Electric and Dielectric Properties of Wet Human Cortical Bone as a Function of Frequency

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Abstract—**In this paper, the electrical and dielectric properties of wet human cortical bone from a distal tibia were examined as a function of frequency and direction. The resistance and capacitance of the cortical bone specimens were measured at near 100% relative humidity. The measurements were made in all three orthogonal directions at discrete frequencies ranging from 120 Hz to 10 MHz using an LCR meter. At a frequency of 100 kHz, the mean resistivity and specific capacitance for the ten cortical bone specimens were 1.55 kΩ-cm and 33.81 pF/cm in the axial direction, 15.79 kΩ-cm and 9.98 pF/cm in the circumferential direction, and 21.5 kΩ-cm and 9.83 pF/cm in the radial direction. All electrical and dielectric properties except the resistivity and the specific impedance were highly frequency dependent for the frequency range tested. However, the resistivity and specific impedance were relatively less frequency dependent. All electrical and dielectric properties were also transversely isotropic in nature, the values for the axial direction being different from the values obtained for the two transverse directions.**

Introduction

ORTHOPAEDIC surgeons have used electrical stimulation in treating nonunions and congenital pseudarthrosis since the early 1970's with indications of its potential use dating back to the fifties [1]–[5]. Additionally, electrical stimulation has been suggested as a prevention for osteoporosis [6]. Although the use of electrical stimulation in orthopaedics has been shown to be beneficial in clinical studies, the basic mechanisms involved are at best poorly understood and basically still unknown [2], [6]. Not only are the uses of electromagnetic stimulation varied, several different methods of stimulation have also been used clinically. For instance, both direct current stimulation by means of implanted electrodes or percutaneous pins [3], [7] as well as induced current stimulation by pulsing electromagnetic fields have been shown to produce the same high rate of clinical success [1], [2], [5]. Recently, capacitively coupled signals have also been demonstrated as a possible treatment for osteoporosis [8].

For a better understanding of the role of electrical stimulation in bone remodeling and for an analysis of the distribution of direct or induced current in bone, we need accurate data on the electrical properties of bone. Several investigators [9]–[14] have measured the electrical and dielectric properties of cortical bone, yet most of these studies [15] used bone tissue from an animal such as a rat or cow or used human bone material that was dried or allowed to dry and rehydrated. Other authors have shown that rehydration does not fully restore the original moisture content of bone and this affects its electrical behavior [15]. Moreover, there are possible differences in the dielectric properties of human cortical bone as compared to animal bone such as rat due to structural differences in their bone tissues [10]. Therefore, the objective of this study was to measure the electrical properties of fully wet human cortical bone and compare our results with other published data. Because previous studies have shown that the dielectric behavior is frequency dependent and as pulsing electromagnetic fields contain a spectrum of several frequencies, we investigated the frequency dependence of the electrical properties of wet human cortical bone.

Reinish and Nowick [16] and Saha, Reddy, and Albright [17] have shown that the dielectric properties of bone varied as a function of the moisture content; therefore, in this study, the measurements were made in a humidity chamber at near 100% relative humidity to allow measurements to be performed on fully moist tissue. Chakkalakal *et al.* [9] have shown that the electrical behavior of bone is anisotropic in that the resistivity was higher in the radial direction than for the longitudinal direction. Reddy and Saha [13] also demonstrated direction dependence of electrical and dielectric properties of bone resulting from anisotropic behavior. Therefore, measurements were performed in all three orthogonal directions at selected frequencies to study the anisotropic nature of human bone. Relationship between the electrical properties and bone density were also investigated.

Methods and Procedures

Sample Preparation

A tibia was obtained from an amputation of a 54-year-old black male diagnosed with gangrene of the left foot. The specimen was obtained shortly after pathological examination and had been maintained under refrigeration from post-surgery until examination. All of the soft tissue was removed and the bone was wrapped in a cotton towel soaked in Ringer's solution and placed in a plastic bag which was then sealed. The specimen was then placed in

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a freezer at -10 to $-20°C$ until the specimen was to be machined.

The frozen specimen was thawed, unwrapped, and machined maintaining the specimens in a moist condition throughout the entire machining process. Five sections approximately 1–1.5 cm long were cut from the distal third of the tibia which appeared normal during the pathological examination. From these sections ten cortical bone samples were machined and tested. As shown in Fig. 1, the samples were machined so that the two transverse faces (radial and circumferential) were flat smooth surfaces correctly oriented with respect to the anatomy. The specimens were cleaned in an ultrasonic cleaner to remove the surface debris. The specimens were maintained in Lactated Ringer's (pH 6.5) solution throughout the experiment and the surfaces perpendicular to the radial direction of each sample were marked so that the orientation was known.

