Electrical Properties of Bone

A Review

S. SINGH, PH.D.,* AND S. SAHA, PH.D.**

A review of the available data on the electrical properties (resistance, capacitance, dielectric constant, dielectric loss factor, and dissipation factor, etc.) of whole as well as standardized bone specimens suggest that impedance was lowest in the longitudinal direction and highest in the radial direction. This is further evidence of the anisotropic nature of bone. The electrical properties of fully hydrated bone were significantly different from those of dry and partially wet bone and these properties were highly frequency-dependent. Other variables that influence the electrical properties, such as moisture content, principles and methods of measurement, temperature, and pH and conductivity of the immersing fluid, etc., have also been reviewed. Delineation of these variables is important in reporting test results on the electrical properties of bone; only then can the data on different electrical properties of bone reported by various authors be compared. Future research is needed to characterize the effect of age, microstructure, mineral content, and various disease processes on the electrical properties of bone. Such information may lead to new insight on the role of electrical properties on bone remodeling. An understanding of the electrical behavior of bone is also important for the design of electrical stimulation devices and their proper use for maximum osteogenic effect.

In recent years, electrical stimulation has been used successfully in the treatment of nonunions and congenital pseudarthrosis.[10,12–15,21–25,79,80] These clinical applications were prompted by the observed strain-related potentials (SRP) in bone[9,44,103,104] and subsequent tests on animals, which showed that the application of external current in the marrow cavity of long bone produced bone around the cathode.[15,25,40,110] Although these animal experiments formed the basis of the clinical use of electrical stimulation, the exact mechanism of the bioelectricity in producing this osteogenesis is still unknown.[21,24,40,115] An analysis of the direct and induced current flow and its associated electric field distribution in bone requires accurate information on bone's electrical properties.[23,28,81] As electromagnetic pulse stimulation contains a spectrum of wide frequency range,[13,52,90] the data on the variation of different electrical properties with frequency are also necessary for optimizing the pulse parameters.

Several authors have measured the impedance of bone *in vivo*.[17,67,98,111] The living bone tissue is an inhomogeneous composite material with fluid-filled pores and is anisotropic in its structure.[28,29,62,86,108] Uncertainties exist, therefore, about the current paths between a pair of electrodes placed in such a material and about the nature of the tissue–electrode interface. This makes it difficult to determine the resistivity of the tissue from such *in vivo* resistance measurements.[28,98] This has prompted other investigators to resort to *in vitro* measurement methods on standardized bone samples.

Measurements have been made to examine the electrical and the dielectric properties on

From the Biomechanic Laboratory, Department of Orthopaedic Surgery, Louisiana State University Medical Center, Shreveport, Louisiana.

* Research Associate. On leave from U.P. College, Varanasi 221002, India.

** Associate Professor.

Reprint requests to S. Saha, Ph.D., Department of Orthopaedic Surgery, L.S.U. Medical Center, P.O. Box 33932, Shreveport, Louisiana 71130.

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vacuum-dried, air-dried,[16,39,70,102,105,113] fluid-saturated, wet,[29,86] fresh, or fixed[62,63] bone samples. Similar measurements have also been conducted to study the variation of these properties as a function of temperature,[39,70,72,91-93,105] relative humidity,[64,72,88,92] and frequency.[39,62,72,86,87,93] Authors have also reported the effect of conductivity, pH, and salt concentration of the bathing medium (occupying the pores in bone) on its electrical and dielectric properties.[2,28,62,63,88,89] Some authors have also compared the electrical properties of normal bone samples with those of bone affected by aging, pathologic conditions, and artificially-induced conditions such as demineralization.[5,57,71,75,76,113]

Observations on electrical properties of bone at different frequencies show that the electrical conductivity remains nearly independent of the frequency below 100 KHz, and beyond this it increases with the frequency. The dielectric properties of bone also depend on the frequency and, generally, they decrease with an increase in frequency.[62,72,86,87,93] Frequency, therefore, is an important parameter in electrical characterization of wet bone. Similarly, the electrode polarization and measurement techniques may introduce errors in electrical measurements.[29,30,62,85,88,91,99,106,107] The role of these factors must be considered in light of their importance in electrical characterization of bone.

As mentioned before, many authors have studied the electrical properties of bone. A comprehensive review elucidating the various factors that may affect the electrical properties of bone, however, has not been published. In this review, the authors have attempted to summarize the published data on electrical properties of bone. They have categorized it in terms of source and physical state of the sample (wet, fluid-saturated, fresh, fixed, stored, air-dried or vacuum-dried), frequency, temperature, relative humidity at the time of measurement, and principles and techniques used in measurement. Factors affecting the electrical and the dielectric properties, such as the time of exposure, *in vivo* environment, normalization of data, electrode polarization, and errors due to wiring capacitance, are reviewed. The relation between the bone structure and its electrical properties is also discussed.

The authors' objectives in the current study are to: (1) summarize the published data on the electrical properties of bone, (2) identify the measurement, environmental and biologic factors that affect the measured values of the electrical properties, and (3) point out the clinical relevance of the information on the electrical properties of bone.

A review of the most relevant studies on the electrical properties of bone allows a view of the gaps in the authors' present knowledge and the authors therefore suggest a number of areas for future research.

ELECTRICAL AND DIELECTRIC PROPERTIES

Electrical properties of bone have been a subject of considerable interest since the discovery of its electromechanical effects in 1957 by Fukada and Yasuda.[44] The electrical properties that have been investigated in detail in the recent years include DC or AC conductivity, specific resistance, specific impedance, dielectric constant, loss-factor and loss-tangent (dissipation factor) over a frequency range of 0.1 Hz to 100 MHz (100,000,000 Hz). The electrical properties of bone may be characterized either in terms of an equivalent parallel combination of resistance and capacitance or a series combination of resistance and capacitance. Most researchers have described the electrical behavior of bone in terms of an equivalent parallel combination of resistance and capacitance. The electrical terms to be used in this paper are defined in the following section.

DEFINITIONS AND TERMINOLOGY

Tables 1 and 2 summarize the symbols and corresponding definitions of the electrical terms used in this review. From Table 2, Ad-

TABLE 1. Definitions of Electrical Terms

Terms	*Definition of Terms*
Capacitor	A system of electrical conductor and insulator that is able to store electrical energy.
Dielectric	A substance in which an electric field gives rise to no net flow of electric charge but only to a displacement of charge. In practice, a dielectric is considered a material having low electrical conductivity in comparison to that of a metal.
Dispersion	The dependence of the electric and dielectric properties on frequency.
Ohmic contact	Conditions in which the net flow of current due to electrode polarization is zero.
Relaxation effect	The time delay due to noninstantaneous changes between stimulus (potential) and its response (current) and its relation to dispersion.
Relaxation time (τ)	The time needed for a change to attain a fraction 1/e of its final value (e = 2.718).
Step function	The waveform (voltage or current) that changes abruptly from one level to another.

mittance (Y, mho) for an equivalent parallel circuit,

$$Y = G + j\omega C \qquad \text{Equation 1.}$$

where $j = \sqrt{-1}$.

