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Technical note

Measurement of thermal conductivity of bovine cortical bone

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Abstract

The thermal conductivity of cortical bone was characterized experimentally. Specimens were taken from the mid-diaphysis of bovine femora, and the rate of heat transfer was measured in three orthogonal directions. The conductivity was found to be 0.58±0.018 W/mK in the longitudinal direction, 0.53±0.030 W/mK in the circumferential direction, and 0.54±0.020 W/mK in the radial direction. Because the directional differences are small, it is concluded that bovine cortical bone can be treated as thermally isotropic.

Keywords: Cortical bone; Thermal conductivity; Anisotropy

1. Introduction

Bone can be exposed to heat from several types of sources, including high speed drilling (see e.g. [1]), laser ablation [2], and the curing of cements used in hip arthroplasty [3]. The elevated temperatures which result from such exposure may lead to cell death, i.e., to thermal necrosis, which in turn can lead to infection and reduced mechanical strength [4]. The extent of necrosis depends on temperature rise and duration [5]. To predict the temperature distribution in bone, one can use the equations of unsteady heat conduction, but doing so requires knowledge of the geometry, the heat input, and two thermal properties of bone: specific heat and thermal conductivity. Hence in any work which has the goal of reducing or eliminating thermal necrosis during procedures in which heat is produced, knowing these two thermal properties is essential.

The specific heats of both cancellous and cortical bone have been well established, as has the thermal conductivity of cancellous bone. A search of the literature reveals, however, that the thermal conductivity of cortical bone has been measured only a handful of times [6–11], and that the measurements do not agree. A summary of existing results is presented in Table 1, which shows values of conductivity spanning almost two orders of magnitude. This large disparity has arisen despite the fact that the experimental apparatuses shared the same operating principle—the specimens were subjected to a heat source, and the thermal conductivity was calculated from measurements of the heat generated, the temperature gradient, and specimen dimensions.

It is well known that the mechanical properties of bone are anisotropic [12,13] and therefore one must consider the isotropy of bone's thermal conductivity. Table 1 indicates that only one investigator [11] directly measured conductivity in different directions, and that a directional difference was found. These directions pertain to long bones and are illustrated in Fig. 1. At the same time, two indirect observations related to isotropy have been made. Lundskog [9] implanted a heated rod in the mid-diaphysis of rabbit tibiae and noted that the isotherms surrounding the rod were circular, leading to the conclusion that cortical bone is thermally isotropic. Abouzgia and James [14], on the other hand, detected different temperature gradients in different directions during bone drilling and concluded that cortical bone was anisotropic. Hence prior work has not established whether bone is isotropic in its thermal properties.

In trying to understand the disparity in Table 1, the experimental apparatuses used in the prior studies were examined in detail. Both Kirkland [8] and Vachon et al. [10] used a "thermal comparator", a device that com-

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Table 1
Prior measurements of thermal conductivity of cortical bone

Investigator(s)	Species	Conductivity [W/mK]	Notes
Biyikli et al. [6]	Human	0.2	Dry specimens
		0.3	Fresh specimens
Zelenov [11]	Human	12.8	Longitudinal
		9.7	Radial
		9.9	Circumferential
Lundskog [9]	Human	3.56	Dry specimens
Vachon et al. [10]	Ox	0.601	Dry specimens
		2.27	Fresh specimens
Kirkland [8]	Bovine and caprine	0.888 to 3.08	
Chato [7] (reported in [3])	Human	0.38	Fresh specimens

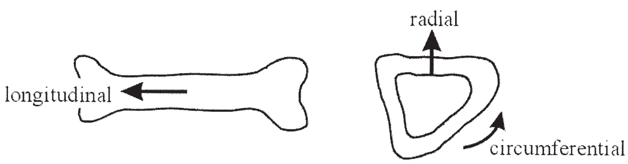

Fig. 1. Anatomical directions of a long bone.

