Annals of Biomedical Engineering, Vol. 17, pp. 143–158, 1989
0090-6964/89 $3.00 + .00
Printed in the USA. All rights reserved.
Copyright © 1989 Pergamon Press plc

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

Subrata Saha and Paul Allen Williams

Biomechanics Laboratory
Department of Orthopaedic Surgery
Louisiana State University Medical Center

(Received 9/3/87; Revised 7/2/88)

In this study the electrical and dielectric properties of wet human cancellous bone from distal tibiae were examined as a function of frequency and direction. The resistance and capacitance of the cancellous 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 thirty cancellous bone specimens were 500 ohm-cm and 8.64 pF/cm in the longitudinal direction, 613 ohm-cm and 15.25 pF/cm in the anterior-posterior direction, and 609 ohm-cm and 14.64 pF/cm in the lateral-medial direction. All electrical and dielectric properties except the resistivity and the impedance were highly frequency dependent for the frequency range tested. All electrical and dielectric properties were transversely isotropic as the values for the longitudinal direction were different from values obtained for the two transverse directions and properties in the two transverse directions were approximately similar.

Keywords—*Electrical properties, Cancellous Bone, Frequency dependence, Resistance, Capacitance.*

INTRODUCTION

Since the early seventies, electrical stimulation has gained wide acceptance amongst orthopaedic surgeons for the treatment of nonunions and congenital pseudarthrosis. Stimulations with direct current by means of implanted electrodes or percutaneous pins and with pulsing electromagnetic fields by means of external coils have been used with almost equal success. However, the basic mechanisms of these treatment modalities are still unknown. For an analysis of the effect of electrical stimulation on bone, it is essential to first characterize its electrical properties (3,11). Several investigators (1,7,9,16,23,24) have studied the electrical and dielectric properties of cortical bone. However, most whole bones are composed of three basic parts: (a) the cortical or

Presented in part at the Fifth Southern Biomedical Engineering Conference held in Shreveport, Louisiana, October 20 and 21, 1988, and at the 13th Annual Meeting of the Society for Biomaterials held in New York, June 3–7, 1987. This work was supported by a grant No. ECS-8312680 from the National Science Foundation.

Address correspondence to Subrata Saha, Biomechanics Laboratory, Department of Orthopaedic Surgery, Louisiana State University Medical Center, P.O. Box 33932, Shreveport, LA 71130.

compact outer portion, (b) the porous cancellous or trabecular portion, and (c) the marrow and other tissues that fill the pores of cancellous, and to some extent cortical, bone (6). Although there are data on the electrical properties of cortical bone and there are some data on bone marrow (25), almost no information is available on the electrical properties of cancellous bone (18,19,20). The objective of this study was to measure the electrical and dielectric properties of cancellous bone. Because electrical stimulation by a pulsed electro-magnetic field contains a wide range of frequencies, we also investigated the frequency-dependence of the electrical properties of cancellous bone.

METHODS AND PROCEDURES

Sample Preparation

Three tibiae were obtained from below-knee amputations, with the details of each as follows:

Sex	Race	Age	Diagnosis
M	Black	71	Peripheral vascular disease of right leg
F	Black	60	Gangrene of right foot
M	Black	54	Gangrene of left foot

The specimens were 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 bones were wrapped in cotton towels soaked in Ringer's solution and placed in plastic bags which were then sealed. The specimens were stored in a freezer at −10 to −20°C until they were machined.

Each frozen specimen was thawed, unwrapped, and machined; they were maintained and kept moist throughout the machining process. Cancellous bone specimens approximately one cubic centimeter (1 cm × 1 cm × 1 cm) were machined from the distal portion of each tibia using the scheme shown in Fig. 1. The tibiae were first cut to remove the distal end and the medial and anterior sides, with enough material removed to give a flat surface across most of the area. They were then sectioned into one centimeter thick sections perpendicular to the lateral-medial plane going from the medial side to the lateral side. The resulting sections were then machined in the same manner for the anterior-posterior direction to produce rectangular bars with the long direction anterior-posterior. The bars were machined into thirty 1 cm^3 specimens, ten from each tibia, which were used for the electrical measurements. Each specimen was 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 samples were marked to indicate the orientation.

Electrical Measurement

Figure 2 shows the experimental set-up used in measuring the electrical properties of the specimens, which were tested in all three directions (longitudinal, anterior-posterior, and lateral-medial). Chlorided-silver metal electrodes 1.5 cm in diameter were used to make the electrical contact. The resistance and capacitance in all three directions were measured at frequencies of 10 k, 100 k, and 1 MHz using a multi-frequency LCR meter (HP 4275A). In the longitudinal direction, additional readings were taken at frequencies of 20 k, 40 k, 200 k, 400 k, 2 M, and 4 MHz using

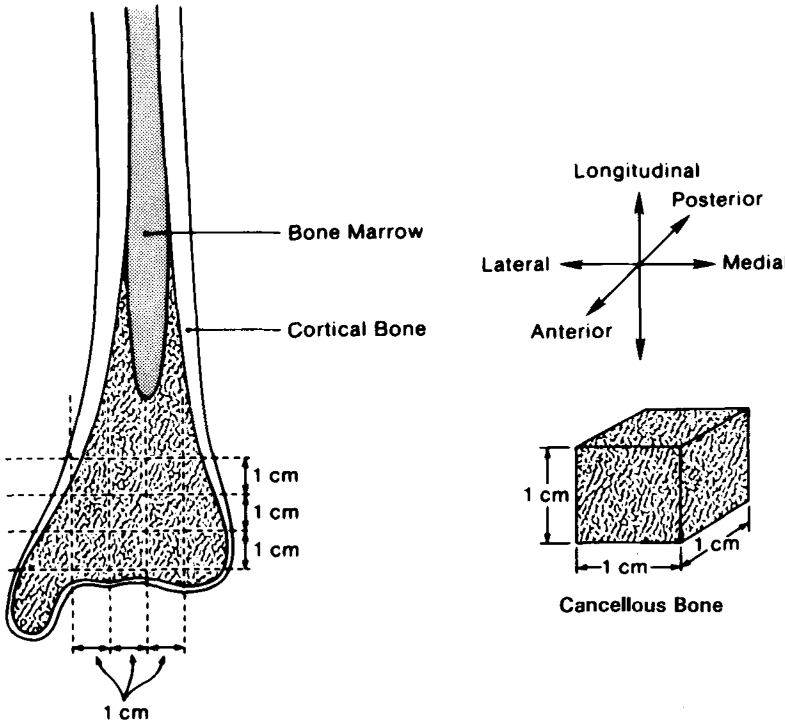

FIGURE 1. Diagram of bone and the machined sample.

