The Coefficient of Thermal Conductivity of Blood and of Various Tissues

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ABSTRACT A method for measuring K, the coefficient of thermal conductivity, for a variety of dog tissues is described. The values of K for muscle and liver are larger than that for water, the value of K for lung is smaller than that for water and the values of K for brain, plasma, and blood are about the same as that of water. The values found for K are given in a table.

The measurement of the coefficient of thermal conductivity of blood and of tissues is of interest in connection with hypothermia, in which blood at low temperatures pumped into the circulation does not cool all parts of the body equally. This is partly because the flow in some parts of the body is greater than in others, and partly because some tissues conduct heat to a greater extent than do others.

APPARATUS

This consists of three cylindrical glass chambers held together by lucite plates (Fig. 1).

Chamber I is 4.2 cm in external diameter, 3.2 cm in internal diameter, and about 4 cm high. It is made with a double wall separated by a vacuum, like a Dewar flask; its lower end is ground nearly flat to enable it to be inserted and cemented into a circular hole in the center of a lucite plate 17 cm in diameter. A disk of copper 0.25 mm thick is recessed into the lucite plate and held to it by 3 screws; this copper plate closes the lower end of the chamber exactly, leaving no space for the collection of air bells. This requires mechanical work with a precision of at least one-thousandth of an inch. About half way up the length of the chamber there are three glass tubes of one-eighth inch internal diameter. *These tubes pass through the double wall of the chamber*, connecting its inside with the outside. One tube is a water inflow, one is a water outflow, and an 18 gauge YSI[1] thermistor probe (probe 1) is sealed into the third with rubber spaghetti tubing and Ambroid cement. About 3 cm of the probe

[1] YSI refers to the products of the Yellow Springs Instrument Company.

lies inside the chamber, through which water at about 28°C is pumped, at a pressure of about 2.5 cm, from and into a large constant temperature bath maintained at 30°C. The pump is a Cole-Parmer pump, which gives a pressure which can be regulated electrically; the constant temperature bath is a standard American Instrument product.

Chamber II is also constructed with double walls between which is a vacuum. Its upper end is ground flat, and is inserted and cemented into the lower side of the

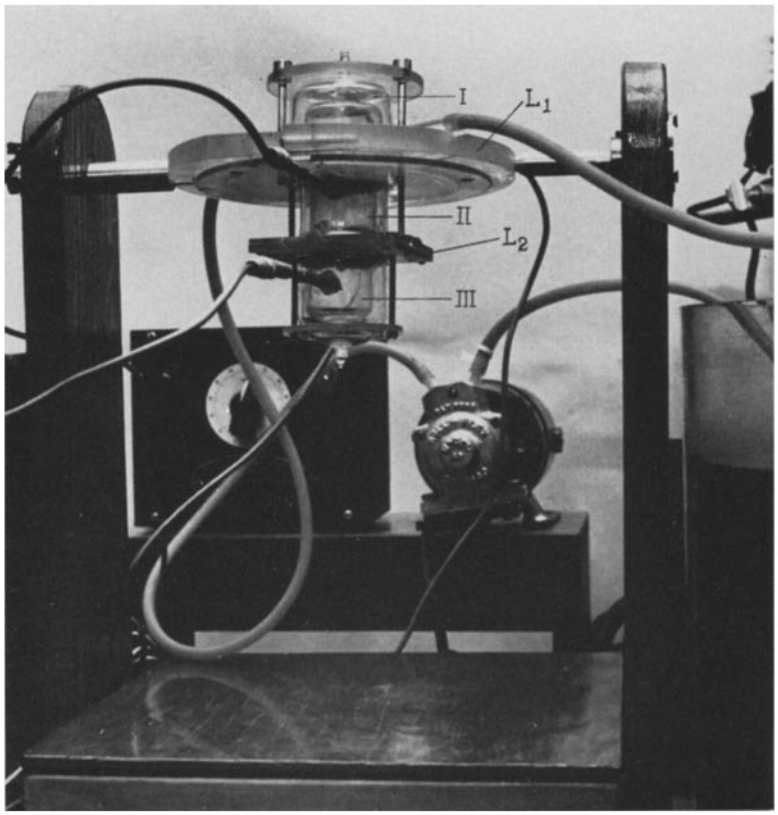

FIGURE 1. The three chambers I, II, and III. The apparatus is in the measuring position; the pump which pumps warm water through chamber I is seen in the background together with its electric regulator.