pares the cooling rates of two heated copper spheres in air, one of which is in contact with the material being tested. Vachon et al. claimed that the comparator successfully measured the conductivity of “a number of engineering materials”, but reported that the device was sensitive to contact pressure. Because of this sensitivity and because the measurement of conductivity is not straightforward with this type of device, it is difficult to assess the reliability of the data of Kirkland and Vachon et al. in Table 1. Two other investigators listed in the table, Lundskog [9] and Zelenov [11], used a more direct method for measuring conductivity but said nothing about insulation in describing their apparatuses and assumed that heat flow through the specimen was equal to the heat generated by a heating element. Without insulation, though, the assumption is not likely a reasonable one and so their results have errors of unknown magnitude. Lundskog, furthermore, drilled holes in the bone specimens to accommodate thermocouples, holes which would have affected heat flow through the specimen. As for Chato, the values in Table 1 are available only in another paper [3]; the apparatus may be described in the original paper [7], but that paper is effectively unavailable. The remaining reference in Table 1 is that of Biyikli et al. [6], and this work has been left to the last because it is the only one where insulation was used and where heat flow was measured directly. These are essential requirements for the determination of thermal conductivity and so, of the various data presented in Table 1, theirs may be considered the most reliable.

Because of the diversity of conductivity values in Table 1 and because the values there have unknown accuracies, it was thought worthwhile to conduct an independent investigation, one with well-controlled experimental conditions. Furthermore, since isotropy is important and since the only measurements of directional difference are questionable, it was decided that isotropy should be investigated as well.

The objectives of this work, then, were to measure the thermal conductivity of cortical bone and to determine its variation with direction. We also wanted to improve upon the experimental method of Biyikli et al. Its one drawback was that specimens had to be machined to specific dimensions before measurements could be made. Heat generated during the preparation may have altered the structure of the specimens and therefore their thermal properties. Hence we sought a method which would minimize the machining of specimens.

2. Methods and materials

2.1. Specimen material

Bovine bone was selected because it is readily available. Furthermore, bovine bone has been used in previous studies of the thermal effects of drilling [1] and cutting [15], indicating that it is an acceptable substitute for human tissue.

Frozen bovine femora were obtained from a local butcher and 1-cm slices were cut from the mid-shaft with a band saw. Then individual specimens were cut from the straightest sections of the slices, as illustrated in Fig. 2.

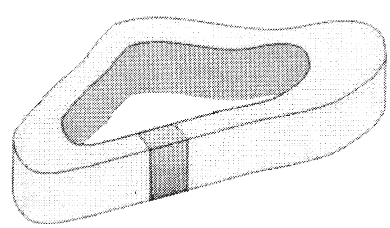

Fig. 2. Schematic drawing of a cross-section of bovine femur, showing the location and shape of a typical specimen.

The average specimen thickness was 0.90 cm and average area of the surface across which heat was applied was 1.0 cm^2. Ordinarily the saw blade was sharp and so cuts were made with minimal heating. But sometimes there was charring, smoke, or boiling around the blade, which was taken as evidence that the temperature generated was excessive. Whenever this occurred, the specimen was rejected and the blade was replaced.

After removal from the femur slice, each specimen was wrapped in gauze soaked in mammalian Ringer's solution. Each specimen, thus wrapped, was placed in a sealed plastic bag, and was kept frozen until used in the thermal conductivity measurements.

2.2. Experimental apparatus and procedure

The experimental apparatus, illustrated schematically in Fig. 3, was designed to create one-dimensional heat flow through a bone specimen.

A Plexiglas block (A in Fig. 3) and a bone specimen (B) were placed between two aluminum blocks (C and D). A heating element (E) was created by embedding coils of resistance wire in thermally conductive cement. The cement affixed the element to the upper aluminum block and power was supplied by a BK Precision DC power source (model 1610A). The lower aluminum block (D) was partially submerged in a large water bath (F) to provide a constant-temperature heat sink. The apparatus was held against the support wall (G) with a C-clamp (not shown).