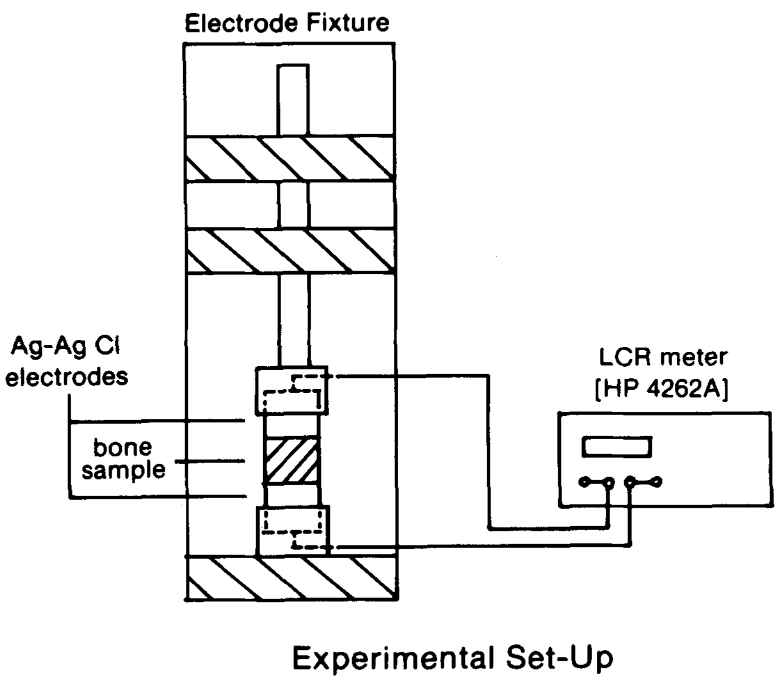

FIGURE 2. Schematic of the experimental set-up.

the LCR meter, and at 120 Hz and 1 kHz utilizing a second LCR meter (HP 4262A). The measurements were taken at 27°C in a humidity chamber at near 100% relative humidity to prevent moisture loss during the test, which may affect the electrical properties (17). By working with a few specimens at one time, all of the measurements could be completed within one or two days after machining. This was done in order to prevent possible changes in the electrical properties with time, as previously reported by Saha and Williams (21) and Liboff *et al.* (10).

Physical Properties

After testing for electrical properties, the dimensions of the bone specimens were measured with a micrometer, and the wet weight was determined. The specimens were then cut to remove a thin section from two or three of the faces and processed for future micro-structure analysis. The specimens were remeasured after these 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 replaced in the ultrasonic cleaner. They were then placed in a dessicator overnight followed by treatment in a vacuum oven (Fisher Isotemp model 281) at 100°C for one hour (under a vacuum). The dry weight of the samples was determined. The samples were then ashed in a laboratory box furnace (Lindberg model 51894) by exposing them for no less than eight hours at 550°C. The ash weight was measured, and from these measured values, the wet density, the dry density, and the ash density were calculated.

Data Analysis

The values of the various electrical and dielectric parameters were calculated by the following procedure (16). The resistivity and the specific capacitance were calculated using the equations

$$R_{sp} = RA/d \tag{1}$$

$$C_{sp} = Cd/A \tag{2}$$

where R_{sp} is the resistivity of the bone tissue in ohm-cm, C_{sp} is the specific capacitance in pF/cm, R and C are the measured resistance and capacitance values of the whole specimen, A is the cross-sectional area of the measured surface, and d is the thickness of the specimen in the direction of measurement. From these two calculated values, the remaining electrical properties were calculated as follows:

$$\sigma = 1/R_{sp} \tag{3}$$

$$\epsilon' = C_{sp}/\epsilon_o \tag{4}$$

$$\epsilon'' = 1/(2\pi f R_{sp} \epsilon_\sigma) \tag{5}$$

$$z_{sp} = R_{sp}/\sqrt{(2\pi f R_{sp}\, C_{sp})^2 + 1} \tag{6}$$

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

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

$$\epsilon^* = \epsilon' - j\epsilon'' \tag{8}$$

where 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 decreased by 15% from 1 kHz to 10 kHz and then remained fairly constant for the remainder of the frequency range measured (Fig. 3). The log of the specific capacitance decreased as the log of the frequency increased showing an inverse relationship, with the change less at higher frequencies (Fig. 4). The specific impedance was almost equal to the resistivity at the lower frequencies. However, as shown in Fig. 5 the specific impedance began to deviate from the resistivity, being 5% less at 10 MHz. This is probably due to an increased contribution of the specific capacitance, to be discussed later. This deviation is better illustrated by the frequency

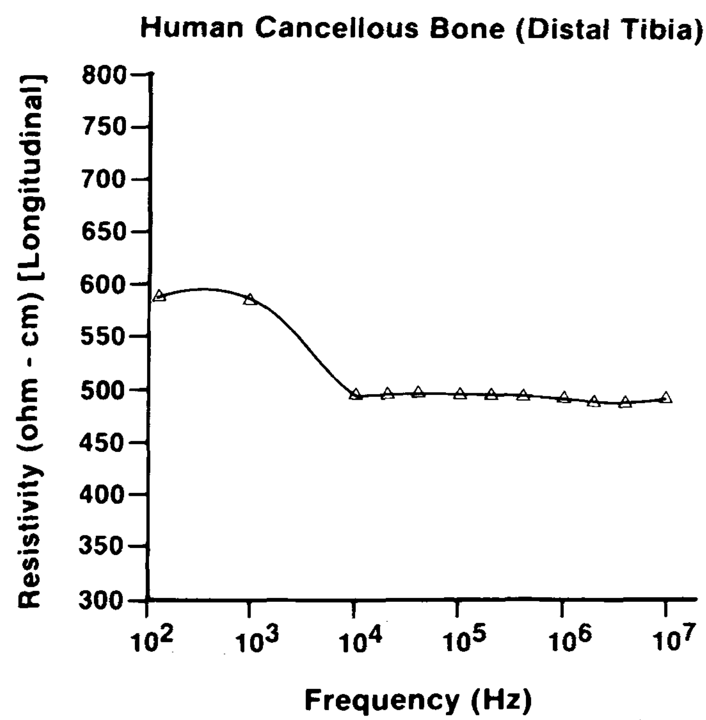

FIGURE 3. Average resistivity for the longitudinal direction as a function of frequency.