Electrical Measurements

Fig. 2 shows the experimental setup used in measuring the electrical properties of the specimens which were tested in all three directions (axial, circumferential, and radial). Chlorided-silver metal electrodes 1.5 cm in diameter were used in the electrical measurement of the specimens. The resistance and capacitance in all three directions were measured at frequencies of 10 k, 100 k, and 1 MHz using a multifrequency LCR meter (Hewlett Packard 4275A). The properties in the axial direction were also measured at frequencies of 120, 1 k, 20 k, 40 k, 200 k, 400 k, 2M, 4M, and 10 MHz utilizing a second LCR meter (Hewlett Packard 4262A) for 120 Hz and 1 kHz. The measurements were made at a temperature of 27°C in a humidity chamber at near 100% relative humidity to prevent moisture loss during the test [17]. Electrode artifacts, particularly at the lower frequencies (<10 kHz) have been previously shown to not be significant for the electrodes used [13].

Physical Properties

After the electrical properties and the dimensions of the specimens were measured, their wet weight was determined by using a balance (Sartorius 2434). Subsequently, thin sections from two or three of the faces of the specimen were cut for future analysis of the bone microstructure. The dimensions of the specimens were remeasured after the sections were removed. The specimens were then cleaned in a solution of acetone in an ultrasonic cleaner (Bransonic 220) for one hour after which the acetone was changed and the specimens were placed back into the ultrasonic cleaner for another hour. The specimens were placed in a desiccator overnight, and then placed in a vacuum over (Fisher Isotemp model 281) at 100°C for one hour under a vacuum. The samples were then weighed in aluminum weighing pans to obtain the dry weight. The samples were finally placed in a laboratory box furnace (Lindberg model 51894) for no less than 4 h at 550°C and

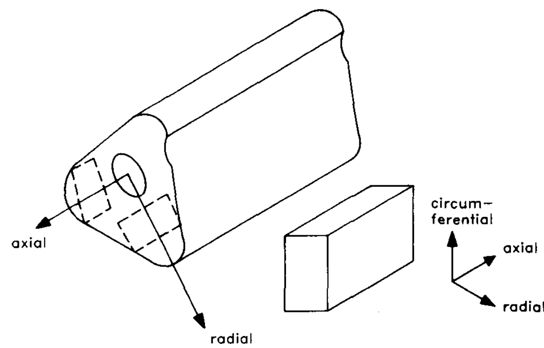


Fig. 1. Diagram of bone and the machined sample.

the ash weight was taken. From these measurements, the wet density, dry density, and ash density were calculated. All densities were calculated in terms of the overall sample volume.

Data Analysis

The values of the various electrical and dielectric parameters were calculated by the following procedure and equations. The resistivity (R_{sp}) and specific capacitance (C_{sp}) were calculated by using the following relations.

$$R_{sp} = R * A/d \quad (1)$$

$$C_{sp} = C * d/A \quad (2)$$

where R and C are the measured resistance and capacitance of the specimen, respectfully, A the cross sectional area of the measured surface, and d the thickness of the specimen in the direction of measurement. From these two calculated values the remaining electrical properties were calculated as follows:

$$\sigma = 1/R_{sp} \quad (3)$$

$$\epsilon' = C_{sp}/\epsilon_o \quad (4)$$

$$\epsilon'' = 1/(2\pi f R_{sp}\epsilon_0) \quad (5)$$

$$Z_{sp} = R_{sp}/[(2\pi f R_{sp}C_{sp})^2 + 1]^{1/2} \quad (6)$$

$$\theta = -\arctan(2\pi f R_{sp}C_{sp}) \quad (7)$$

where σ is the conductivity, ϵ' and ϵ'' are the dielectric permittivity (or dielectric constant) and dielectric loss factor, respectively, which together express the complex dielectric permittivity given by

$$\epsilon^* = \epsilon' + j\epsilon''. \quad (8)$$

Z_{sp} is the specific impedance, θ is the phase angle in degrees, f is the frequency in hertz, and ϵ_o is the permittivity of free space, which is equal to 8.854×10^{-12} F/m.