Polyurethane foam insulation (H), approximately 2.5 cm thick, was placed around the Plexiglas block and specimen. To determine whether the insulation was sufficient to prevent heat loss to the environment, two Plexiglas blocks were placed in the apparatus, one to measure the heat flow, the other to serve as a test specimen. A series of 11 measurements yielded an average conductivity of 0.234 W/mK with a standard deviation (SD) of 0.00632 W/mK, which was 2.6% higher than the Plexiglas conductivity measured in a separate experiment (see Section 2.3 below). With such a small discrepancy, and given that the standard deviation was small, it was concluded that heat loss was negligible. For the subsequent tests with bone, a specimen replaced one of the Plexiglas blocks. In these tests, it was assumed that heat flow through the bone, Q, calculated using Eq. (1), was the same as that through the adjacent Plexiglas block,

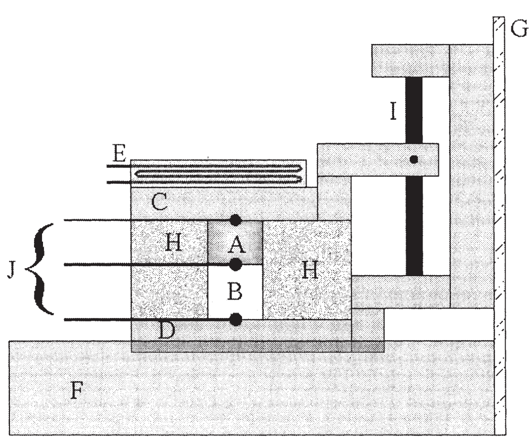

Fig. 3. Schematic cross-section of the experimental apparatus used to measure the thermal conductivity of cortical bone. A, Plexiglas block; B, bone specimen; C,D, aluminum plates; E, heating element; F, water bath; G, support wall; H, insulation; I, guide rods; J, thermocouples.

$$Q=k_0 A_0 \frac{\Delta T_0}{t_0} \quad (1)$$

where k_0=thermal conductivity of the Plexiglas block (Section 2.3) [W/mK], A_0=cross-sectional area normal to the heat flow [m^2], t_0=block thickness [m], and ΔT_0=measured temperature drop across the block [K].

A different Plexiglas block was used for each bone specimen. Each block was machined such that its cross-sectional area was the same as that of the specimen being tested. Furthermore, the top aluminum block could slide on two rods (I), permitting specimens with different thicknesses. Thus specimens with a range of sizes were tested and specimen machining was kept to a minimum.

The thermal conductivity of the bone specimens was calculated from Eq. (2)

$$k_b=\frac{Q t_b}{A_b \Delta T_b}, \quad (2)$$

where k_b=thermal conductivity of bone (in the direction being measured) [W/mK], Q=heat flow through the bone specimen [W], t_b=its thickness [m], A_b = its cross-sectional area [m^2], ΔT_b=temperature drop across the bone specimen [K].

Substituting the expression for Q from (1) into (2) and taking into account that A_0=A_b results in the equation which was ultimately used to calculate k_b:

$$k_b=k_0 \frac{t_b}{t_0} \frac{\Delta T_0}{\Delta T_b}. \quad (3)$$

The temperature drops ΔT_b and ΔT_0 were measured by three thermocouples (J). All thermocouples were type K with a junction bead diameter of 0.3 mm. One thermocouple was placed between the heated aluminum block (C) and the Plexiglas block (A), another between (A) and the specimen (B), and the third between (B) and the lower aluminum block (D). Although the thermocouple beads were small, they created gaps between the flat surfaces, and thus each gap was filled with thermally conductive paste (Omegatherm 201, Omega, Stamford, CT). As a result, the temperature drop measured by two thermocouples included a drop within the paste. The drop across a distance equal to the bead diameter was, however, estimated to be less than 0.2°C, which was small compared with a typical total temperature drop of 30°C. It was therefore not necessary to adjust the measured temperature differences. Signals from the three thermocouples were fed into a Fluke digital multimeter (model 8050A) via a home made amplifier [14]. The thermocouples were calibrated against a laboratory thermometer in a water bath at various temperatures and were checked periodically to ensure that the linear calibration curve had not changed.