The following relationships apply for a prismatic specimen of thickness 'd' (distance between the electrodes), and area 'A',

$$C = \epsilon A/d \qquad \text{Equation 2.}$$

$$G = \sigma A/d \qquad \text{Equation 3.}$$

Bone is a dispersive and viscous material. The electrical properties of bone under alternating current conditions, therefore, are related to the relaxation phenomena.[99] There always exists an exponential time lag (τ) between a step function stimulus and the response produced by it. For such a medium, the ratio of the response to the stimulus is expressed as,[99]

$$Z = a + \frac{b}{1 + j\omega T} \qquad \text{Equation 4.}$$

and this ratio depends upon the frequency. For example, the stimulus may be a potential, and its response is the current or charge accumulation evoked by the potential. In this case, the ratio of the response to the stimulus is expressed in terms of the admittance or the complex dielectric constant respectively.[99]

The complex dielectric constant ϵ^* is represented as[32,81]

$$\epsilon^* = \epsilon' - j\epsilon'' \qquad \text{Equation 5.}$$

where ϵ' = dielectric constant, and ϵ'' = loss factor.

The relative complex dielectric constant is then given by:

$$k^* = \epsilon^*/\epsilon_0$$

$$= \epsilon'/\epsilon_0 - j\epsilon''/\epsilon_0 = k' - jk'' \qquad \text{Equation 6.}$$

where k^* = relative complex dielectric constant, k' = relative dielectric constant, k'' = relative loss-factor, and ϵ_0 = dielectric constant of free space.

The values of k^*, k', and k'' are related to σ and ϵ' as below[32,81]

$$k^* = (\epsilon'/\epsilon_0 - j\sigma/\omega\epsilon_0) \qquad \text{Equation 7.}$$

$$k' = \epsilon'/\epsilon_0 \qquad \text{Equation 8.}$$

$$k'' = (\sigma/\omega\epsilon_0) \qquad \text{Equation 9.}$$

The dissipation factor is given by

$$D = \tan\delta = \frac{k''}{k'} = (\sigma/\omega\epsilon') \qquad \text{Equation 10.}$$

Equations 8, 9, and 10 show that the dielectric properties are related to the specific resistance (resistivity) and the dielectric con-

TABLE 2. Units and Symbols for Electrical Terms

Term (symbol)	*Unit (symbol)*	*Comments*
Angular frequency (ω)		$\omega = 2\pi f$
Admittance ($Y = 1/Z$)	mho or siemens (S)	For an equivalent parallel circuit, $Y = G + j\omega C$
Capacitance (C)	farad (F)	The principal characteristic of a capacitor to store electrical energy.
Complex dielectric constant (ϵ^*)		$\epsilon^* = \epsilon' - j\epsilon''$
Conductance (G)	mho or siemens (S)	The ability to allow the flow of an electric current. It is the reciprocal of the resistance.
Conductivity (σ)	mho/cm or siemens/cm (S/cm)	The conductance of a centimeter cube of a material and the reciprocal of the resistivity.
Dielectric constant (ϵ')		The dielectric constant is the ratio of the strength of an electric field in a vacuum to that in the dielectric for the same charge distribution. It may also be defined and measured as the ratio of the capacitance 'C' of an electric condenser filled with the dielectric to the capacitance 'C_0' of the evacuated condenser.
Dielectric constant of free space (ϵ_0)		$\epsilon_0 = 8.85 \times 10^{-12}$ F/cm
Dissipation factor (D) or loss tangent ($\tan \delta$)		This is defined as the ratio of the loss factor to the dielectric constant ($\tan \delta = \epsilon''/\epsilon'$)
Frequency (f)	hertz (Hz)	Number of cycles in one second 1 kHz = 1,000 Hz 1 MHz = 1,000,000 Hz 1 GHz = 1,000 MHz
Impedance (Z)	ohm (Ω)	It is defined as the ratio of the alternating voltage to the alternating current ($Z = v/i$). It is analogous to the resistance for direct current. For an equivalent series circuit, $Z = R + jX$
Loss-factor (ϵ'')		It is the ratio of the conductivity to the angular frequency and is related to the loss-current (conduction) component.
Relative complex dielectric constant (k^*)		The ratio of the complex dielectric constant to the dielectric constant of vacuum ($k^* = \epsilon^*/\epsilon_0$). It is expressed as $k^* = k' - jk''$.
Relative dielectric constant (k')		The ratio of the dielectric constant of a substance to the dielectric constant of vacuum ($k' = \epsilon'/\epsilon_0$). It is related to the charging and discharging of the capacitor.
Relative loss-factor (k'')		The ratio of the loss-factor to the dielectric constant of vacuum ($k'' = \epsilon''/\epsilon_0$).
Resistance (R)	ohm (Ω)	The ability of a material to resist the flow of electric current. It is usually determined by the ratio of the voltage to the current ($R = V/I$).
Specific impedance (Z_{sp})	ohm–cm (Ω–cm)	Impedance of a centimeter cube of material. It is expressed as $$Z_{sp} = \frac{\rho X_{sp}}{(\rho^2 + X_{sp}^2)^{1/2}}$$
Resistivity (ρ) or specific resistance (R_{sp})	ohm-cm (Ω-cm)	Resistance of a centimeter cube of a material.

stant. From the values of the resistivity and the dielectric constant at a particular frequency, the values of the dielectric constant and the loss-factor can be calculated.

Summary of Reported Data

Osswald[77] was perhaps the first investigator to measure the electrical properties (resistivity) of bone as mentioned by Geddes and Baker.[46] Since then several authors have investigated the electrical properties of whole bone, and their results are summarized in Table 3.[17,34,67,97,98,108] Liboff *et al.*[67] studied the electrical conduction in rabbit femur and human tibia for *in vivo* bone. They reported a resistance value of 2–5 × 10^5 ohm/cm (200,000–500,000 ohm/cm) for rabbit femur and 0.7–1 × 10^5 ohm/cm (70,000–100,000 ohm/cm) for human tibia. Behari and Singh[17] also reported data on the electrical impedance to be approximately 8 k-ohm/cm for intact *in vivo* rabbit femur.