Results

Frequency Dependence

The resistivity of the bone samples for the axial direction, shown in Fig. 3, exhibited a slight frequency depen-

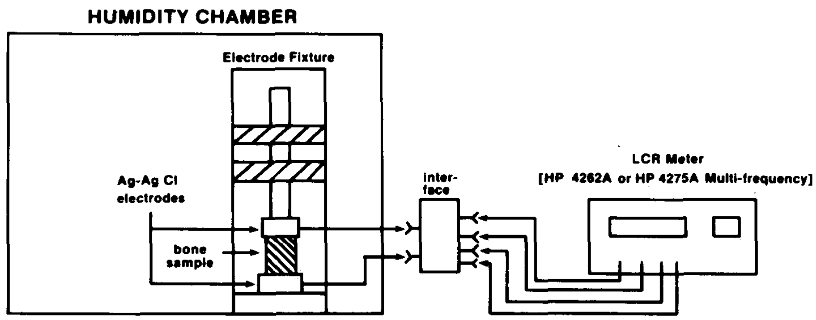


Fig. 2. Schematic of the experimental setup.

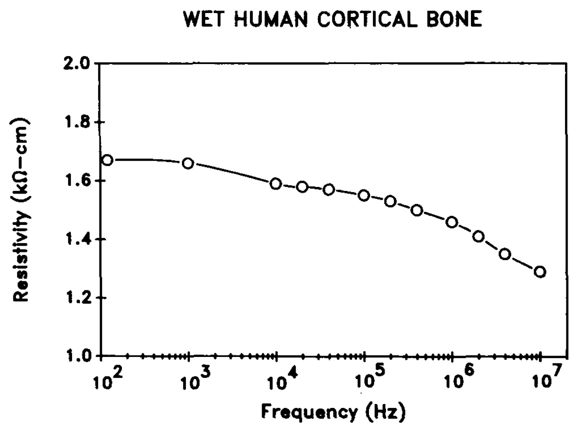


Fig. 3. Average resistivity for the axial direction as a function of frequency.

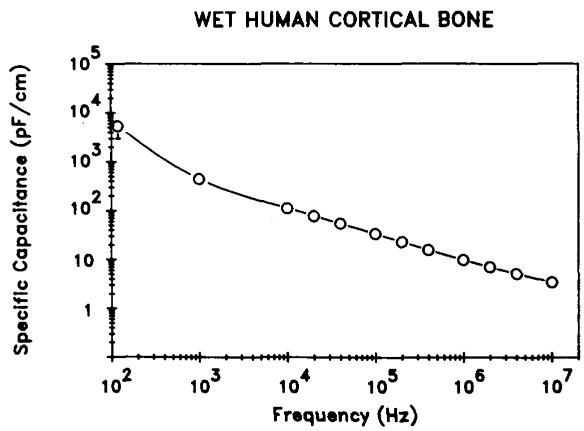


Fig. 4. Average specific capacitance for the axial direction as a function of frequency.

dence. The values decreased gradually from 120 Hz to 10 MHz where they were approximately 23% less than at 120 Hz. The specific capacitance, shown in Fig. 4, illustrated an inverse log-log relationship with frequency, with specific capacitance decreasing with increasing frequency. Figs. 3 and 4 show two distinct regions with different behaviors, the first region being below 1 kHz and the second region above 1 kHz.

Direction Dependence

Table I shows the means and standard deviations for the resistivity and the specific capacitance for the cortical bone specimens at a frequency of 100 kHz in the three directions. It is evident that the resistivity was considerably lower in the axial direction compared to the circumferential or radial directions. The circumferential and radial directions differed although this was not found to be significant ($p > 0.05$). In a previous study on bovine cortical bone, we also found a lower specific resistance in the longitudinal direction compared to the radial and circumferential directions [13]. It is also shown in Table I that the specific capacitance is higher in the axial direction than in the two transverse directions. It is of interest that as in our previous study on bovine cortical bone [13] the following relationship axial < circumferential < radial was found to hold for the resistivity and the relationship axial > circumferential > radial was true for the specific capacitance, although it should be noted again that the difference between the two transverse directions found in this study, was not found to be statistically significant ($p > 0.05$).