The specimens were oriented in the apparatus such that heat flowed in one of the three directions in which the thermal conductivity was sought: longitudinal, circumferential, or radial, as defined in Fig. 1.

Before each measurement, the specimen was weighed, and then the specimen, the Plexiglas block, the insulation and the thermocouples were inserted in the apparatus. The top aluminum plate was held in place with two screws pressing against the guide rods, which ensured that the components were held together securely. The apparatus was fastened to the wall, as described earlier, and the water level in the bath was raised so that the bottom aluminum plate was partially submerged. Power leads were then attached to the heating element, and the power source turned on. After at least 2 h, temperature readings were taken every 15 min until the system reached steady state. It was assumed that this state was reached if three conductivity measurements in a row were identical to three significant figures. A set of three identical readings out of four consecutive ones was also accepted as steady state.

At the end of each test, and after the insulation was removed, the set-up was examined to confirm that the alignment of the Plexiglas block and specimen had not changed and that thermal contact had been proper. Poor alignment, poor thermal contact, or an improper thermocouple position was considered sufficient reason for discarding the results.

After the test, the specimen was removed, wiped clean, and weighed again. The change in mass was recorded to determine the amount of evaporation. The specimens were stored in sealed plastic bags between measurements.

2.3. Measurement of Plexiglas conductivity

The thermal conductivity of Plexiglas, k_0, is crucial for the calculation of k_b, but literature values for Plexiglas conductivity differ [16,17]. Thus a separate apparatus, shown schematically in Fig. 4, was built to measure the conductivity of Plexiglas.

A multi-layer sandwich was formed with a 5×5 cm Kapton flexible heater (A) at the centre and, on each side of the heater, a 5 cm square block of steel (B1), a 5 cm square block of Plexiglas (C), and another 5 cm square block of steel (B2). The inner steel plates were used to smooth out the temperature profile generated by the heater, and the outer plates were used as support as well as heat sinks. Three thermocouples (D) were placed on each side of one of the Plexiglas blocks. Thermally conductive paste was applied between all layers. The entire sandwich was surrounded by approx. 4 cm of Styrofoam insulation (E), into which a groove was cut to accommodate the power leads and thermocouple wires (not shown).

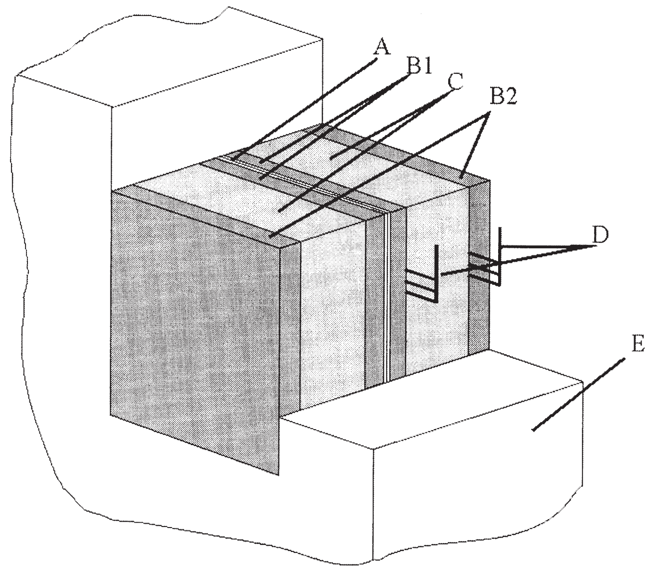

Fig. 4. Schematic drawing of the apparatus used to measure the thermal conductivity of Plexiglas. A, thin film heater; B1 and B2, steel plates; C, Plexiglas specimens; D, thermocouples; E, insulation, partially removed to reveal sandwich construction.