large lucite plate, so that its upper end is closed by the disk of copper already referred to. The internal diameter of chamber II is 3.2 cm, and its length is 4 cm. Its lower end is ground flat and fits *exactly* into a circular hole in the center of a small rectangular lucite plate (7.6 × 6.3 cm) which is attached to the large lucite plate by long screws which insure stability. The small rectangular plate has two lucite strips, 7.6 cm long and 0.7 cm wide, each screwed with three screws to its long sides. These strips are beveled, the bevel being made so that each strip is 2 mm narrower where it is in contact with the lucite plate. Two one-eighth inch internal diameter glass

tubes pass *through* the double wall of chamber II. The first is placed near the top of the chamber, *i.e.* just below the copper plate and the second near the bottom of the chamber. Thermistor probes 2 and 3 (18 gauge) are sealed into these two tubes, both projecting about 3 cm into the interior of the chamber. The capacity of the chamber is 32 ml.

Chamber III is also made of double-walled glass, the two walls being separated by a vacuum. Its internal diameter is 3.2 cm. Its upper end is ground flat, and inserted into a circular hole in the center of a rectangular lucite plate about the same size as the small lucite plate of chamber II. A copper plate, 0.25 mm thick and 4.2 cm in diameter, is recessed into the lucite plate so that the upper end of chamber III is closed with copper of a somewhat greater diameter than that of the internal diameter of the chamber. This copper plate is perforated by two holes 2.5 cm apart, just large enough to admit an 18 gauge needle. The long edges of the lucite plate of chamber III are beveled so as to fit exactly into the beveled strips attached to the lucite plate at the bottom of chamber II, and the copper plates sealing the top of chamber II and the top of chamber III are aligned when chamber III is pushed along the beveled surfaces until further movement is prevented by a lucite pin. A glass tube of one-eighth inch internal diameter passes *through* the double wall of chamber III, and into this an 18 gauge thermistor probe (probe 4) is sealed. The probe projects about 3 cm into the interior of the chamber. The capacity of chamber III is 26 ml.

The large lucite plate attached to the lower end of chamber I can be turned (and the other chambers with it), by being rotated through 180° on a stand (see Fig. 1). In the "filling position" chamber II is uppermost, but in the "measuring position," after chamber III has been placed in position, rotation of the large lucite plate brings chamber I to the top, and chamber III to the bottom.

The four thermistor probes are connected to a telethermometer. They are individually calibrated and calibration curves are supplied with each. The scale of the telethermometer is such that 1 °C is 5 mm long, so that a twentieth of a degree change in the temperature of chamber III makes it necessary to be able to make readings at intervals on the scale of 0.25 mm. This is done by observing each 1 °C division with a small telescope which contains a scale 5 mm long divided into twentieths.

OPERATION

With the apparatus in the measuring position, *i.e.* with chamber I uppermost, water is circulated by means of the pump from the large water bath controlled at 30°C. After 1 to 2 minutes, during which time all air should have been expelled, the temperature in chamber I is measured by thermistor 1; it is usually between 28 and 29°C. The apparatus is then turned to the filling position, with chamber I below chamber II, which is open at the top.

Chamber II is now filled with the material, *e.g.* water, blood, packed red cells, or tissue, for which the coefficient of thermal conductivity has to be found. In the case of tissues, such as liver, a question arises as to how they should be homogenized, or indeed whether they should be homogenized at all, for the greater the degree of homogenization the greater will be the destruction of tissue architecture. No problem of this kind arises with blood or packed red cells, and in the experiments to be reported

here the heat conduction of liver, muscle, lung, and brain will be given for the unhomogenized tissues *en bloc*.

