H_2}/P_{H_2O}	PH2/P_{H_2O}
〃	〃	21	〃	太り成長	太さ成長
13	〃	8	本　文	浸透圧	透浸圧
14	〃	1	〃	$-\bar{v}_\omega\left(L_{\omega\omega}\frac{d\mu_\omega}{dx}+L_{\omega s}\frac{d\mu_s}{dx}\right)$	$-\bar{v}_\omega\left(L_{\omega\omega}\frac{d\mu_s}{dx}+L_{\omega s}\frac{d\mu_\omega}{dx}\right)$
17	右	26	参考文献	斎藤博，海水誌，21，245	斎藤博，21，245
22	〃	30	本　文	定常流粘性の	定常粘性の
23	左	10	〃	$\dot{\gamma}\tau_0/2=(\dot{\gamma}\tau_0/2)_0(1+K_2E_0g)/\cdots$	$\dot{\gamma}\tau_0/2=(\dot{\gamma}\tau_0/2)_0(1+K_2E_0)g/\cdots$
24	〃	29	〃	$J_e=K/2\eta_0^2$	$J_e=K/\eta_0^2$
30	〃	22	References	S_{ER}	SER
〃	右	23	〃	IIS	11S