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Genuine and Pseudo-Thermophysical Properties of Biological Media[1]

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There is an increasing demand for data on the thermophysical properties of biological materials, in response to the rapid progress of bioengineering and technology. However, there have been only limited sources of reliable data. A state-of-the-art review is presented on the measurement of thermophysical properties of biological media, mainly focusing attention on the difficulties in measuring techniques and the complicated characteristics of living organs and tissues. Some recent results are introduced in the hope of drawing increased attention to the interdisciplinary area of thermophysical properties research.

KEY WORDS: bio-heat transfer; biological media; measurement techniques; thermophysical properties.

1. INTRODUCTION

Measurement (especially *in vivo* measurement) of the thermophysical properties of tissues or organs of plants and animals has been attempted in response to the demand from various fields of biological science and technology. Such attempts, however, have achieved only limited success, mainly due to the difficulty in dealing with living objects.

Thermophysical properties of living objects have characteristics quite different from those of lifeless substances. The living tissue or organ is, so to speak, a composite material whose structure varies intricately within the

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medium. The thermophysical property of a pure substance is a function of the pressure (or density) and the temperature, while that of a living object varies with the component and structure. Furthermore, both component and structure change with the exterior and interior environments of the living object. It might be stated that the thermophysical properties of biological media are often not the *genuine* thermophysical properties in the strict sense of the words. They might rather be considered as apparent or *pseudo*-thermophysical properties.

Listed below are four criteria that the authors consider to be important in the measurement of the thermophysical properties of living objects.

1. Thermophysical properties of living tissue may differ, in most cases considerably, from those of a dead one. Therefore, *in vivo* measurement is desirable.

2. Since most tissues are neither uniform nor homogeneous, measurement on as small a portion as possible is desirable.

3. In the case when a measuring device is inevitably introduced into living tissue, local destruction of the tissue and influence upon the surroundings should be minimized.

4. In connection with the above, the time required for the measurement should be as short as possible.

In this brief article, attention is mainly focused on two important thermal properties, thermal conductivity and thermal diffusivity. Molecular diffusivities of oxygen and carbon dioxide in blood are also mentioned briefly. Because of limited space, certain significant contributions to this area will have to be neglected.

The methods used to measure the thermal conductivity and diffusivity of biological media may be roughly classified into the following three procedures:

1. Cut the object off from the living body and use a conventional (*in vitro*) method of measurement.

2. Introduce a temperature sensor (such as a thermistor or a thermocouple) into the living tissue and measure the change of the temperature or the heat flow under an appropriate condition. The thermal properties of the media can be obtained from the response.

3. Bring a material whose thermophysical properties are known in advance into contact with the object, measure the change in the temperature inside the material, and then calculate the unknown properties of the tissue.

Comparing crudely these three methods to the requirements stated before, it is obvious that the first method, which was employed in most past measurements [1, 2], is irrelevant when *in vivo* measurement is strongly required. Thus, only the second and third methods are feasible. However, for tissues or organs whose thermal properties remain substantially un-

changed even if separated from the living body, the first method could of course be applicable.

2. *IN VITRO* MEASUREMENT

Miyabe *et al.* [3, 4] devised an excellent method for the measurement of thermal properties of a small solid object, applying it to obtain the thermal diffusivity of human tooth. Application of the same technique to the measurement of the thermal properties of bovine cornea was reported