Durand *et al.*[34] examined the electrical impedance characteristics of whole bones *in vitro* by using a four-point measurement technique.[98] They (Durand *et al.*) measured a resistance of 2–3 kilo-ohm per unit length (cm) of whole bone and also observed a linear variation of the interelectrode distance. Recently, this was verified by Saha *et al.*,[97] who used a similar measurement technique. In agreement with the results of Durand *et al.*, Saha *et al.* also found that the resistivity of the bone cortex was several times higher than that of the marrow. The previously mentioned studies[17,34,67,97,98] were mainly conducted on whole bones, and they do not provide information about the specific resistance and the specific capacitance of bone as a material. In a recent study on bovine long bone, Singh *et al.*[108] found the impedance in the circumferential direction to be much higher (<100%) than that in the longitudinal direction, indicating the highly anisotropic character of bone.

Several investigators have studied the electrical properties of bone tissue, and these (specific resistance, specific capacitance, specific impedance, dielectric constant, loss-factor, and dissipation-factor) are summarized in Tables 4 and 5. Unlike Table 3, which contains data on electrical impedance for whole bone, Tables 4 and 5 show the electric and dielectric properties of standardized bone samples respectively. From these tables, it is clear that most data on electrical characteristics of bone have been reported in terms of capacitance and resistance. These data are dependent on both the material characteristics and the geometry of the bone specimen. In order to take into account the different geometries of the specimens, it is essential to normalize the resistance and the capacitance components to obtain the specific resistance and the specific capacitance, since these represent the resistance and the capacitance of bone as a material.[32,81,88]

FACTORS AFFECTING ELECTRICAL MEASUREMENTS

Measurement Factors

Principles and techniques of measurement. The electrical properties of a bone specimen are usually measured by introducing it into a sample cell or other container that forms part of an electrical circuit. This circuit is subjected to an external electric field in the form of DC or AC, or to a sudden voltage step function. Broadly speaking, the measurement techniques fall into distinct groups, according to the frequency range and specimen hydration state (*in vitro* or *in vivo*). Measurements based on step-function method will be considered first.

The use of a step-function method, involving the measurement of charging and discharging currents for the determination of the dielectric properties, dates back to the early part of this century.[53] This method yields results for $\epsilon^*(\omega)$ at a very low frequency (<1.0 Hz). In this method, however, the measurement of the charging current demands a voltmeter of very high input impedance and quick response time in the external circuits.[32] It also requires ohmic contacts between a bone sample and an electrode to avoid conduction current.[32] In practice, contacts are not usually ohmic, and this may result in significant errors in the measurement of the electrical properties.[99,101,106,107] Recently, this method was used by Chakkalakal *et al.*[29] and Lakes *et al.*[64] to determine the dielectric properties of bone.

Alternating-current measurement is generally used for frequencies below ten megahertz. The frequency between .01 Hz and ten megahertz is the most convenient frequency range where the bridge method may be used. For all frequencies higher than a few megahertz and up to one gigahertz, resonant circuits are commonly used. In this case, the specimen is combined with a known inductance.[32]

The electrical properties of bone have been studied primarily below 100 KHz except by a few workers in recent years.[62,86] One of the reasons for not studying the electrical properties of bone at higher frequencies is probably the nonavailability of a suitable apparatus. In most studies, an electrometer or ohmmeter was used for measuring the electrical impedance of bone specimens. Results did not contain any data on the phase angle and, therefore, could not be used to resolve the resistive and capacitive components of the electrical impedance.[17,34,67,94,97,98] Recently, however, techniques and apparatus suitable for high-frequency measurements have been used. Reddy and Saha[85] developed a differential technique to measure the electric and dielectric properties of the wet bone over a frequency range of DC to one megahertz. In another investigation of the high-frequency measurements of the electric and dielectric properties of bone, Kosterich *et al.*[62] used an impedance analyzer and a vector impedance meter to study the electrical properties in the frequency range of 10 Hz–100 MHz. The problem of electrode polarization, however, was still continuously a point of concern to these investigators.[62,86] A detailed description of the sample cell and electrode polarization is given in the next section.

Sample cell and electrode polarization. One of the major sources of error in the measurement of the electrical properties of bone is caused by the polarization that arises at the boundary between electrodes and the bone sample. Electrode polarization is particularly disturbing when measurements are carried out on bone samples with high conductivity at low frequencies, which are of predominant interest in physiological research.[99–101]

Selection of the proper electrode to minimize the electrode polarization is important for an accurate measurement of the electrical properties of all biologic tissues.[45,99] For examining the electrical behavior of bone, different investigators have used various electrodes, *e.g.*, platinum,[62,67,91,94] stainless steel,[17,98,108] Ag–AgCl wick,[29] silver enamel coating and chlorided silver wire,[34,97] conducting epoxy paste,[39] conducting silver paint,[16,105] and chlorided metal electrodes.[85,86] The use of a conducting silver paint was found to be suitable for dry bone; however, for partially hydrated wet bone, it may result in some electrode polarization.[106,107] Use of stainless-steel electrodes in alternating current measurements may result in larger electrode polarization, as suggested by Schwan.[100]

Recently, several investigators have used different sample cells to suit their individual experimental needs and thereby were able to reduce the electrode polarization effect.[29,62] Chakkalakal *et al.*[29] maintained the bone sample under fluid-saturated conditions during the measurement of its electrical properties. Electrical contact with the specimen was made through the fluid in which the specimen was soaked, and this fluid was in contact with the Ag–AgCl electrodes, which in turn were connected to the outside circuitry. The electrodes were in external mode.[99] Chakkalakal *et al.*[29] observed large variations in the electrode impedance with time and found it to be often a source of major error, especially for increasing conductance of the specimen. Other factors that may cause significant variations in the measured data are current density and thickness of the sample.[99] Chakkalakal *et al.*[29] used current density of 242 mA/cm^2, which is many times larger than the value suggested by Schwan[99] for the platinum (black) electrode to be within the linear limit at a frequency of one kilohertz. In another study, Kosterich *et al.*[62] used a new type of sample cell wherein the platinum electrodes were used in the internal–external mode.[99] A cylindrical, platinum tube served as one electrode, and a platinum wire, placed centrally, was the inner electrode (Fig. 1). Each electrode was covered with a layer of electrolytically deposited platinum black to reduce the electrode polarization impedance. These authors[62] found that the permittivity measurements at low frequencies were chiefly limited by this polarization impedance. The reactive part clearly dominated the measurement below 100 Hz. These authors[62] also found that the electrode polarization impedance depended on the current density through the electrode surface. Similarly, many others have also expressed serious concern about errors in electrical measurements due to the sample cell and the electrode polarization.[45,47,91,97,98] The sample cell and the choice of electrode metal is governed by many factors, namely, frequency range, thickness and geometry of the specimen, current density at the cross-sectional area of the electrode, and its chloriding or platinization process.[99] Some authors[51,61,99] reported that Ag–AgCl wick and platinum black electrodes have aging effects. A single electrode, therefore, should not be used for a very long period so that the error due to the aging effect can be avoided. As pointed out by Schwan,[99] the authors also observed that the electrode polarization was a dominant factor influencing the measurements of electrical properties below a frequency of ten kilohertz, while stray-fields components were a major source of error in the higher frequency range (>1.0 kHz).[106,107]