About 15 minutes before the beginning of the experiment, chamber III is filled with water at about 10°C, and is kept in a small refrigerator at about 10°C, its temperature being measured by thermistor 4. A little additional cold water is added just before chamber III is attached to chamber II. Immediately after chamber II has been filled with the material, the volume of which should be a little greater than it can contain so that a meniscus is formed, chamber III is pushed along the beveled sides of the small plastic plate surrounding the top of chamber II. This cuts the meniscus, and brings the copper plate of chamber III into contact with the material in chamber II. The apparatus is then turned into the measuring position, with chamber I on top. The temperatures in chamber I and chamber III are checked by means of their thermistor probes at what corresponds to zero time. The placing in position of the cold chamber III, the turning of the apparatus to the measuring position, and the registering of the temperatures at zero time should be done within about 30 seconds.

As a rule it is not desirable to homogenize tissues such as liver, muscle, lung, and brain but rather to fill chamber II with a number of half-cylinders of unhomogenized tissue. These half-cylinders must fit chamber II exactly, and are obtained by using a hollow cylinder of thin metal, 3.0 cm in external diameter, 4.1 cm in height and sharpened like a knife edge at its lower end. This cutting cylinder is divided along its diameter by a sharp-edged metal plate, so that two half-cylinders are cut from the tissue. The cylinder is applied, like a biscuit-cutter, to the tissue, and cuts out two half-cylinders of the same size as chamber II, except that the half-cylinders of tissue are 1 mm greater in height than chamber II. The excess 1 mm can either be cut off with a knife, or cut off when chamber III is pushed along the beveled strips on the small lucite plate of chamber II.

The advantages of using blocks of tissue rather than homogenized tissue are that the block contains blood in its vessels to much the same extent as does the tissue in the living animal, and also that the tissue architecture is not broken up. If it is desirable to know how much blood is contained in the block of tissue, the animal can be injected with P^{32} just before it is killed and its liver or other tissue removed. The amount of blood in the two half-cylinders can be found by standard radioisotope technique; the only precaution to be taken is that this technique applied to two half-cylinders should be a "blank" determination; *i.e.*, radioactive tissue should not be placed in chamber II.

CALCULATION

For each specimen in chamber II there is a so called "relaxation time" equal to the reciprocal of

$$\frac{K}{C}\left(\frac{2\pi}{l}\right)^2$$

where K is the thermal conductivity of the material, C is the thermal capacity per

unit volume, and l is the length of the chamber. Any self-consistent set of units will give this time in ordinary time units. Thus if K is in calories, centimeters, seconds, and degrees Centigrade, C must be in calories, centimeters and degrees Centigrade and l in centimeters. Then the relaxation time will be in seconds. The significance of the relaxation time is that it is necessary to let the flow of heat continue for a period greater, by a not very well defined factor, than the relaxation time before taking data to be used in calculating the conductivity K by using steady-state equations. The factor depends on the accuracy desired. If the results are to be reproducible to about 10 per cent because of the variability of the tissue, data taken after twice the relaxation period could be used, but a longer time would be preferable (three, four, or five times the relaxation time).

For water in a chamber 4 cm long the relaxation time is about 5 minutes. Preliminary experiments show that for plasma, blood, brain, and perhaps lung, it is about the same as this, for liver about half this, and for muscle about one-third or one-fourth. Thus the method and the apparatus have the advantage, in respect to this difficulty at least, that the greatest uncertainty occurs for the material (water) for which there is the best agreement with data obtained by other methods.

If the time lag in the specimen in chamber II were the only significant source of error, the errors would always be in the same sense, and calculated conductivities would always be somewhat greater than the true values. However, there is also a time lag in chamber III. It requires a separate calculation, because of different boundary conditions, but it is probably relatively unimportant.

In the case of water, the steady-state equations can reasonably be applied to the data obtained from the average of the fourth and fifth relaxation periods. Let the mean difference in temperature, in degrees Centigrade, between chamber I and chamber III be θ, let the length of chamber II be l (4 cm in this apparatus), and let the area of each copper plate be A (8 cm^2 in this apparatus).