TABLE I
ELECTRICAL PROPERTIES (MEAN ± 1 SD) OF CORTICAL BONE SPECIMENS MEASURED AT A FREQUENCY OF 100 kHz ($n = 10$)

	Direction		
	Longitudinal	Circumferential	Radial
Resistivity (kΩ-cm)	1.55 ± 0.33	15.79 ± 5.59	21.50 ± 9.12
Specific Capacitance (pF/cm)	33.81 ± 2.34	9.98 ± 2.06	9.83 ± 2.28

Highly significant positive correlations were found to exist between the resistivities in the longitudinal and transverse directions as is shown in Fig. 5. For the specimens used in this study, the relationship can be expressed as

$$R_c = -8.59 + 15.89\, R_l$$
$$(r = 0.9077 \text{ and } P < 0.001)$$

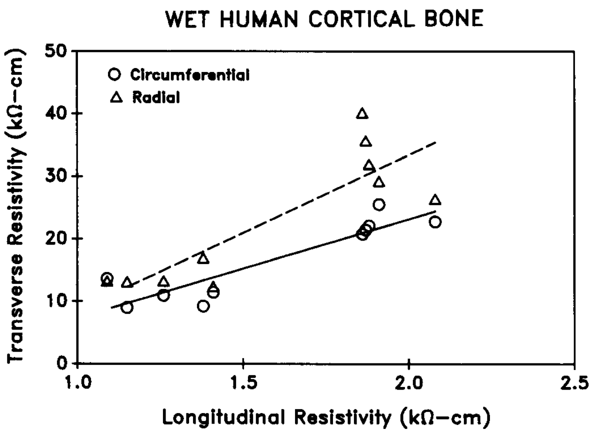


Fig. 5. Relationships between the resistivities in the longitudinal and transverse directions.

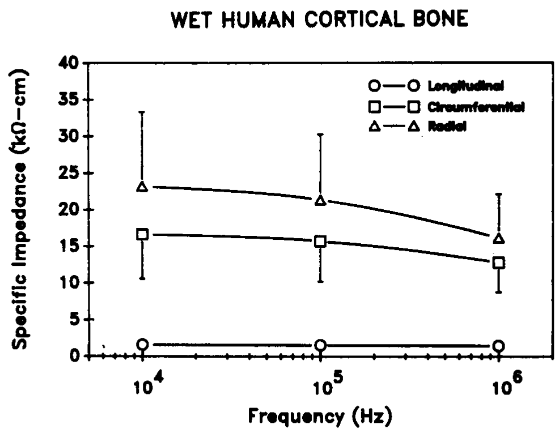


Fig. 7. The average specific impedance for the axial, circumferential, and radial directions as a function of frequency for 10 k to 1 MHz.

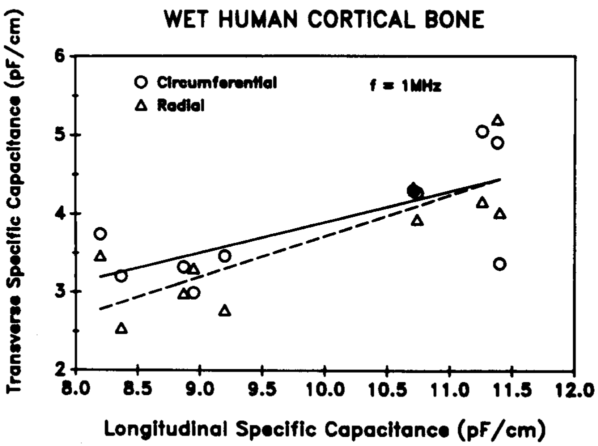


Fig. 6. Relationships between the specific capacitances in the longitudinal and transverse directions at a frequency of 1 MHz.

and

$$R_r = -16.53 + 24.99\,R_l$$

$$(r = 0.8562 \text{ and } p < 0.001)$$

where R_c, R_r, and R_l are the resistivities in the circumferential, radial, and longitudinal or axial directions, respectively, expressed in kΩ-cm. Similarly, positive correlations were also found between the specific capacitance at 1 MHz in the longitudinal and transverse directions as shown in Fig. 6. These relationships can be expressed as

$$C_c = -0.025 + 0.392\,C_l$$

$$(r = 0.7026 \text{ and } p < 0.002)$$

and

$$C_r = -1.496 + 0.521\,C_l$$

$$(r = 0.8360 \text{ and } p < 0.001)$$

where C_c, C_r, and C_l are the specific capacitances in the circumferential, radial, and longitudinal directions, respectively expressed in pF/cm. However, this was not true at other frequencies.