Preparation and preservation of sample. For measuring the electrical properties of bone as a material, standardized bone specimens are

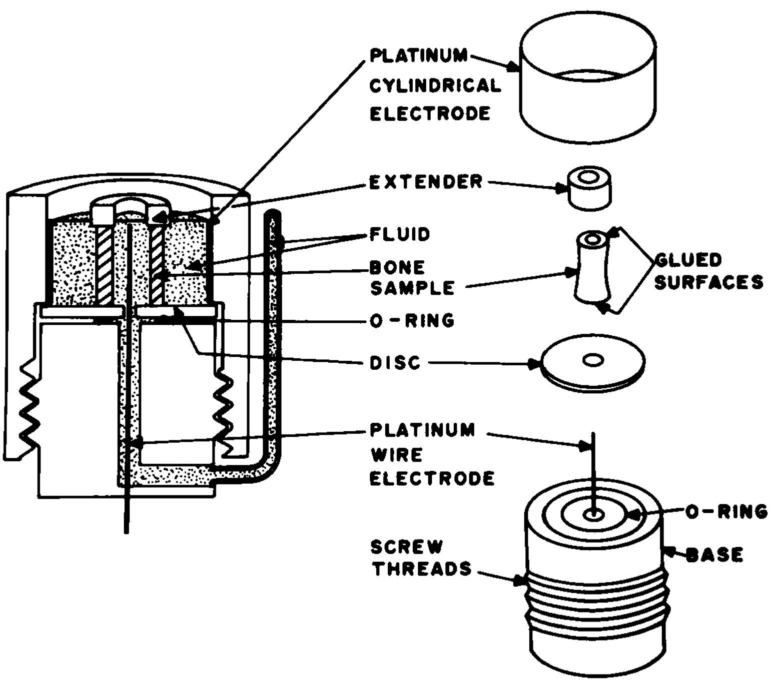

FIG. 1. Schematic diagram of sample cell. (Left) Cross-sectional view of sample cell with bone sample and fluid in place and (right) expanded view of the sample cell and bone specimen. (From Kosterich *et al.*,[62] with permission, © 1983 IEEE)

generally machined from whole bones. During this process, if a high-speed saw is used, the temperature may rise considerably and may damage the organic phase of bone. Such a process, therefore, may change the electrical properties of the sample. The machining may also produce bone debris, which may clog the haversian canals and other pores in the bone structure and thus may reduce the conductivity of a wet bone specimen.

Storage of the bone specimens in open air will reduce the moisture content and thus will change the impedance.[88,89] There are three common methods to preserve the bone specimens: (1) fixation in formalin; (2) fixation in alcohol; and (3) freezing. Previous investigations (Kosterich *et al.*[62]) have shown that fixation in formalin significantly affects the electrical properties (Fig. 2). Fresh bone specimens, when not being used for electrical measurements, can be stored in closed containers soaked in Hank's balanced salt solution (HBSS) or in Ringer's solution with some

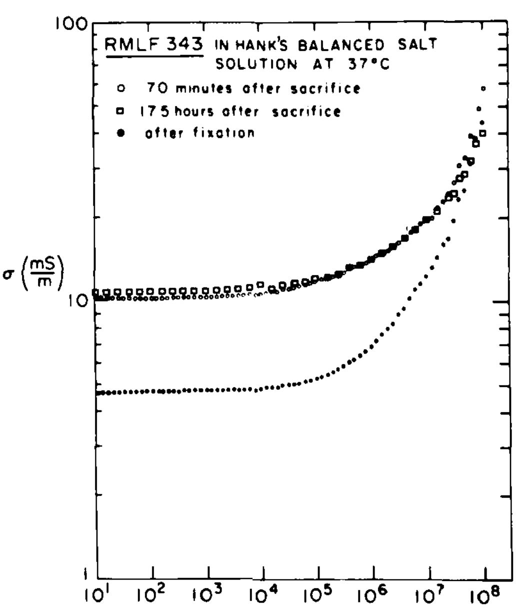

FIG. 2. Electrical conductivity *versus* frequency of a freshly excised sample of bone and the same sample after formalin fixation. (From Kosterich *et al.*,[62] with permission, © 1983 IEEE)

added bacteriostatic agent. The authors' own experience, during the measurement of electrical properties of wet bone, showed that the data were repeatable for several weeks with this method of preservation.[86] Steinberg *et al.*,[112] however, have suggested that the peak voltage of strain-related potential dropped markedly after only a few days of preservation. As an added precaution in experiments with bone specimens, therefore, the samples should be machined as soon as possible after obtaining the fresh limbs, and the electrical and dielectric properties should be measured within a few days of making the samples. To preserve the *in vivo* condition, the bone specimens should always be maintained fully wet, and they should never be allowed to dry. This precaution is necessary in view of the observations made by Chakkalakal *et al.*,[29] Reddy and Saha,[88,89] and Kosterich *et al.*,[62] which state that if bone samples are allowed to dry and then equilibrated at 98% relative humidity, only the outer layer of the bone specimen becomes fluid-saturated and the inner pores may still remain dry.

Normalization of data (sample size). The electrical properties of bone as a material should be described in terms of the normalized data (properties of a centimeter cube of bone) so that the properties are independent of the specimen's geometry. The discrepancies in the reported values of bone impedance are largely due to the normalization procedures adopted for different-sized bone specimens. For a bone sample of cross-sectional area 'A', thickness 'd' (distance between the electrodes), measured resistance R, and capacitance C, the normalized electrical properties are given as [88,89]

$$\sigma = RA/d \qquad \text{Equation 11.}$$

$$\epsilon = Cd/A \qquad \text{Equation 12.}$$

$$X_{sp} = 1/(2\pi fC) \qquad \text{Equation 13.}$$

$$Z_{sp} = X_{sp}/(\rho^2 + X_{sp}^2)^{1/2} \qquad \text{Equation 14.}$$

$$\theta_{sp} = \tan^{-1}(-\rho/X_{sp}) \qquad \text{Equation 15.}$$

If the calculation of the impedance is based on normalization of only resistance (R only) or only capacitance (C only) components, instead of being based on equation 14, errors may be introduced in the reported values.[88,89]

Figure 3 illustrates the errors that may be introduced if the impedance of bone is not based on the normalized values of both R and C. This suggests that when computing the specific impedance of a bone sample, both its resistive and capacitive components should be resolved separately by measuring its phase angle. From the known geometry of the sample, both R and C should then be normalized and its specific impedance and phase angle be computed using equations 14 and 15.