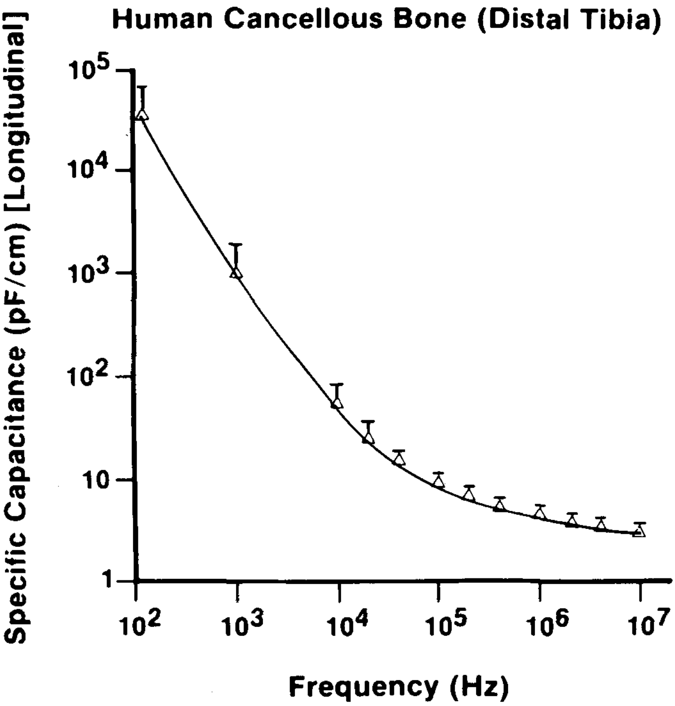

FIGURE 4. Average specific capacitance for the longitudinal direction as a function of frequency.

dependence of the phase angle, as shown in Fig. 6. Even with this slight deviation, the specific impedance changed similarly with frequency, as did the resistivity. The dielectric permittivity shown in Fig. 7 had a relationship to frequency similar to that of the specific capacitance due to its relation to the specific capacitance. Figure 8 shows that the dielectric loss factor had an inverse log-log relationship with the frequency.

Direction Dependence

Table 1 shows the means and the standard deviations for the resistivity and specific capacitance of the cancellous bone specimens measured in the three directions at a frequency of 100 kHz. The specific capacitance was considerably lower in the longitudinal direction, and the resistivity was also somewhat lower in the longitudinal direction compared with the anterior-posterior (AP) or lateral-medial (LM) directions, although properties in the AP and LM directions were similar (Table 1). This shows the transversely isotropic nature of the cancellous bone in the distal tibia. The difference in the capacitance values between the longitudinal and transverse directions were significant ($p < 0.01$) at 100 kHz and 1 MHz but not significant at the lower frequency of 10 kHz.

A highly significant ($p < 0.001$) positive correlation was found between the

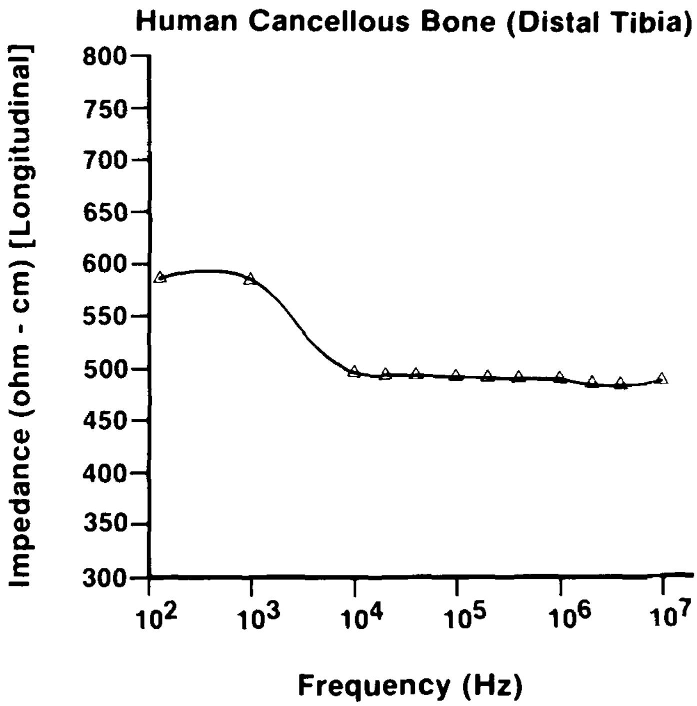

FIGURE 5. Average specific impedance capacitance for the longitudinal direction as a function of frequency.

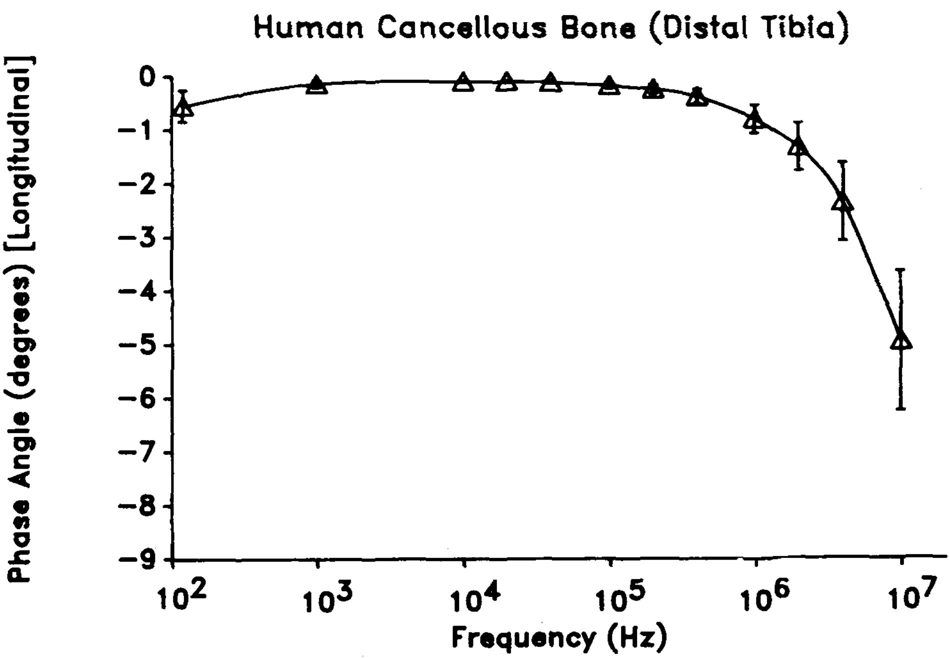

FIGURE 6. Average phase angle for the longitudinal direction as a function of frequency.