Fig. 7 shows the specific impedance for the three directions as a function of the frequencies measured. The specific capacitance did not contribute much to the specific impedance in the circumferential or radial directions. However, the specific capacitance did contribute to the phase angle for all three directions, as shown in Fig. 8. From these figures (Figs. 7 and 8) and Table I it can be seen that although the electrical properties in the axial direction is considerably different from those in the two transverse directions, the properties in the circumferential and radial directions are only slightly different from one another. In addition, Figs. 5 and 6 demonstrate a near linear relationship between the axial direction and transverse (circumferential and radial) directions. However, these relationships appear to be different for each transverse direction. In other words, the relation between the axial and circumferential directions is different from the relation between the axial and radial directions.

Physical Properties

Table II shows the means, standard deviations, and ranges of the wet, dry, and ash densities, as well as the ash content of the cortical bone samples. As can be seen from Table II, there were small variances in the tissue densities. The percent ash content of 67.03% is a little higher than that obtained by Gong, Arnold, and Cohn [18] yet still in general agreement. By subtracting the dry density and dividing the difference by the density of water, a value of 27.8% for the percent volume fraction for water was obtained. This is somewhat low in comparison with 32.9% obtained by Gong, Arnold, and Cohn [18] yet it is acceptable considering that if the mean age for the samples of Gong, Arnold, and Cohn was less than 50 years then their value would be higher according to Timmins and Wall [19].

The specific capacitance and resistivity showed no correlation with wet density. For the specific capacitance the

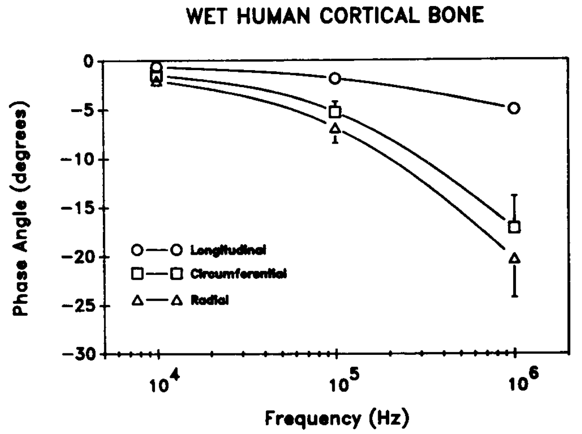


Fig. 8. The average phase angle for the axial, circumferential, and radial directions as a function of frequency for 10 k to 1 MHz.

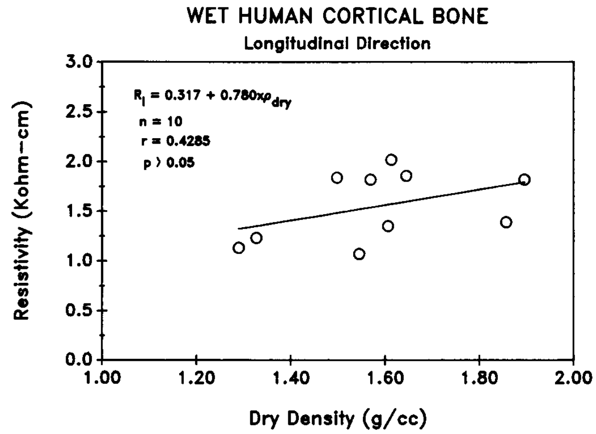


Fig. 9. Relationship between the resistivity in the longitudinal direction and the dry density.

TABLE II
PHYSICAL PROPERTIES (MEAN, STANDARD DEVIATION, AND RANGE) OF THE TEN CORTICAL BONE SPECIMENS

	Density (g/cc)			
	Wet	Dry	Ash	Ash Content (% of dry wt.)
Mean	1.857	1.579	1.059	67.03
SD	0.043	0.053	0.050	1.09
Range	1.805–1.908	1.498–1.645	0.983–1.121	65.6–68.5

TABLE III
COMPARISON OF THE CONDUCTIVITY AND RELATIVE DIELECTRIC PERMITTIVITY FOR CORTICAL BONE AND OTHER INVESTIGATIONS ON RAT, HUMAN, AND BOVINE IN THE RADIAL DIRECTION

	Conductivity (mS/m)		
frequency	rat Kosterich, Foster, and Pollack [10]	bovine Reddy and Saha [13]	human Present Study
10 kHz	13.3 ± 2.8	1.85	5.26 ± 2.22
100 kHz	14.4 ± 2.9	1.84	5.59 ± 2.28
1 MHz	17.3 ± 3.2	3.39	6.71 ± 2.53

	Dielectric Permittivity		
frequency	rat Kosterich, Foster, and Pollack [10]	bovine Reddy and Saha [13]	human Present Study
10 kHz	640 ± 240	240	308 ± 72.00
100 kHz	280 ± 30	74	111 ± 26.00
1 MHz	87 ± 13	27	41.4 ± 8.70

correlation coefficients were less than 0.1 for frequencies of 10 kHz, 100 kHz, and 1 MHz. Although in this study no correlation was found between the electrical properties and wet density it is possible that this could be due to the small sample size ($n = 10$). Fig. 9 shows the relationship between dry density and resistivity in the longitudinal direction. Although the correlation coefficient is not large enough to be statistically significant ($r = 0.4285$), it shows a trend of a positive correlation which may become significant with a larger sample size.