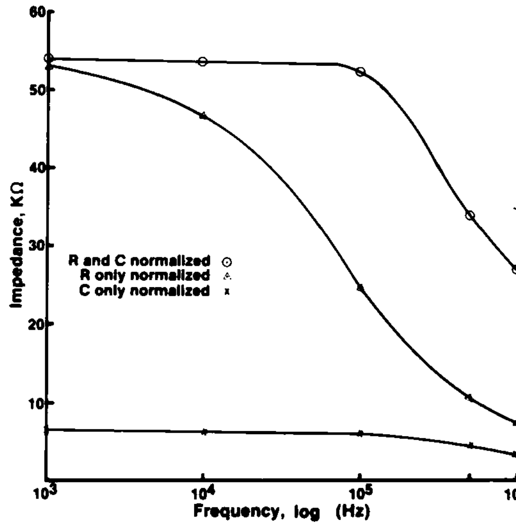

FIG. 3. Effect of the various normalization procedures on computed values of the electrical properties of bone. (From Reddy and Saha,[88] with permission)

ENVIRONMENTAL FACTORS

Effect of moisture content/relative humidity. The dielectric properties of biologic macromolecules have been the subject of experimental and theoretic investigations for some time.[23,26,81] One undisputed fact to emerge from these studies is that the measured values of electrical properties are greatly affected by the presence of water. These data suggest that the dielectric behavior is intimately related to the rotational mobility of the water molecules. Early investigations on the electrical properties of bone were carried out mostly on dry or hydrated specimens because of the difficulties in experimental procedures for fully wet bone.[39,64,70,72,92,93] Synonymous use of the relative humidity (r.h.) and moisture content terms in reporting the data on hydrated bone samples, however, produced a source of confusion in the literature.[91]

Marino *et al.*[72] reported results on the dielectric properties of bone at moisture content of 0% to 6.5% at different frequencies. Specimens were equilibrated with the environment maintained at a particular relative humidity with the help of saturated salt solutions. The relative humidity was maintained between 12% and 82% to minimize the hysteresis effects. Results showed that both the dielectric constant (ϵ'), and the dielectric loss (ϵ'') increased with the hydration percentage. Curves of ϵ' and ϵ'' versus hydration were found to alter sharply at a particular value of the hydration, defined as the critical hydration of bone. The quantity ranged from 3.7% to 4.8% depending on the density of the sample. It was interpreted as the amount of water necessary to occupy the primary absorption sites in bone.

Reinish and Nowick[92] measured both the AC (1 kHz) and the DC electrical conductivity of human cortical bone at various relative humidities. They found nearly an order of magnitude increase in the conductivity per percentage change of the moisture content. Reinish[91] also studied the adsorption and desorption hysteresis and found a different equilibrium value for drying than for wetting. She further stated that the relative humidity was related to the surface properties, whereas the moisture content was concerned with the bulk properties (Figs. 4 and 5). Lakes *et al.*[64] measured the dielectric relaxation properties of cortical bone. These authors found that the permittivity k′ of bone was large and increased with increasing humidity. The maximum k′ exceeded 10^5 (one hundred thousand times) and the maximum tanδ exceeded unity. When the electric field was parallel to the bone axis,

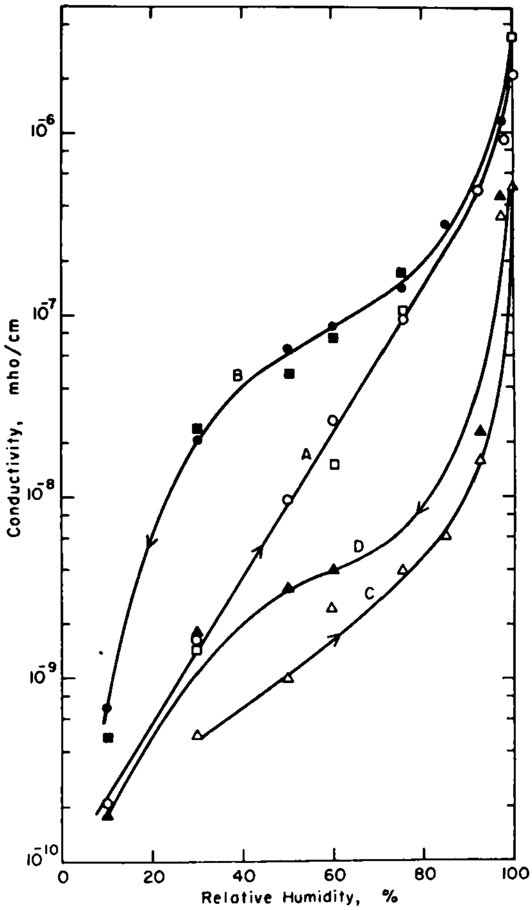

FIG. 4. Conductivity of bone sample at 1000 Hz, with electric field perpendicular to bone axis, as a function of relative humidity. (From Reinish and Nowick,[92] reprinted by permission of the publisher, The Electrochemical Society, Inc.)

both k′ and tanδ were larger than if the electric field were perpendicular to the bone axis. Their[64] data, however, do not agree with the results of Reinish and Nowick.[92,93] According to Lakes *et al.*,[64] this difference in values may be attributed to the different types of bone species examined. Marino *et al.*[72] and Lakes *et al.*[64] did not measure the dielectric properties of bone for relative humidities above 90%. Although Reinish and Nowick[92,93] measured the dielectric properties of bones equilibrated at 98% relative humidity, they allowed these bone samples to dry initially.