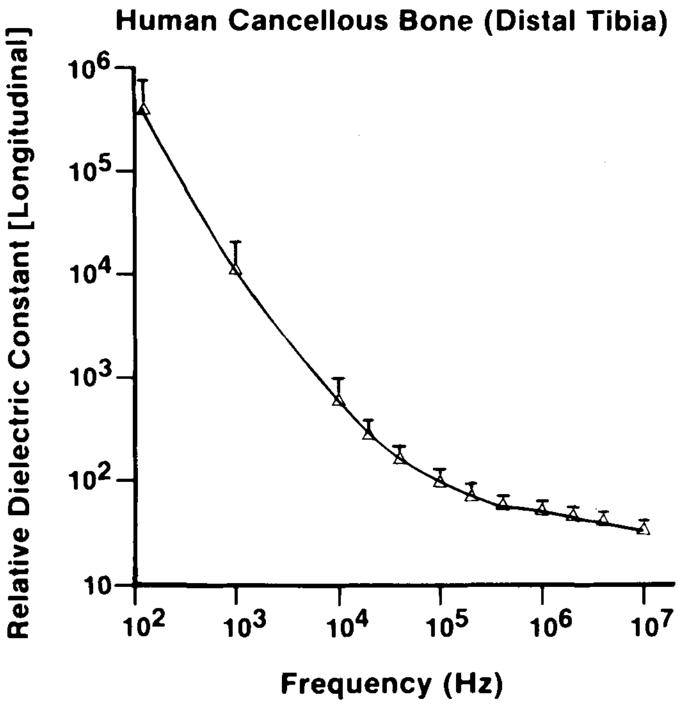

FIGURE 7. Average dielectric permittivity for the longitudinal direction as a function of frequency.

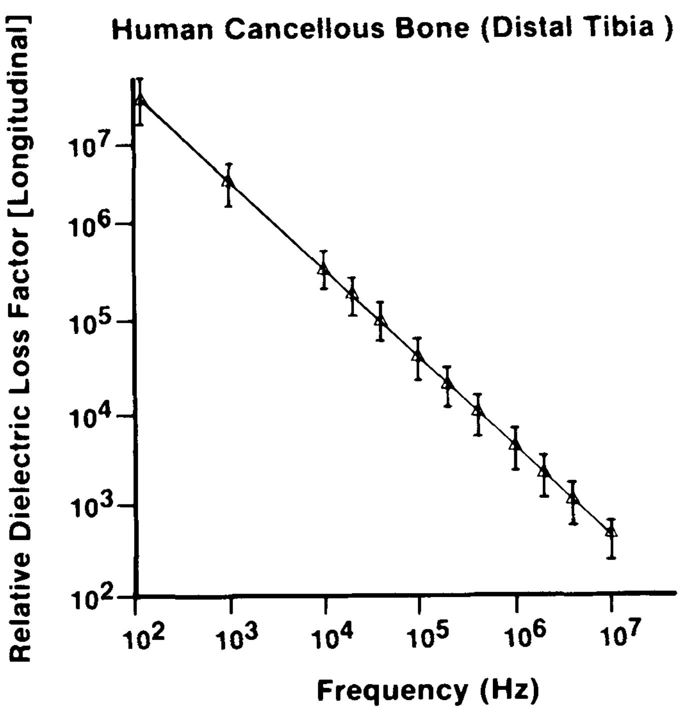

FIGURE 8. Average dielectric loss for the longitudinal direction as a function of frequency.

TABLE 1. Electrical properties (mean + 1 s.d.) of 30 cancellous bone specimens measured at a frequency of 100 khz.

	Direction		
	Longitudinal	Anterior-Posterior	Lateral-Medial
Resistivity (ohm-cm)	500 ± 170	613 ± 221	609 ± 242
Specific capacitance (pF/cm)	8.64 ± 2.53	15.25 ± 3.71	14.64 ± 4.56

resistivities in the longitudinal direction (R_L) and the AP direction (R_{AP}) (Fig. 9). This relationship can be expressed as

$$R_{AP} = -1.70 + 1.23 R_L$$

where both R_{AP} and R_L are expressed in Ohm-cm.

Figure 10 shows the specific impedance for the three directions as a function of the frequency. For the frequency range examined, the specific impedance did not change except for the increasing contribution of the specific capacitance to the impedance at the higher frequencies. This was most evident in the relationship between the phase angle and the frequency (Fig. 11), which makes it clear that the

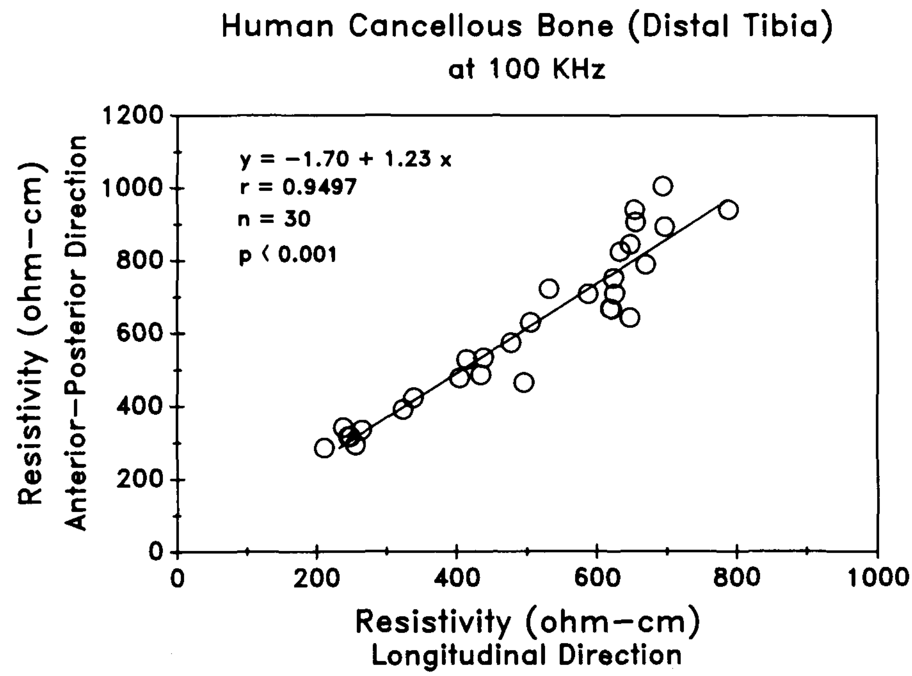

FIGURE 9. Relationships between the resistivities (measured at 100 kHz) in the longitudinal and the anterior-posterior directions of the human cancellous bone samples from distal tibia.