DISCUSSION

Table III shows a comparison of the values obtained from this study with those obtained previously [13] and with those obtained by Kosterich, Foster, and Pollack [10] for conductivity and dielectric permittivity in the radial direction. As can be seen from Table III for both conductivity and dielectric permittivity from the indicated studies rat > human > bovine bone. However, Chakkalakal *et al.* [9] found a value of 5.9 to 7.73 mS/m for the conductivity in the radial direction for bovine cortical bone. Our previously reported value of conductivity for bovine compact bone is considerably lower than this [13]. There are two factors that could partly account for these low values. First, the specimens measured by Reddy and Saha [13] were machined, soaked in Ringer's solution, and stored in a freezer which has been shown to possibly increase the impedance (decreased conductivity) during prolonged periods of storage in a freezer [20]. Second, the specimens were measured exposed to air which was at 65% relative humidity which has been shown by Saha, Reddy, and Albright [17] to increase the resistivity. Although the samples were measured within a short period of time after removal from the solution, increases of up to 50% in resistance can occur within 2 min [17]. Kosterich, Foster, and Pollack, [10] found a value of about ten for the high-frequency limit of permittivity, with other sets of data suggesting 7–16. In this study, a value of 15.32 was obtained from the extrapolation of the experimental data shown in Fig. 10. Using the Maxwell mixture theory, it is possible to estimate the contribution of the water present in the tissue to the permittivity. If ϵ_b and ϵ_w are the permittivity values of the solid matrix and the electrolyte, respectively, and p is the volume fraction of the electrolyte in the tissue, the permittivity of the bone

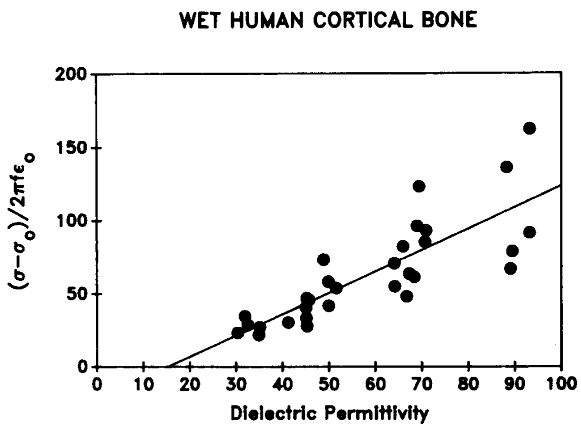


Fig. 10. Dielectric loss versus dielectric permittivity for human cortical bone. Only the dielectric loss arising from the relaxation process is shown as obtained by Kosterich *et al.* [10].

should be approximately equal to that given by the Maxwell formula:

$$\epsilon' = \epsilon_b \frac{2\epsilon_b + \epsilon_w - 2p(\epsilon_b - \epsilon_w)}{2\epsilon_b + \epsilon_w + 2p(\epsilon_b - \epsilon_w)}.$$

Assuming that the permittivity of the bone matrix is about six as cited by Kosterich, Foster, and Pollack, [10] and the interstitial fluid has a value of approximately 77, which is the value for water at 27°C, with the fluid volume fraction of 27.8%, the resulting value of 15.57 is calculated which agrees with the value obtained experimentally. Therefore, the data presented agree well with the findings of Kosterich, Foster, and Pollack [10] yet there are differences between the data obtained for rat and bovine, and human bone which may relate to the difference in structure mentioned previously [10]. Although the difference in the high-frequency limit of the permittivity between that of rat bone as reported by Kosterich, Foster, and Pollack [10] and for human bone from this study can be possibly explained by the difference in volume fraction of water in the tissue, this does not necessarily account for all the differences in conductivity. Kosterich, Foster, and Pollack [21] later found that the electrical properties of rat bone was related to the conductivity of the immersion fluid and the number of pores containing the fluid. Furthermore, Chakkalakal and Johnson [22] also found a relation between the electrical properties and the structure of bovine cortical bone. Therefore, study of the microstructure of the human cortical bone specimens may add additional insight regarding how the microstructural variables affect the electrical properties. At this time, such a study is in progress with the results to be reported later. Chakkalakal and Johnson [22] also found that the resistivity in the radial direction was three–four times greater than the resistivity in the longitudinal direction, yet it was found in this study that the resistivity was about ten times larger in the radial direction than in the longitudinal direction. This could also be possibly explained by potential differences in the bone microstructure.