To calculate the conductivity of a specimen block, one needs to know the heat transported, the temperature drop across it, and its dimensions. The insulation surrounding the apparatus forced the heat towards the outer layers of the sandwich, and the symmetry of the sandwich permitted the assumption that half of the heat passed through each Plexiglas block. The total heat generated was taken to be the product of the voltage and current to the heater, both of which were measured by a digital multimeter. The temperature drop across the specimen block was calculated as the difference of the average temperatures of the three thermocouples on each side. The thermal conductivity was calculated using Eq. (2), applied to Plexiglas instead of bone.

The tests were run in a manner similar to those for the measurement of the thermal conductivity of bone. That is, 3 h after the heater was turned on, thermocouple readings were taken at 15-min intervals. If three consecutive conductivity values (or three out of four consecutive ones) were identical to three significant figures, it was assumed that steady state had been achieved and the conductivity was recorded.

A set of nine measurements resulted in an average thermal conductivity of 0.228 W/mK with a standard deviation of 0.00345 W/mK (1.51%). This value falls slightly above the range of values for Plexiglas published in engineering reference texts (0.187 W/mK [16], 0.2 W/mK [17]).

3. Results

The specimens were divided into three groups. The first group was used for conductivity measurements in the longitudinal direction, the second for circumferential measurements and the third for radial measurements. No specimen was tested in more than one direction. A total of 21 specimens were taken from six animals, with specimens from three of the six included in each group to obtain an average across individuals within the species. Multiple specimens were included from each animal to obtain an average over location in the femur. Measurements on each specimen were repeated at least four times to reduce the effect of random error. The conductivity was calculated using Eq. (3) and the values are presented in Table 2; these values are averages of all measurements taken in each of the three directions.

The average standard deviation of the measurements on an individual specimen was 0.0135 W/mK, or 2.2% of the mean specimen conductivity. The standard deviation for all measurements on an individual animal was also calculated, and the average was 3.1% of the mean animal conductivity. The excellent repeatability provides confidence in the reliability of the apparatus and technique.

A statistical analysis of the directional differences was performed using Student's *t*-test. Differences in thermal conductivity between the longitudinal and radial directions, and between the longitudinal and circumferential directions were found to be statistically significant ($p<0.001$). At the same time, no statistically significant difference was found between the circumferential and the radial directions ($p>0.05$). Statistical significance, however, does not necessarily translate to practical significance, i.e., it is apparent that the difference between the longitudinal direction and the other two has a negligible effect on the temperatures generated in bone during operations such as surgical drilling.

As for evaporation during the measurements, it was found that the average mass loss from a specimen over the course of *all* measurements on that specimen was 0.046 g, or 2.8% of the initial mass, which ranged from 1.14 to 2.57 g. Put another way, the percentage mass loss ranged from 1.3% to 6.1%. Since the average mass loss was well below 5%, it was concluded that evaporation did not significantly affect the thermal conductivity measurements.

4. Discussion

As indicated earlier, our apparatus was based on the design used by Biyikli et al. [6] They measured a thermal conductivity of 0.3 W/mK for fresh human cortical bone, a value that is just over half of that measured in the current research. Their apparatus was well designed but the descriptions of the apparatus and experimental technique do not mention the use of a substance, such as the thermally conductive paste we applied, to eliminate air gaps between the specimen and other components of the system. The additional thermal resistance created by an air gap would have increased the temperature drop across the specimen and thereby artificially lowered the thermal conductivity calculated from the measurements. Air gaps may therefore account for their smaller conductivity values. It should also be noted that, although the disparity between Biyikli et al.'s results and our own is significant, it is not unreasonable when compared to the large disparity amongst the results reported by other researchers (Table 1).