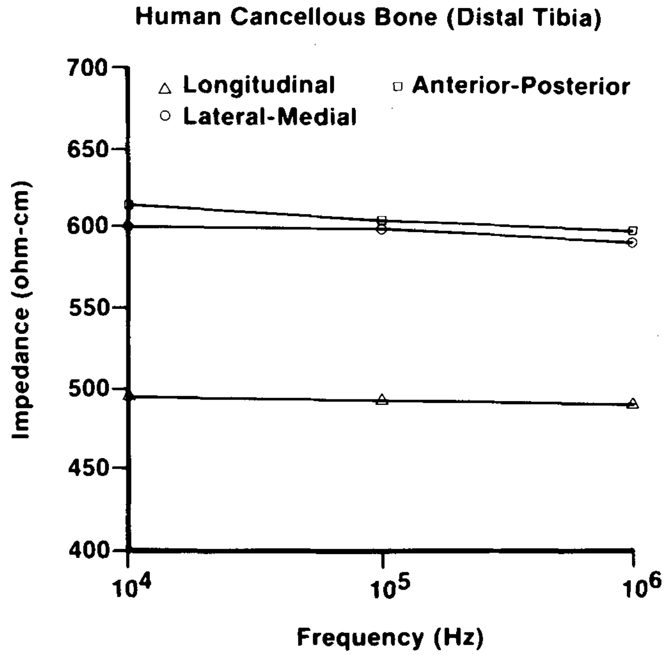

FIGURE 10. The average specific impedance for the longitudinal, lateral-medial, and anterior-posterior directions as a function of frequency for 10K to 1 MHz.

contribution of the specific capacitance at the higher frequencies was greater for the two transverse directions than for the longitudinal direction. This increased difference at higher frequencies can also be verified from the relationship between the relative dielectric constant and frequency, as shown in Fig. 12. At lower frequencies, the difference is less than at higher frequencies. As shown in Fig. 13, the dielectric loss factor in the longitudinal direction was slightly higher than it was in the two transverse directions, showing the transversely isotropic nature of cancellous bone.

It is important to point out that, as shown in Table 1, the values and the electrical properties varied by as much as 30% or more of the mean for the 30 specimens. Although the resistivity varied greatly, the dielectric properties varied much less at higher frequencies than at lower frequencies. Figures 9 through 12 also indicate that although the electrical properties in the longitudinal direction were generally much different from these in the two transverse directions, properties in the two transverse directions were not much different from each other.

Physical Properties

Table 2 shows the mean and standard deviations of the wet, dry, and ash densities for the 30 specimens. The difference between the highest value and the lowest value of the apparent wet density for the 30 specimens was only 0.2971 g/cc, yet the dry density varied by 0.35818 g/cc and the ash density varied by 0.22925 g/cc. The percent ash content of the dry weight was approximately 54.2%, which is in good

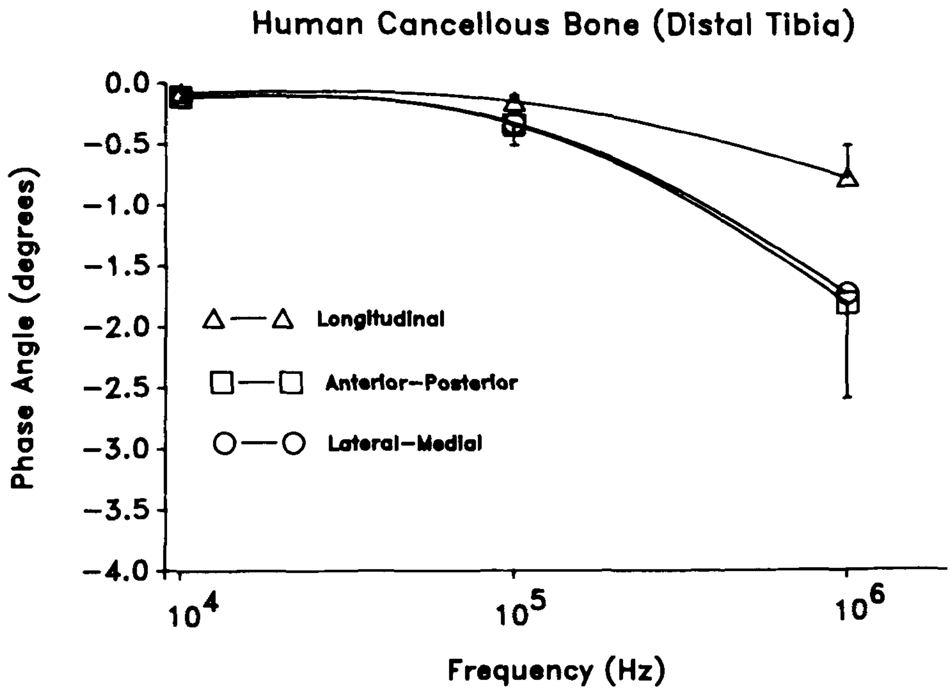

FIGURE 11. The average phase angle for the longitudinal, lateral-medial, and anterior-posterior directions as a function of frequency for 10K to 1 MHz.

agreement with 56.2% obtained by Gong *et al.* (5). The bone material represented 21% to 46% of the tissue by weight.

The specific capacitance showed a highly significant positive ($p < 0.001$) correlation with the wet density (ρ) at 100 kHz and at 1 MHz (Fig. 14). These relationships are given by

$$C_{sp} = -15.97 + 24.2\rho \quad \text{at 100 kHz}$$

and

$$C_{sp} = -6.96 + 11.2\rho \quad \text{at 1 MHz}$$

TABLE 2. Physical properties (mean, standard deviation, and range) of 30 human cancellous bone specimens (n = 10).