Chakkalakal *et al.*[29] investigated the dielectric relaxation behavior of bovine, compact bone saturated with 0.9% NaCl solution. To obtain the relaxation time, they applied a constant current pulse and measured the change in the voltage with time. The resistivity in the radial direction measured by them was two orders of magnitude smaller than that reported by Reinish and Nowick[92] at 98% relative humidity. Based on this, Chakkalakal *et al.*[29] suggested that at 98% relative humidity, the inner pores in bone are not filled with fluid and that Reinish and Nowick[92] were measuring the dielectric properties of the solid phase and perhaps a thin layer of absorbed water on that phase. Kosterich *et al.*[62] in their recent paper reported that the conductivity of fixed and fresh bone was nearly independent

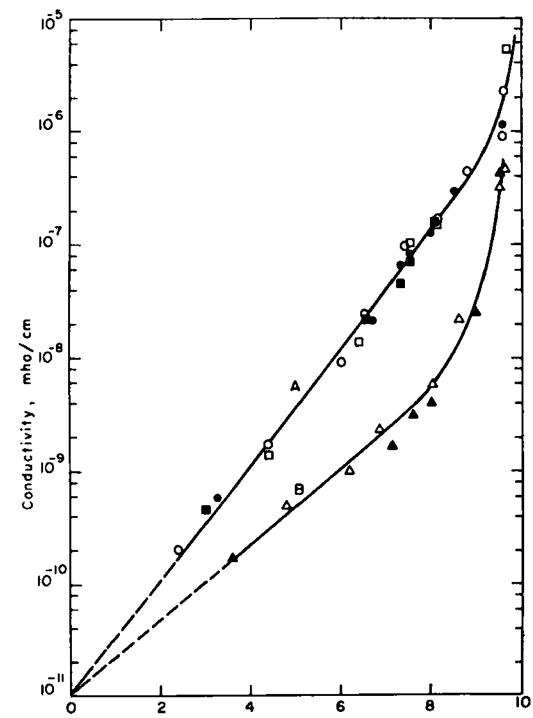

FIG. 5. Conductivity of bone sample at 1000 Hz, with electric field perpendicular to bone axis, as a function of moisture content. Curve A: Ringer's specimen; Curve B: washed specimen. (From Reinish and Nowick,[92] reprinted by permission of the publisher, The Electrochemical Society, Inc.)

of frequency below 100 kHz and that the conductivity of fresh bone was two to three times greater than that of the fixed sample. These authors[62] further observed that "moist bone, which is equilibrated with air at various relative humidities but not fluid-saturated, has a conductivity that is much larger than dry bone, but still smaller than the values measured in the fluid-saturated bone." In a recent study, Reddy and Saha[88,89] observed similar effects of exposure to air on the electrical properties of wet bone. Their results of capacitance and resistance measurements show that even a brief exposure of five minutes could affect the measured values significantly by a 92% increase in resistance and a 35% decrease in capacitance.[88,89] This is indicative of the fact that if a fresh bone specimen is exposed to air, it loses its moisture content and thus the electrical properties are affected.[88,89]

Temperature. Observations on the electric and dielectric properties at different temperatures show that these properties depend on the temperature of the bone sample.[16,39,70,93,105] Freeman[39] examined the variation of the electrical properties of bone with temperature, frequency, and orientation in the range of 20° to 180°, ten hertz to 100 kHz and 0° to 90° respectively. His results suggest that the water molecules in the sample are largely responsible for the change in C_p (equivalent parallel capacitance) and R_p (equivalent parallel resistance) with frequency. To support this conclusion, the author (Freeman[39]) further observed that: (1) for the samples subjected to high preheating, the variations of R_p and C_p were less sensitive to frequency, and their absolute values decreased for higher preheating; (2) the relative change in R_p was more pronounced as compared with C_p with the frequency in the case of nonheated samples; and (3) the capacitance variation with temperature was more pronounced in the case of samples having higher moisture content. Although Freeman[39] was an early worker in investigating the electrical properties of bone, his results have been criticized by Reinish.[91] Behari *et al.*[16] studied the effect of temperature on DC conductivity of human bone in the temperature range extending from 30° to 60°. These authors[16] observed that the DC conductivity increased with an increase in temperature. Reinish and Nowick[93] measured the dielectric constant (ϵ') for three temperatures: 25°, 30° and 35°, at constant moisture content. These data show that increasing the temperature results in slightly increased values of ϵ'. Similarly, Singh[105] studied the effect of the temperature on the capacitance and the loss-factor in dry bone and its two major components, namely, collagen and apatite. It was observed that in all three cases, the capacitance first increased with increasing temperature and then decreased when the temperature was raised further. The temperatures corresponding to peaks in the capacitance for three materials (apatite, bone, and collagen) were found to be 145°, 125° and 95° respectively. These measurements were made using an LCR meter at one kilohertz. Maeda and Fukada[70] determined the effect of temperature in the range from −150° to 50° on the dielectric properties of bone at ten hertz. They observed that with increasing hydration, both ϵ' and ϵ'' increased. Temperatures corresponding to peaks in ϵ' and ϵ'' shifted toward the lower range for higher hydration. Thus, it is evident from the previous discussion that temperature is an important variable and should be specified while reporting data on the electrical properties of bone.

Conductivity and pH. Anderson and Eriksson[2] were perhaps the first authors to report the effect of the pH of the bathing solutions on the mechanically induced electrical voltage in bone samples. They[3] found that the mechanically induced voltage depended on the properties (pH) of the immersing fluid. In a recent paper, Chakkalakal and Johnson[28] showed that the electrical and dielectric properties of fluid-saturated wet bone were influenced to a significant degree by the properties of the fluid in the pores (Fig. 6). Kosterich *et al.*[62,63] and Pienkowaski and Pollack[83] have also pointed out that the dielectric properties and stain-related potentials (SRP) of bone are

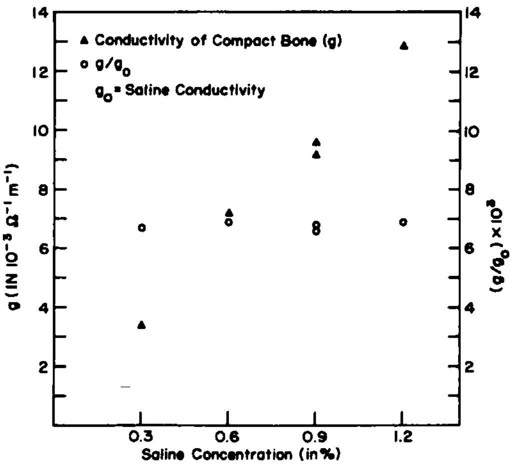

FIG. 6. The dc conductivity of a radial specimen of compact bone as a function of saline concentration. (From Chakkalakal and Johnson[28] with permission)

dependent on the electrical properties of the fluid occupying the porous spaces in the matrix. Kosterich *et al.*[62,63] found that the electrical conductivity of wet bone was proportional to the conductivity of the immersing solution. The conductivity of the bone was only 1%–2% of that of the immersion solution in spite of the net fluid content of about 15% by weight. Recently, Reddy and Saha[88,89] examined the effect of pH in the range of one through 13 on the resistance (R) and capacitance (C) of the bone samples immersed in solutions of different pH. They found that the pH of the preserving solution significantly affected the measured values of the electrical properties. At a very high or very low pH, the resistance was several orders of magnitude lower and the capacitance several magnitudes higher than those measured at a pH of 7.0. A change in pH by ±2 from the neutral solution (pH = 7.0) altered the measured resistive, conductive, and capacitive component by 70%, 125% and 190% respectively.[88,89] It is essential, therefore, to specify the pH of the preserving solutions while presenting results on the electrical properties of wet bone.