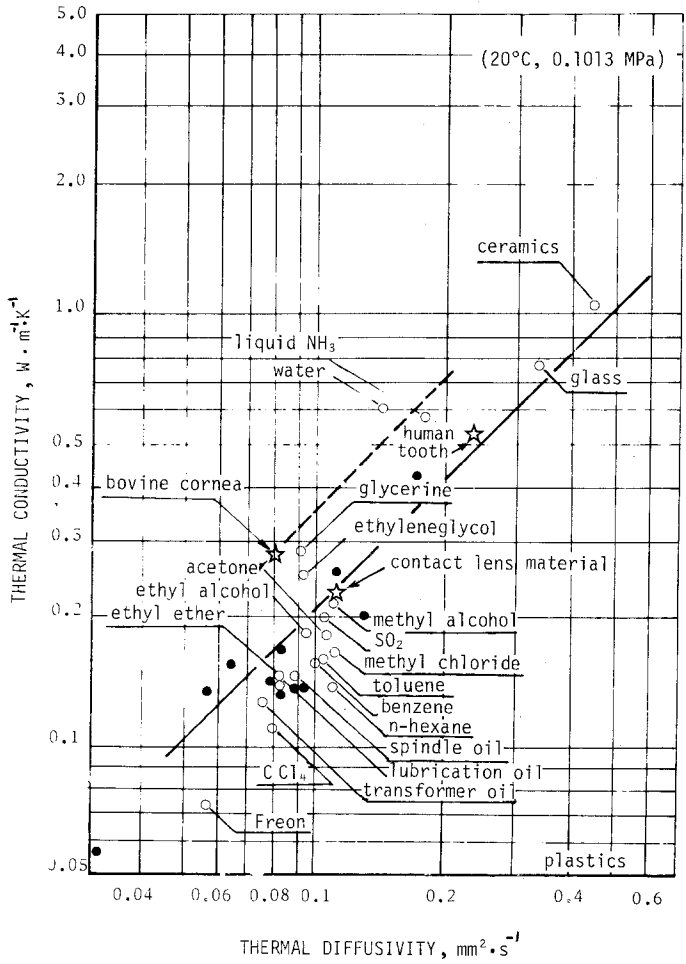

Fig. 1. Thermal conductivity versus thermal diffusivity relation of liquids and solids [6].

by Mitsunaga *et al.* [5] at the First Japan Symposium on Thermophysical Properties. The principle of the measurement is, in short, based on a similarity principle of transient heat conduction. The thermal diffusivity a of the object of interest is obtained by comparing the timewise (where the Fourier number is employed as the dimensionless time) change of the dimensionless temperature with that of a reference object having a geometrically similar shape. The specific heat c and the density ρ are measured separately. The thermal conductivity k is obtained as a product of these three quantities, $k = ac\rho$.

Figure 1 [6] shows the relation between the thermal conductivity and the thermal diffusivity of various materials. The values for the bovine cornea and the human tooth measured by the above authors are indicated. Also indicated in the figure is the value for a contact lens material, and it should be noted here that one of the purposes of the measurement on bovine cornea was to find contact lens material having similar thermophysical properties as that of human cornea.

Thermophysical properties of blood can also be measured *in vitro*. A possible difficulty to avoid is sedimentation and coagulation of blood cells. A useful result has been obtained by Tanishita *et al.* [7] with the use of the modified transient hot-wire method. A feature of this method is that a fine platinum wire coated with polyester resin is employed. The polyester coating is necessary to electrically insulate the platinum wire from the blood, since the latter is electrically conducting. Shown in Fig. 2 [7] is the dependence of the thermal conductivity of canine blood upon the hematocrit value (the volume fraction of cells in the whole blood).

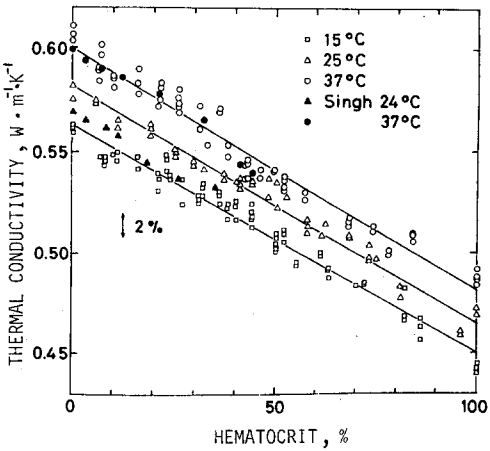

Fig. 2. Thermal conductivity of blood.

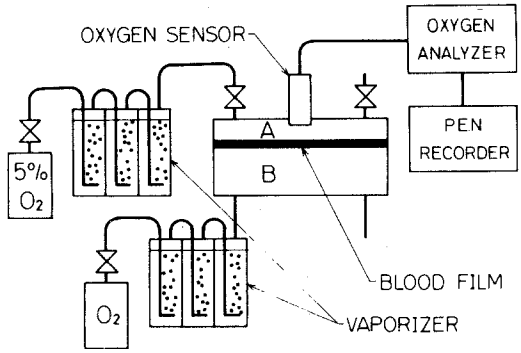

Fig. 3. Schematic diagram of experimental apparatus.