	Apparent Density (g/cc)			Ash Content
	Wet	Dry	Ash	(% of dry wt.)
Mean	1.0176	0.3358	0.1840	54.2
S.D.	0.0679	0.0865	0.0546	3.2
Range	0.8793-1.1764	0.1838-0.5420	0.0857-0.3150	46.2-58.3

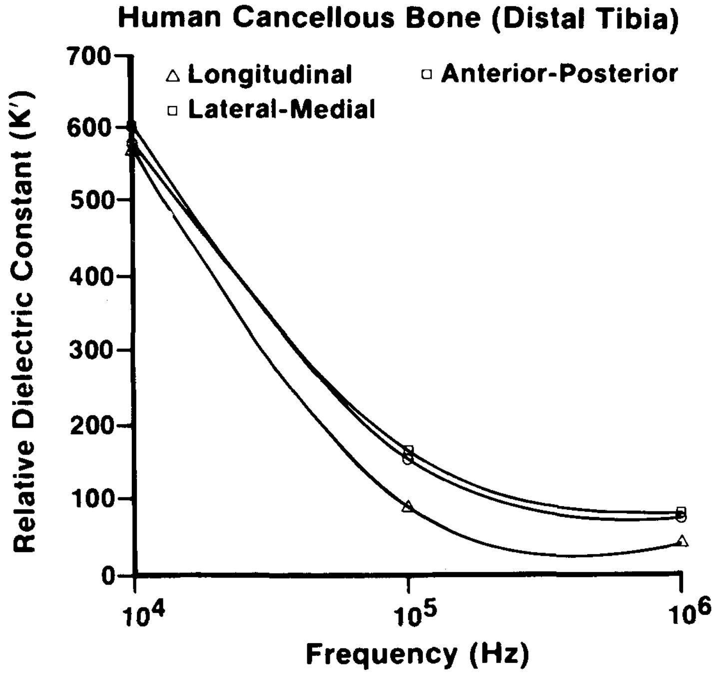

FIGURE 12. The average dielectric permittivity for the longitudinal, lateral-medial, and anterior-posterior directions as a function of frequency for 10K to 1 MHz.

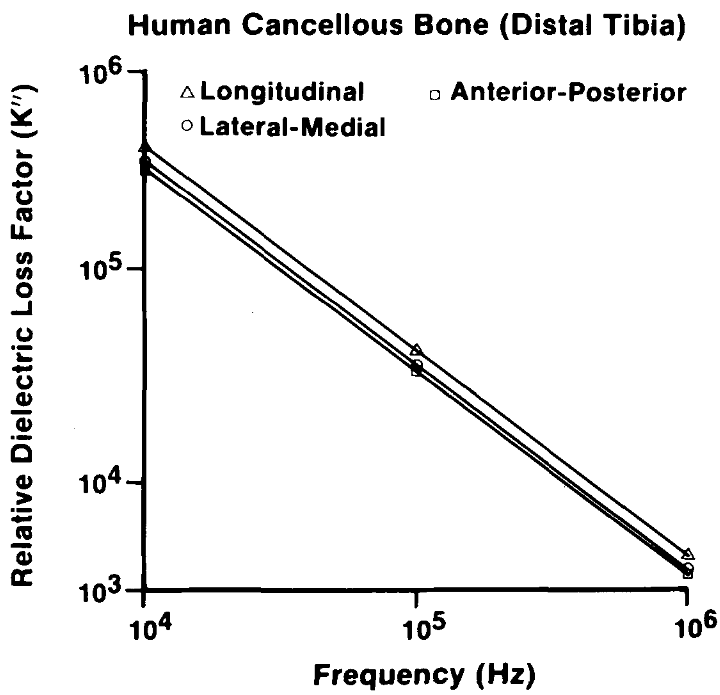

FIGURE 13. The average dielectric loss for the longitudinal, lateral-medial, and anterior-posterior directions as a function of frequency for 10K to 1 MHz.

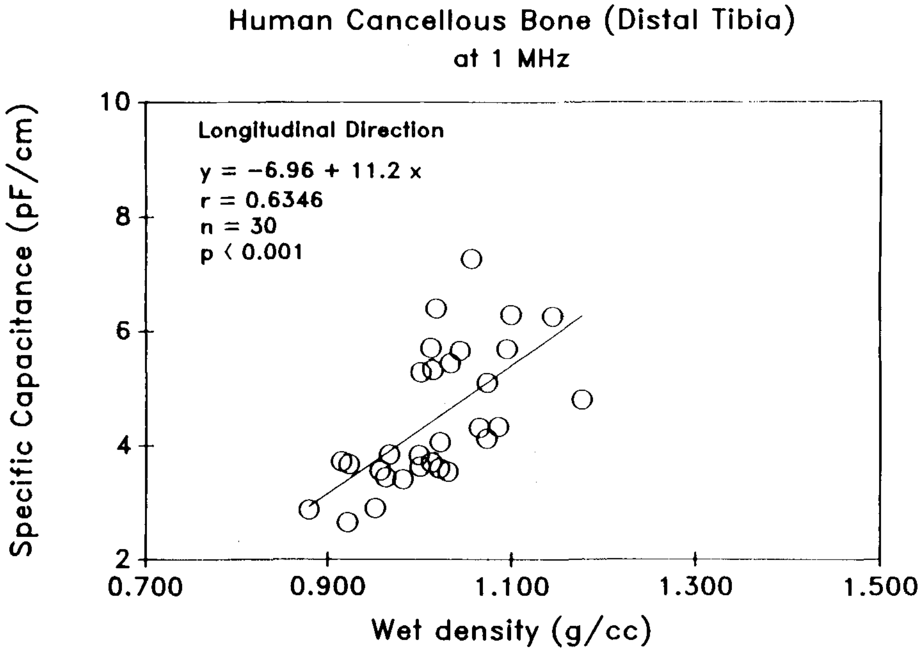

FIGURE 14. Relationship between the specific capacitance in the longitudinal direction at 1 MHz and the wet density of human cancellous bone samples from distal tibia.

where C_{sp} is measured in pF/cm and ρ in g/cc. However, at the low frequency of 10 kHz, although there was a slight increase in capacitance with increasing wet density, this relationship was not statistically significant ($p > 0.1$). Similarly, the resistivity did not show a significant positive correlation with the wet density at 100 kHz. We are continuing our investigation on the relationships between other physical and electrical properties of cancellous bone, and these results will be reported in detail in a future paper.