The results of the current research are closest in value to Vachon et al.'s [10] measurement of the conductivity of dry ox bone. Our samples were fresh, however, and there is a large difference between their values for fresh (2.3 W/mK) and dry (0.60 W/mK) specimens. As mentioned in the Introduction, results from that study may be unreliable because the authors indicated that their apparatus, the thermal comparator, was sensitive to contact pressure. The large difference between fresh and dry bone conductivity may also be caused by surface moisture, which, if present, would provide an alternate path for the heat flowing from the copper sphere to the bone, thereby affecting their measurements. The apparent agreement between their conductivity value for dry ox bone and our value for fresh bovine bone is likely coincidental. Kirkland [8], using a modified version of the tthermal comparator, divided steer, bulls, and goats by age and then took conductivity measurements at various

Table 2
Results of thermal conductivity measurements

Direction	No. specimens	No. animals	No. measurements	Conductivity (k±SD) [W/mK]
Longitudinal	8	3	34	0.58±0.018 (3.1%)
Circumferential	7	3	29	0.53±0.030 (5.7%)
Radial	6	3	25	0.54±0.020 (3.7%)

anatomical locations. The variation due to animal type, age and bone location was quite large. For example, in 1.5 year old Holstein steers, tibia conductivity was 3.09 W/mK while rib conductivity was 1.11 W/mK. Since a rib contains mostly cancellous bone with only a thin layer of cortical bone, the variation in Kirkland's values may reflect a difference in composition rather than a difference in cortical bone conductivity.

The conductivity value measured by Lundskog [9], 3.56 W/mK, is almost an order of magnitude greater than that measured in the current study. As mentioned in the Introduction, Lundskog assumed negligible heat loss to the surroundings, yet did not use insulation. The heating element and the specimen were exposed to air within a box. Eq. (2) shows that any heat loss would cause an overestimation of the conductivity. Lundskog tested the apparatus by using specimen materials of known conductivity, but the value reported for Plexiglass [sic], 3.6 W/mK, is an order of magnitude greater than our own and literature values. This large discrepancy provides further evidence that unaccounted-for heat losses resulted in higher conductivity values.

We mentioned earlier that Lundskog observed circular isotherms generated about a heated rod implanted in rabbit tibiae and concluded that cortical bone was isotropic. Our conclusion about the isotropy of bone is similar. Table 2 indicates that the largest directional difference is 0.5 W/mK, or 8.9% of the mean conductivity, between the circumferential and longitudinal directions. Zelenov [11], on the other hand, measured a directional difference of 28.7% of the mean between the longitudinal and radial directions (Table 1). The reason for the larger conductivity values is probably, like Lundskog, due to the lack of insulation and the assumption of negligible heat loss, but this was a systemic error and does not explain the greater anisotropy. Abouzgia and James [14] were the only other investigators to observe a large directional difference. During drilling experiments, they measured an average temperature drop of about 20°C in the longitudinal direction and about 8°C over the same distance in the circumferential direction. This would seem to indicate significant anisotropy. Their results, however, suffer from a large amount of scatter. For example, the temperature rise measured in one location varied between 20°C and 50°C. This high degree of scatter puts the accuracy of their measurements and their observation of anisotropy into question.

There is a difference in the structure of bovine and human cortical bone. While the diaphyses of human long bones are almost entirely composed of Haversian bone, with the primary structural units, the osteons, aligned with the long axis, bovine bones have a higher concentration of plexiform bone. This difference leads to the question of whether the results of the current research can be applied to procedures on human bone. Given that the constituents of bone are similar in both species, it is likely that magnitudes of the thermal conductivity are similar. Differences in structure are more likely to have an influence on directional dependence of the conductivity. Since there is no direct evidence regarding differences in thermal anisotropy between the two species, a reasonable alternative is to examine differences in the anisotropy of elastic properties. These properties—Young's modulus, shear modulus and Poisson's ratio—have been investigated many times in several species. The most relevant evidence comes from Kohles [13], who assessed elastic anisotropy by examining the results from a wide range of studies. Mixed results were obtained, to the extent that it cannot be said that bovine bone is either more or less anisotropic than human bone. Therefore, there is likely little difference in thermal anisotropy.

5. Conclusion

Results from our heat transfer experiments show that bovine cortical bone has a thermal conductivity of 0.56±0.039 W/mK (SD) and that this bone may be treated as thermally isotropic. The value of the conductivity is likely appropriate for human cortical bone as well.

Acknowledgements

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