3. MEASUREMENT OF DIFFUSION COEFFICIENTS OF OXYGEN AND CARBON DIOXIDE IN BLOOD

An accurate knowledge of the molecular diffusivities or diffusion coefficients of oxygen and carbon dioxide in blood is important in the design and analysis of extracorporeal blood oxygenators because the process of diffusion invariably constitutes the dominant resistance to mass transport.

Although measurements have been made by various methods, the results generally involve inaccuracies. Moreover, the measurements have been done at constant-temperature conditions, giving almost no information at all on the effect of temperature. Also, little information exists on the dependence of the diffusion coefficient on the hematocrit value, pH value, albumin content, etc.

Recently, the diffusion coefficient of oxygen in blood was measured by Hori *et al.* [8] and the diffusion coefficient of carbon dioxide was measured by Tanishita *et al.* [9–11]. These measurements were made *in vitro*, using a

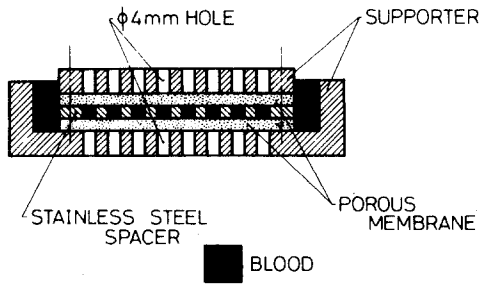

Fig. 4. Blood layer, porous membranes, and supporters.

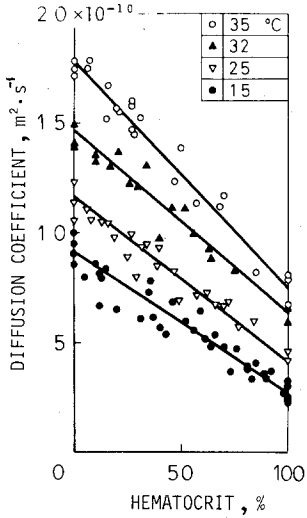

Fig. 5. The O_2 diffusion coefficient in blood as a function of hematocrit.

thin blood layer with uniform thickness held between two sheets of porous membranes having very small resistance to gas diffusion. A schematic diagram of the experimental apparatus for the oxygen measurement and a diagram showing the blood layer supported by porous membranes for the measurement of oxygen diffusion coefficient are shown in Figs. 3 and 4.

Shown in Figs. 5 and 6 are the dependence of the oxygen diffusion coefficient on the hematocrit value and on the temperature. The result for

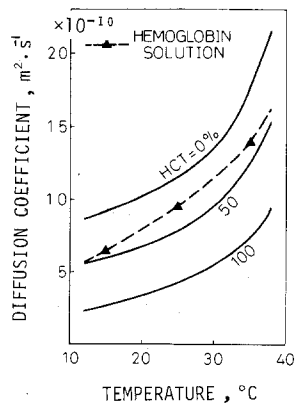

Fig. 6. Increase of oxygen diffusion coefficient in blood with increasing temperature.

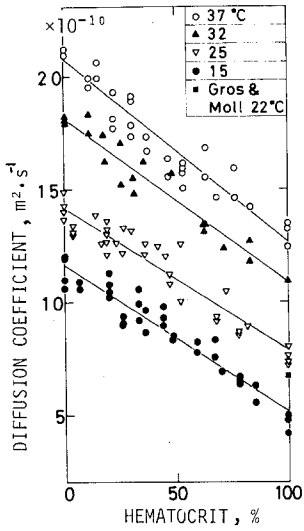

Fig. 7. The CO_2 diffusion coefficient of blood as a function of hematocrit.

carbon dioxide is shown in Fig. 7. An essential difference in the transport mechanism in blood exists between oxygen and carbon dioxide. However, according to Tanishita *et al.* [11], the complex mechanism of the transport of carbon dioxide in blood affects the apparent diffusion coefficient only when the partial pressure of carbon dioxide is lower than 1 kPa or when the hematocrit value is higher than 90%.