Comparison with Other Tissues

In Figs. 15 and 16, the conductivity and the dielectric data are compared with data from human ligament (15) and from muscle, spleen, and liver (26). It can be seen from Fig. 15 that both the ligament and the cancellous bone, which are tissues of low cellular content, have a similar relationship with frequency but are different from the other tissues, which are characterized by higher cellular content. Perhaps the relatively low water content of cancellous bone and ligament is the main factor contributing to the differences for the permittivity data as noted by the shift in the values as explained by Pethig (12,13,14). From Eq. 6, it can be shown that $R_{sp} \simeq Z_{sp}$ provided that $(2\pi f R_{sp} C_{sp})^2 \ll 1$. This explains why at the higher frequencies the specific impedance begins to be less than the resistivity. This effect is better illustrated by the phase angle relationship shown in Fig. 6, which is derived from Eq. 7 indicating as $2\pi f R_{sp} C_{sp}$ increases that the phase angle will become more negative. This effect is important because it clearly shows that the electrical behavior is increasingly influenced by capacitance at higher frequencies. Figure 7 illustrates that the cancellous

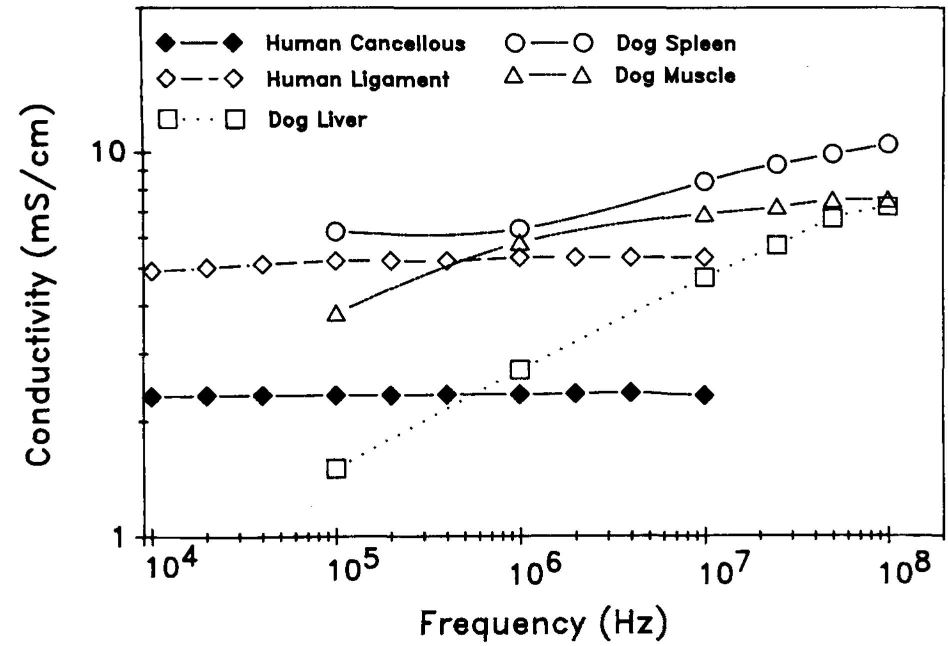

FIGURE 15. The conductivity of human cancellous bone and various soft tissues as a function of frequency. Data for liver, spleen, and muscle taken from Stoy *et al.* (26).

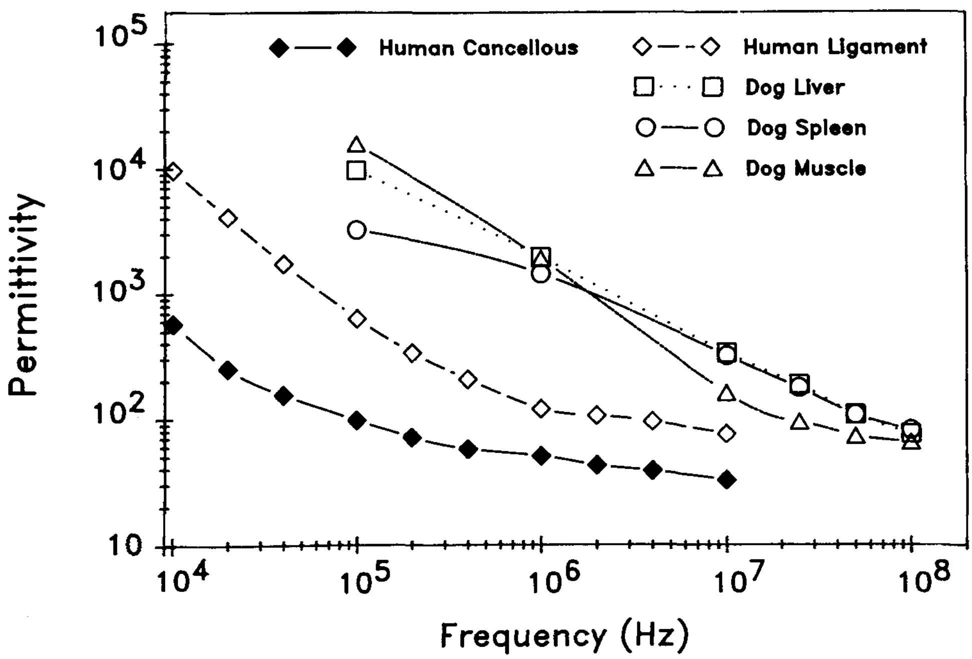

FIGURE 16. The dielectric permittivity of human cancellous bone and various soft tissues as a function of frequency. Data for liver, spleen, and muscle taken from Stoy *et al.* (26).

bone, similar to most other tissues, reaches a value close to a million for the dielectric permittivity as the frequency approaches 100 Hz (22).

The conductivity data in the longitudinal direction for the frequency range 120 Hz to 10 MHz are similar to those of Smith and Foster (25) for bone marrow indicating that the major contribution to the conductivity was probably made by the bone marrow. Yet the permittivity data appear to be different, with the mean and standard deviation values at 10 MHz for the 30 cancellous bone specimens being 33.06 ± 8.82, which is higher than 22.8 ± 8.6 obtained by Smith and Foster (25) using a parallel-plate cell for the measurement.