The fundamental equation is

$$Q = K \cdot \theta \cdot A \cdot t/l$$

where Q is the heat in calories which passes into chamber III in t seconds and where K is the coefficient of thermal conductivity. Since one calorie raises the temperature of 26 ml of water 0.038°C, we have

$$\frac{\text{Increase in temperature in chamber III}}{0.038} = Q \text{ cals.}$$

or, rearranging,

$$\frac{Q}{\theta \cdot A \cdot t/l} = K.$$

RESULTS

The apparatus is first calibrated with chamber II empty, the heat transferred from chamber I to chamber III constituting a series of values which have to

be subtracted from the values[2] obtained at various times when chamber II is filled with some material for which it is desired to measure K, which represents the heat conducted through air, the walls of chamber II, etc., and is plotted, minute by minute, against time for 25 or 30 minutes; *i.e.*, for five to six relaxation times for water. Except for the points corresponding to 5 minutes or less, which are not reliable, the relation is almost linear (very slightly concave towards the time axis).

Chamber II is next filled with water at an average temperature of 22°C, and heat is allowed to flow from chamber I to chamber III for 15 minutes or for three relaxation times; the heat flowing during the fourth and fifth relaxation times is measured and averaged, and the average value found between

TABLE I

Material	Average Probes 2 and 3	Mean $K \times 10^3$	Extreme values of $K \times 10^3$
	°C		
Water	20–22	1.5	1.52–1.59
Plasma (anticoagulant EDTA)	20–22	1.6	1.5 –1.7
Blood, $\rho = 0.77$ (anticoagulant EDTA)	21–23	1.6	1.6 –1.8*
Liver	20–21	3.3	3.0 –3.4
Lung	20–23	0.6	0.57–0.63
Brain	22–24	1.7	1.7 –1.9
Muscle	22–24	5.5	5.2 –5.8

* The value of K for centrifuged blood is subject to a little greater error than that for water, plasma, liver, lung, brain, and muscle, and this is almost certainly because the centrifuged blood has not always been of the same volume concentration in these experiments. It would have been possible to adjust each volume concentration to some arbitrary figure such as 0.77, but the effect on the mean value of K and on the extreme values of K would be so small that this did not seem worthwhile.

15 and 25 minutes with chamber II empty is subtracted. The steady-state equations are then used to calculate K. The average value of K found lies between 0.00152 and 0.00159, which is between 4.8 and 8.5 per cent greater than 0.00145, the value given in the Handbook of Chemistry and Physics for water at 22°C. Since water has such a long relaxation time, this is a good test of the method. (The only tissue investigated which has a lower value of K is lung tissue, and this is attributable to the variable amount of contained air.)

The same procedure is carried out when chamber II is filled with plasma, blood, and a variety of tissues, the observations used for determining K being

[2] A few short metal rods can be placed in chamber III and a magnetic stirrer placed beneath the entire apparatus when chamber III is in the measuring position. This results in the contents of chamber III being stirred continuously, and it seemed possible that such stirring might influence the results, but it does not.

the same as in the case of water, *i.e.* the heat gained in chamber III during 15 to 25 minutes after zero time, with the average correction for the empty chamber II subtracted. These values of the mean K are shown in Table I. Each value, which is the average of from six to nine separate determinations of K, is followed by the extreme values of K found. The consistency is such that each mean value of K involves only six to nine separate determinations, made on[3] six to nine samples of tissue obtained from different dogs.

These results lead to several conclusions. (*a*) The coefficients of thermal conductivity of muscle and liver are greater than that of water, while those of brain, plasma, and blood are about the same as that of water, and, for the tissues examined, only that of lung is smaller. The low value of K for brain may be due to its high lipid content, while that for lung is certainly due to the amount of entrapped air (K for air, about 0.5×10^{-4}). (*b*) Most of the differences in thermal conductivity are not only statistically significant, but surprisingly large; K for muscle, for example, is about 10 times greater than K for lung. (*c*) Homogenates of muscle and liver (although not reported here in detail) give smaller values of K than do blocks of muscle and liver; this may be due to heat being able to move better when it has structural pathways along which to move than when it has none.

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[3] This method of showing the variation found in the values of K for different materials is preferable to calculations of the standard error of the mean K. This is partly because the number of dogs from which tissues were removed varied in the case of each tissue, although the mean value of K given in Table I was never based on less than 6; this is a small number from which to determine the standard error of a mean, and it is more informative to record the extreme variations of K, which in the case of any one material are remarkably small.