4. PROBE INSERTION METHOD: *IN VIVO* "INVASIVE" METHOD

As a representative example of the second type of method, Choto's method [12, 13] of embedding a thermistor element inside a tissue is reviewed here.

A spherical thermistor element of 1–2 mm in radius is prepared and inserted into the body tissue with the aid of a hypodermic needle. Electric power is supplied through lead wires drawn from the thermistor bead. At a certain instant the temperature of the bead is suddenly raised above that of the surroundings, and after this the temperature is kept constant at this elevated level by controlling the power supply. A theoretical analysis of the system using the biothermal equation has been carried out on the basis of a model of a spherical heat source in an infinite conducting medium. A transient thermal conduction analysis gives the heat flux q equivalent to the

electrical input required to maintain the temperature of the thermistor element:

$$q = 4\pi Rk(T - T_0) + 4R^2(\pi k\rho c)^{1/2}(T - T_0)t^{-1/2} \tag{1}$$

where R is the radius of the thermistor bead, k is the thermal conductivity of the tissue to be measured, T is the temperature of the bead, T_0 is the initial temperature of the tissue, ρ and c are the density and the specific heat of the tissue, respectively, and t is time. From Eq. (1) it is found that a graphical plot of q versus $t^{-1/2}$ should be linear, the intersection at $t^{-1/2} = 0$ $(t \to \infty)$ depends on the thermal conductivity, and the slope of the straight line is proportional to $(k\rho c)^{1/2}$ or $k\sqrt{a}$ (where a is the thermal diffusivity). Thus one can obtain both k and a from the same plot. Similar techniques have been used by other researchers [14, 15].

A thermocouple can be used in place of a thermistor. Cooper and Trezek [16] designed a small, needlelike probe consisting of a thin copper rod having a diameter of 1.5 mm and a length of 22.5 mm. Constantan and copper leads were attached to the center and top of the rod, respectively, and as a consequence the probe acted as a thermocouple. This probe was suddenly inserted into a medium having a different temperature, and the thermal properties of the medium could be calculated from the duration of the temperature–time response.

Some unavoidable drawbacks are common to such "invasive" methods. For example, the insertion of the probe (such as a thermistor bead or a thermocouple needle) may cause local destruction and inflammation of the tissue; the exact location of the embedded probe, especially whether or not the probe comes into contact with capillary blood vessels running through the tissue, may be difficult to determine; the theoretical analysis is carried out under the assumption that the probe is placed in the midst of an infinite medium, while in reality the probe is embedded in a relatively shallow position beneath the surface; the lead wires may have a considerable effect upon the transient heat conduction, etc.

5. PROBE CONTACT METHOD: *IN VIVO* "NONINVASIVE" METHOD

When two solid objects having different temperatures are brought into contact, a flow of heat takes place. The flow of heat is dependent upon the geometry and the thermal properties of both solids. In this situation, if the properties of one object are known in advance, the properties of the other can be obtained by measuring the heat flow or the temperature change in the reference object.

A major advantage of this method over the previous one is that it causes no destruction of tissue ("noninvasive" method), while a major disadvantage is that only the properties in the vicinity of the surface are measurable.

Vendrik and Vos [17], Nukiyama [18], and Umehara [19] measured the thermophysical properties of biological tissues with the use of the analytical solution to the transient heat conduction problem between two semiinfinite solid media. Although this method is excellent for its simplicity, it should be borne in mind that a contact between semiinfinite solids never occurs in an actual measurement. The surfaces of living tissues are in general of complex shape and it is not always possible to ensure sufficient plane area. Also, the criterion of using small, uniform surfaces is likely to be violated. Another disadvantage of this contact method is that only a single thermal property can be determined. That is, the thermal diffusivity $a = k/\rho c$, for example, may be obtained by the measurement, but one has to measure ρ and c by some means if the value of the thermal conductivity k is also required.