When we compare the resistivity of human cancellous bone (Fig. 3) with that of bovine compact bone measured in our earlier study (16), we found that the resistivity of cancellous bone was significantly lower (by an order of magnitude or more) than that of compact bone. This is not surprising because cancellous bone has more bone marrow than compact bone. On the other hand, the specific capacitance of the cancellous bone samples was much higher than that of compact bone samples (16,24). Moreover, the electrical properties of compact bone were more direction-dependent (1,16) when compared with the cancellous bone, as shown in Figs. 10 to 13. Thus, while compact bone behaved more as a truly anisotropic material, the human cancellous bone samples showed a transversely isotropic behavior.

DISCUSSION

The bone specimens used in this study were taken from individuals 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 (4,28). However, the gangrene portion was only in the distal feet, and the tibia appeared to be normal. Also, the bone specimens were taken from individuals who were between 50 and 80 and therefore may have had different electrical properties than specimens taken from younger individuals (27).

Due to limitations of our measurement system, the electrical properties at very low frequencies (<120 Hz) were not measured. A separate study should be conducted to characterize the electrical properties at these lower frequencies, which are dominant during locomotion and other physiological activities.

The variations in the electrical properties for longitudinal and transverse directions that we report can perhaps be explained in terms of the orientation of trabeculae in the cancellous bone samples. Relationships between the electrical properties and microstructure for cortical bone have been previously investigated by Kosterich *et al.* (8) and by Chakkalakal and Johnson (2). We are presently examining the microstructure of the tested cancellous bone samples in different directions. In a future communication, we hope to correlate the electrical properties with microstructural variables and other physical characteristics.

REFERENCES

1. Chakkalakal, D.A.; Johnson, M.W.; Harper, R.A.; Katz, J.L. Dielectric properties of fluid-saturated bone. IEEE Trans. Biomed. Eng. 27:95–100; 1980.
2. Chakkalakal, D.A.; Johnson, M.W. Electrical properties of compact bone. Clin. Orthop. Rel. Res. 161:133–145; 1981.

3. Chen, I.I.H.; Saha, S. Analysis of current distribution in bone produced by pulsed electro-magnetic field stimulation of bone. Biomat. Art. Cells Art. Org. 15:737–744; 1987–88.
4. Davies, R.J.; Renah, J.; Kaplan, D.; et al. Epithelial impedance analysis in experimentally induced colon cancer. Biophysical J. 52:783–790; 1987.
5. Gong, J.K.; Arnold, J.S.; Cohn, S.H. Composition of trabecular and cortical bone. Anatomical Record. 149:325–332; 1964.
6. Hancox, N.M. Biology of Bone. London: Cambridge University; 1972.
7. Kosterich, J.D.; Foster, K.R.; Pollack, S.R. Dielectric permittivity and electrical conductivity of fluid saturated bone. IEEE Trans. Biomed. Eng. 30:81–86; 1983.
8. Kosterich, J.D.; Foster, K.R.; Pollack, S.R. Dielectric properties of fluid-saturated bone—the effect of variation in conductivity of immersion fluid. IEEE Trans. Biomed. Eng. 31:369–373; 1984.
9. Lakes, R.S.; Harper, R.A.; Katz, J.L. Dielectric relaxation in cortical bone. J. Appl. Physics 48:808–811; 1977.
10. Liboff, A.R.; Rinaldi, R.A.; Lavine, L.S.; Shamos, M.H. On electrical conduction in living bone. Clin. Orthop. 106:330–335; 1975.
11. Martin, R.B. Comparison of capacitive and inductive bone stimulation devices. Ann. Biomed. Eng. 7:387–409; 1979.
12. Pethig, R. Dielectric properties of body tissues. Clin. Phys. Physiol. Meas. 8:5–12; 1987.
13. Pethig, R. Dielectric and Electronic Properties of Biological Materials. New York: John Wiley and Sons; 1979.
14. Pethig, R.; Kell, D.B. The passive electrical properties of biological systems: their significance in physiology, biophysics, and biotechnology (review article). Phys. Med. Biol. 32:933–970; 1987.
15. Rai, D.V.; Saha, S.; Williams, P.A.; Saha, K. Electrical properties of ligaments. Digest of Papers, 6th Southern Biomed. Eng. Conf.: pp. 150–151; 1987.
16. Reddy, G.N.; Saha, S. Electrical and dielectric properties of wet bone as a function of frequency. IEEE Trans. Biomed. Eng. 31:296–302; 1984.
17. Saha, S.; Reddy, G.N.; Albright, J.A. Factors affecting the measurement of bone impedance. Med. Biol. Eng. and Comp. 22:123–129; 1984.
18. Saha, S.; Williams, P.A. Electrical properties of cancellous bone. Fed. Proc. 45:172; 1986.
19. Saha, S.; Williams, P.A. Electrical properties of human cancellous bone from distal femur. Trans. 12th Ann. Meet. Soc. Biomat. 9:80; 1986.
20. Saha, S.; Williams, P.A. Electrical and dielectric properties of wet human cancellous bone as a function of frequency. In: Saha, S., ed. Biomedical Engineering V: Recent Developments. New York: Pergamon Press; 1986: pp. 217–220.
21. Saha, S.; Williams, P.A. Effect of various storage methods on the dielectric properties of compact bone. Med. and Biol. Eng. and Comput. 26:199–202; 1988.
22. Schwan, H.P. Dielectric Properties of Cells and Tissues. In: Chiabrera, A.; Nicolini, C.; Schwan, H.P., eds. Interactions Between Electromagnetic Fields and Cells. New York: Plenum Press; 1985.
23. Singh, S.; Behari, J. Frequency dependence of electrical properties of human bone. J. Bioelectricity 3:347–356; 1984.
24. Singh, S.; Saha, S. Electrical properties of bone: a review. Clin. Orthop. Rel. Res. 186:249–271; 1984.
25. Smith, S.R.; Foster, K.R. Dielectric properties of low-water-content tissues. Phys. Med. Biol. 30: 965–973; 1985.
26. Stoy, R.D.; Foster, K.R.; Schwan, H.P. Dielectric properties of mammalian tissues from 0.1 to 100 MHz: a summary of recent data. Phys. Med. Biol. 27:501–513; 1985.
27. Swanson, G.T.; Lafferty, J.F. Electrical properties of bone as a function of age, immobilization, and vibration. J. Biomech. 5:261–266; 1972.
28. Yamamoto, Y.; Yamamoto, T.; Ohta, S.; et al. The measurement principle for evaluating the performance of drugs and cosmetics by skin impedance. Med. and Biol. Eng. and Comp. 16:623–632; 1978.