There are several important factors that should be considered while comparing our results with other published data. First, for all biological tissues the electrical behavior is temperature dependent [23]–[26] which has been shown for bone in its electromechanical potentials [27]. Also, it has been shown that the electrical properties of bone can vary with age in rats [28]. Therefore, the data for the 54-year-old male may not be identical to a younger or older person. There is little information available on age related changes in the electrical properties of bone and there is a definite need for more such data especially for human bone. The bone specimens used in this study were taken from an individual that had some peripheral vascular disease with arterial insufficiency in the limb, which may have affected bone circulation; which in turn may have had some effect on the properties of bone tissue, as is sometimes the case for other tissues [29], [30]. However, the gangrene portion was only in the distal foot, and the tibia appeared to be normal.

In summary, some of the results that have been obtained by others for cortical rat bone [10] and bovine cortical bone [9] have been confirmed for human cortical bone, yet some differences have also been shown to exist as discussed earlier. The frequency dependence and anisotropic nature of the electrical properties of human cortical bone reported in this paper are in general agreement with similar data for animal bone as reported by other investigators [13], [9]. This study has illustrated that reliable accurate data can be obtained from human specimens if proper care in the preparation and measurement of the specimens is taken. However, the slight difference found between the two transverse directions suggest a transverse or near transverse isotropic nature for the human samples used. Additionally, the relation between the longitudinal and transverse directions as shown in Figs. 5 and 6 suggest a strong correlation which has not been previously reported in the literature [15]. Further work is in progress to examine this transverse isotropic nature of the electrical properties of human compact bone and its dependence on bone microstructure.

REFERENCES

[1] C. A. L. Bassett, S. N. Mitchell, and S. R. Gaston, "Treatment of ununited tibial diaphyseal fractures with pulsing electromagnetic fields," *J. Bone Joint Surg.*, vol. 63-A, no. 4, pp. 511-523, 1981.

[2] C. A. L. Bassett, A. A. Pilla, S. N. Mitchell, and L. Norton, "Repair of non-unions by pulsing electromagnetic fields," *Acta Orthop Belgica*, vol. 44, pp. 706-724, 1978.

[3] C. T. Brighton, Z. B. Friedenberg, E. I. Mitchell, and R. E. Booth, "Treatment of nonunion with constant direct current," *Clin. Ortho.*, vol. 124, pp. 106-123, 1977.

[4] D. C. Paterson and R. B. Simonis, "Electrical stimulation in the treatment of congenital pseudarthrosis of the tibia," *J. Bone Joint Surg.*, vol. 67-B, no. 3, pp. 454-462, 1985.

[5] W. J. W. Sharrard, "A double-blind trial of pulsed electromagnetic fields for delayed union of tibial fractures," *J. Bone Joint Surg.*, vol. 72-B, no. 3, pp. 347-355, 1990.

[6] C. T. Rubin, K. J. McLeod, and L. E. Lanyon, "Prevention of osteoporosis by pulsed electromagnetic fields," *J. Bone Joint Surg.*, vol. 71-A, no. 3, pp. 411-417, 1989.

[7] R. B. Heppenstall, "Constant direct-current treatment for established

nonunion of the tibia," *Clin. Ortho. Rel. Res.*, vol. 178, pp. 179-184, 1983.

[8] C. T. Brighton, G. T. Tadduni, S. R. Goll, and S. R. Pollack, "Treatment of denervation/disuse osteoporosis in the rat with a capacitively coupled electrical signal: Effects on bone formation and bone resorption," *J. Orthop. Res.*, vol. 6, no. 5, pp. 676-684, 1988.

[9] D. A. Chakkalakal, M. W. Johnson, R. A. Harper, and J. L. Katz, "Dielectric properties of fluid-saturated bone," *IEEE Trans. Biomed. Eng.*, vol. 27, pp. 95-100, Feb. 1980.