Tanasawa and Katsuda [20] have improved the above-mentioned contact method and measured the thermophysical properties of human skin and some other objects. The contact method as modified by these authors is as follows: one end of a solid cylindrical copper rod (probe) whose thermophysical properties are known and whose temperature is initially kept uniform is brought into contact with the surface of a tissue having a temperature different from that of the rod. The change of the temperature inside the copper probe is measured and recorded from this instant. Using this record, the thermophysical properties are calculated by applying the result of the transient heat conduction analysis.

The details of the analysis are presented elsewhere [20]. An advantage of this method is that two independent thermal properties are determined by a single measurement. Measurements on standard materials (glass, rubber, and Teflon) have revealed that the maximum error of this method is within $\pm 20\%$. It should be borne in mind that in the case of a composite medium, as is the case for biological materials, the thermal properties measured by this method represent an indefinable average of the properties of the tissue, which is usually heterogeneous. This average value varies with the period of contact of the probe.

6. THERMOPHYSICAL PROPERTIES OF BIOLOGICAL MEDIA: DATA

Chato [13] has summarized the available data for the thermophysical properties of biological media. Shown in Table I are some examples. Since

Table I. Thermal Properties of Biological Media (I)

Material	k ($W \cdot m^{-1} \cdot K^{-1}$)	$b\ [=(kc\rho)^{1/2}]$ ($kJ \cdot m^{-2} \cdot s^{-1/2} \cdot K^{-1}$)	Ref.
Beef muscle	0.198–0.528	—	[1, 21–23]
Human muscle	0.384–0.440	—	[1, 22]
Dog liver	0.125–0.145	—	[2]
Beef fat	0.204–0.222	—	[1, 21, 22]
Human fat	0.200–0.204	0.677 ± 0.042	[1, 22, 23]
Skin	0.188–0.335	—	[24–26]
Excised skin (dry)	—	0.98	[23]
Excised skin (moist)	—	1.14	[23]
Living skin (no blood flow)	—	1.26	[23]
Living skin (with blood flow)	—	1.26–2.64	[23]
Human blood	0.506	—	—
Cow's milk	0.531	—	[27]
Egg white	0.556	—	[28]
Egg yolk	0.338–0.419	—	[23, 28]
Urine	0.561	—	[23]
Gastric juice	0.445	—	[23]

Table II. Thermal Properties of Biological Media (II)

Material	k ($W \cdot m^{-1} \cdot K^{-1}$)	$b\ [=(kc\rho)^{1/2}]$ ($kJ \cdot m^{-2} \cdot s^{-1/2} \cdot K^{-1}$)
Forehead	0.55	1.47
Cheek	0.49	1.28
Nose	0.49	1.19
Ear	0.53	1.55
Ear (frostbitten part)	0.66	1.66
Jaw	0.50	1.20
Arm	0.53	1.36
Hand (back)	0.59	1.35
Hand (palm)	0.51	1.26
Hand (scabbed part)	0.37	0.81
Foot (back)	0.59	1.35
Foot (sole)	0.41	1.01
Egg (yolk)	0.29	0.59
Egg (white)	0.51	1.13
Pork (raw)	0.38	1.01
Pork (baked)	0.33	0.61
Pig (raw fat)	0.31	0.58
Pig (baked fat)	0.27	0.53
Pig (liver, raw)	0.42	1.00
Pig, (liver, baked)	0.40	0.89
Fish meat (yellow-tail)	0.53	0.97
Rice-cake	0.28	0.41
Cow's milk	0.64	1.17

Table III. Effect of Blood Flow on Thermal Properties

Condition	k ($W \cdot m^{-1} \cdot K^{-1}$)	b ($kJ \cdot m^{-2} \cdot s^{-1/2} \cdot K^{-1}$)	Temperature (°C)
Ordinary	0.48	1.29	28.0
Restricted circulation	0.36	1.00	26.6
Ordinary	0.49	1.12	35.5
Enhanced circulation	0.59	1.39	34.3

the method and the condition of measurement are quite different for each result, it is difficult to evaluate the accuracy. The number of digits of significant figures seems too large.

Tables II and III show the results of measurements carried out by Tanasawa and Katsuda [20]. Table III is included to emphasize that the thermal properties of skin tissue are seriously influenced by blood flow. This is one of the reasons we stated that the thermal constants of biological tissues are not the *genuine* thermophysical properties in the strict sense of the words.

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