RELATIONSHIP WITH FREQUENCY

Although it is generally accepted that electrical stimulation can produce osteogenesis, opinions differ over whether DC, AC, or pulsed type of electrical stimulation yields the best results.[13,52,79,90,110] For an analysis of the role of these various modes of electrical stimulation, it is important to characterize the electrical properties of bone as a function of frequency.

Several authors have studied the frequency response of the dielectric and electrical properties of bone. Shamos and Lavine[102] reported the value for dielectric constant to be 9.2 for dry bone at room temperature (~300°K) and at 100 kHz. Freeman[39] showed that the change in R_p (equivalent parallel resistance) with frequency in the range of 100 Hz to 100 kHz was more pronounced than that in Cp (equivalent parallel capacitance). Singh[105] reported data on the resistivity, dielectric constant, and dissipation factor for dry bone, collagen, and apatite in the frequency range of one megahertz to 70 MHz. He observed that the resistivity, dielectric constant, and dissipation factor decreased with increasing frequency for all bone materials. The data on electrical properties reported by these authors,[39,102,105] however, were for dry bone specimens and do not provide information regarding the *in vivo* or the hydrated bone conditions. Marino *et al.*[72] measured the dielectric properties of human cortical bone for frequencies of 1, 10, 50 and 100 kHz for different hydrations. Their[72] results show that the dielectric constant (ϵ') and loss-factor (ϵ'') decreased with increasing frequency. Reinish[91] and Reinish and Nowick[92,93] measured the conductivity and the dielectric properties of hydrated bone over a frequency range of 50 Hz to 20,000 Hz. They reported that for different moisture content, in general, the dielectric constant (ϵ') and the dielectric loss (ϵ'') decreased while conductivity increased with each increase in frequency. Although Maeda and Fukada,[70] Marino *et al.*,[72] Reinish,[91] and Reinish and Nowick[92,93] studied frequency response of dielectric properties, their aim was to emphasize the role of moisture content in determination of the dielectric properties. Their results, therefore, do not provide full information on the electrical characterization of bone over a wide frequency range. Recently, Reddy and Saha[85-87] used a differential technique to measure the electrical (specific resistance, specific capacitance, and specific impedance) and the dielectric (dielectric constant, loss-factor and dissipation-factor) properties in three orthogonal planes for bovine, compact bone for a frequency range of one kilohertz to one megahertz. Their results showed that the electrical and dielectric properties of wet, compact, bovine bone were highly frequency-dependent (Figs. 7 and 8). These authors,[86] however, also noted that the impedance was almost independent of frequency up to 70 kHz, and above this frequency it decreased rapidly with each increase in frequency (Fig. 7). In a similar study, Kosterich *et al.*[62] reported that the conductivity and the dielectric properties of fresh as well as fixed rat bone also varied with frequency. These

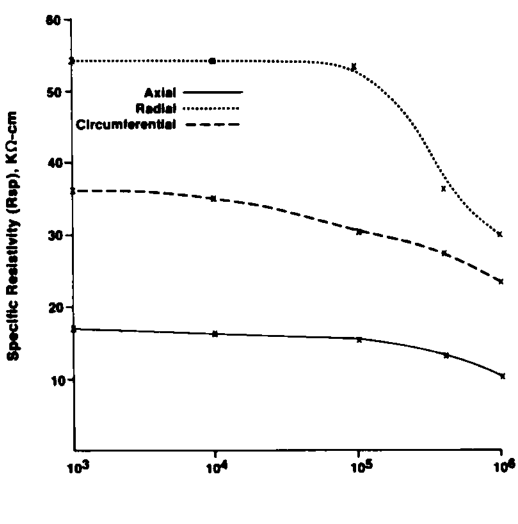

FIG. 7. Impedance in axial, radial, and circumferential directions as a function of frequency. (From Reddy and Saha,[86] with permission)

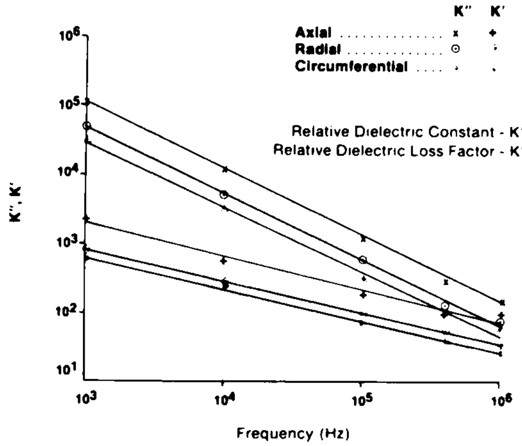

FIG. 8. Relative dielectric constant in axial, radial, and circumferential directions as a function of frequency. (From Reddy and Saha,[86] with permission.)

authors found that the conductivity was nearly independent of frequency below 100 kHz and above this it increased with increasing frequency. Similarly, the dielectric properties decreased with increasing frequency.[62,86,87] Some other authors have also reported the electrical and dielectric properties of bone for DC or at very low frequency.[14,29,64]

It is evident from the previously mentioned studies that frequency is an important parameter that governs the electrical behavior of bone, and it needs to be specified when reporting data on these properties.

BIOLOGIC FACTORS

Previously mentioned factors, as described in the above sections, are important variables that may affect the measurement of the electrical properties of a bone specimen. In addition to these factors, however, the electrical properties of bone are likely to be dependent on the microstructure and the chemical composition of the bone samples. As the structure and chemical composition of bone vary with the age, sex, species, direction, location, and even with nutritional factors and disease states of bone,[5,20,33,68,109,113] it is expected that the electrical properties of bone will also be affected by the above-mentioned biologic variables.

Microstructure and orientation. Marked variations are found in the microscopic structure of bone among different animals, among different bones of the same individual, and among different areas of the same bone. The characteristic microscopic appearance of constantly remodeling bone tissue reflects its response to both structural and biochemical demands.[35,37,69,84,95,114] In general, the diaphysis of an adult, human, long bone consists of several layers of inner and outer circumferential lamellae, enclosing a middle zone of longitudinally oriented osteons. Presence of these lamellae, osteons, and haversian canals produces different microstructures in the longitudinal, radial, and circumferential sections of the bone.