[10] J. D. Kosterich, K. R. Foster, and S. R. Pollack, "Dielectric permittivity and electrical conductivity of fluid saturated bone," *IEEE Trans. Biomed. Eng.*, vol. 30, pp. 81-86. Feb. 1983.

[11] R. S. Lakes, R. A. Harper, and J. L. Katz, "Dielectric relaxation in cortical bone," *J. Appl. Physics*, vol., 48, pp. 808-811, 1977.

[12] A. R. Liboff, R. A. Rinaldi, L. S. Lavine, and M. H. Shamos, "On electrical conduction in living bone," *Clin. Ortho.*, vol. 106, pp. 330-335, 1975.

[13] G. N. Reddy and S. Saha, "Electrical and dielectric properties of wet bone as a function of frequency," *IEEE Trans. Biomed. Eng.*, vol. 31, pp. 296-302, 1984.

[14] S. Singh and J. Behari, "Frequency dependence of electrical properties of human bone," *J. Bioelect.*, vol. 3, pp. 347-356, 1984.

[15] S. Singh and S. Saha, "Electrical properties of bone: A review," *Clin. Ortho. Rel. Res.*, vol. 186, pp. 249-271, 1984.

[16] G. B. Reinish and A. S. Nowick, "Effect of moisture on the electrical properties of bone," *J. Electrochem. Soc.*, vol. 123, no. 10, pp. 1452-1455, 1976.

[17] S. Saha, G. N. Reddy, and J. A. Albright, "Factors affecting the measurement of bone impedance," *Med. Biol. Eng. Comp.*, vol. 22, pp. 123-129, 1984.

[18] J. K. Gong, J. S. Arnold, and S. H. Cohn, "Composition of trabecular and cortical bone," *Anatom. Record*, vol. 149, pp. 325-332, 1964.

[19] P. A. Timmins and J. C. Wall, "Review: Bone water," *Calcif. Tiss. Res.*, vol. 23, pp. 1-5, 1977.

[20] S. Saha and P. A. Williams, "Effect of various storage methods on the dielectric properties of compact bone," *Med. Biol. Eng. Comput.*, vol. 26, pp. 199-202, 1988.

[21] J. D. Kosterich, K. R. Foster, and S. R. Pollack, "Dielectric properties of fluid-saturated bone—The effect of variation in conductivity of immersion fluid," *IEEE Trans. Biomed. Eng.*, vol. 31, pp. 369-373, Apr. 1984.

[22] D. A. Chakkalakal and M. W. Johnson, "Electrical properties of compact bone," *Clin. Orthop. Rel. Res.*, vol. 161, pp. 133-145, 1981.

[23] L. A. Geddes and L. E. Baker, "The specific resistance of biological material—A compendium of data for the biomedical engineer and physiologist," *Med. Biol. Eng.*, vol. 5, pp. 271-293, 1967.

[24] R. Pethig, *Dielectric and Electronic Properties of Biological Materials*. New York: Wiley, 1979.

[25] R. Pethig and D. B. Kell, "The passive electrical properties of biological systems: Their significance in physiology, biophysics, and biotechnology (review article)," *Phys. Med. Biol.*, vol. 32, no. 8, pp. 933-970, 1987.

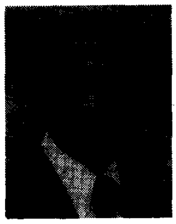
[26] H. P. Schwan, "Dielectric properties of cells and tissues," in *Interactions Between Electromagnetic Fields and Cells*, A. Chiabrera, C. Nicolini, and H. P. Schwan, Eds. New York: Plenum, 1985.

[27] M. E. Steinberg, W. J. Finnegan, D. A. Labosky, and J. Black, "Temporal and thermal effects on deformation potentials in bone," *Calcif. Tiss. Res.*, vol. 21, pp. 135-144, 1976.

[28] G. T. Swanson and J. F. Lafferty, "Electrical properties of bone as a function of age, immobilization, and vibration," *J. Biomech.* vol. 5, pp. 261-266, 1972.

[29] R. J. Davies, J. Renah, D. Kaplan *et al.*, "Epithelial impedance analysis in experimentally induced colon cancer," *Biophys. J.*, vol. 52, pp. 783-790, 1987.

[30] Y. Yamamoto, T. Yamamoto, S. Ohta *et al.*, "The measurement principle for evaluating the performance of drugs and cosmetics by skin impedance," *Med. Biol. Eng. Comp.*, vol. 16, pp. 623-632, 1978.



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