Several workers have reported that the electrical and electromechanical properties of bone depend on the sample orientation.[27,39,44,64,91] Fukada and Yasuda[44] reported that the piezoelectric coefficient for bone varied with the angle between the long axis of bone and the direction of applied stress, and it was found maximum for an angle of 45°. In a similar study, Bur[27] reported the orientation effects in the piezoelectric coefficient of bone.

Freeman[39] was perhaps the first to suggest that the capacitance of bone specimens varied with orientation. However, he reported data only for maple wood and ivory. Lakes *et al.*[64] observed that if the electric field is parallel to the bone axis, both k' and $\tan\delta$ are larger than if the electric field is perpendicular to the bone axis. Reinish[91] found different values of conductivity for bone specimens for electric fields parallel and perpendicular to the bone axis. Saha *et al.*[97] found a large variation in the values of specific impedance measured in the three principal orthogonal directions, it being maximum and minimum in radial and longitudinal directions respectively. Chakkalakal and co-workers[28,29] reported a large difference in the values of resistivity, there being three to four times more resistivity in the radial than is in the longitudinal direction (Table 4). Recently, Reddy and Saha[86,87] and Singh *et al.*[108] also found a large variation in the values of the electrical properties measured in the three principal orthogonal directions (Tables 3, 4, and 5). They reported the largest value of resistance in the radial direction and the smallest value in the longitudinal direction (Fig. 7). For capacitance, the maximum value was in the longitudinal direction and the minimum in the radial direction (Fig. 8). According to Reddy and Saha,[86] Singh *et al.*,[108] and Chakkalakal and Johnson,[28] this variation in the electrical properties with orientation can be partly explained in terms of the different microstructures in the longitudinal, radial, and circumferential directions of a bone sample.

Source and type of the specimen. While studying the electromechanical effects in bone, Alexander[1] found that, for identical mechanical deformation, the electrical response in human bone was different from the electrical response in bovine bone. He noted that human bone with a regular morphology did not exhibit a strain-related potential (SRP) when subjected to a uniform strain field, while an SRP was generated when a nonuniform (bending) strain was applied. Bovine bone, composed of more irregular structures, exhibited an SRP for both uniform and nonuniform strain fields. The presence of an SRP for a uniformly strained specimen was attributed to the irregular microstructure of the bone sample.[1] In another study, Yoon and Katz[119] have shown that bovine bone is more compact, dense, and brittle than human bone. Recently, other authors also suggested that the animal bone may differ structurally from human bone, and this may result in significant differences in its dielectric properties.[62,64] As small bone specimens obtained from different regions of the same whole bone also differ considerably in their microstructure and mineral content,[96] the exact locations of bone samples should also be mentioned when characterizing the electrical properties of bone.

Remodeling. The growth of bone involves not only a continuous accretion on the surface

TABLE 3. Electrical Properties of Whole Bone

Reference	*Source and condition*	*Measurement Technique*	*Electrical Properties*	*Comments*
Lavine *et al.*[66] (1972)	Human tibia	DC, V *versus* I curve	R = 0.7×10^5 Ω/cm	Two-points method
Liboff *et al.*[67] (1975)	Rabbit femur (*in vivo*) Human tibia (*in vivo*)	DC, V *versus* I curve	R = $2 - 5 \times 10^5$ Ω/cm R = 1×10^5 Ω/cm	Two-points method
Stan *et al.*[111] (1976)	Rabbit tibia (*in vivo*)	AC (0.01 to 1 kHz) V *versus* I curve	For medullary canal R = 200 kΩ + 25% For cortical bone R = 3–5 MΩ C = 20 ± 8 μF	Two-points method
Sansen *et al.*[98] (1978)	Rabbit femur (*in vivo*)	DC, V *versus* I curve AC (0.01 to 1 kHz) V *versus* I curve	R = 20 kΩ/cm C = 5 $\mu F/mm^2$ R_b* = 10–100 Ω/cm	Two-points method Two-points method Four-points method
Durand *et al.*[34] (1978)	Sheep bone (fresh without periosteum)	AC (100 Hz to 5 kHz) V *versus* I curve	R = 2 to 3 kΩ/cm (For whole bone) For cortical bone R_L† = 7–12 kΩ/cm R_T‡ = 1.8 kΩ/cm R_m§ = 2.5–4 kΩ/cm	Four-points method
Saha *et al.*[97] (1981)	Fresh bovine	AC (1 kHz), V *versus* I curve	Impedance increased by 37% in absence of marrow	Four-points method
Behari and Singh[17] (1981)	Rabbit femur (*in vivo*)	AC (500 Hz)	Z_L‖ = 8 kΩ/cm	Two-points method
Singh *et al.*[108] (1984)	Fresh bovine	AC (1 Hz to 1 MHz)	Z_L = 48.21 kΩ Z_C¶ = 94.5 kΩ at 1 KHz	Four-points method Phase angle measured

* R_b = resistance due to blood and tissue
† R_L = resistance for unit length in longitudinal direction
‡ R_T = resistance for unit length in transverse direction
§ R_m = resistance for bone marrow per unit length in longitudinal direction
‖ Z_L = longitudinal impedance
¶ Z_c = circumferential impedance

TABLE 4. Electrical Properties of Compact Bone Tissues

Reference	*Source and Condition*	*Measurement Technique*	*Electrical Properties*	*Comments*
Shamos and Lavine[102] (1964)	Femur	Ohmmeter	$\rho = 1.2 \times 10^{12}\ \Omega$-cm	Frequency = 1 kHz Temperature = 300 °K
Freeman (1967)[39]	Fresh cow femur Dried human femur	Capacitance bridge		Only normalized resistance is reported.
Behari *et al.*[16] (1974)	Dried human tibia	DC, V *versus* I curve		Measurements were made at different temperatures.
Reinish and Nowick[92] (1976)	Human femur (dry)	AC, (1kHz) Impedance DC, Electrometer	$\sigma \simeq 10^{-10}\ \Omega\text{-cm}^{-1}$ $\sigma \simeq 10^{-11}\ \Omega\text{-cm}^{-1}$	Direction-dependent (electric field perpendicular to bone axis)
Chakkalakal *et al.*[29] (1980)	Bovine femur (fluid saturated)	DC, Step function	$\rho_l = 4.5 - 4.8$ k Ω-cm $\rho_r = 4\ \rho_l$	
Kosterich *et al.*[62] (1983)	Rat femur	AC (1kHz) Impedance analyzer, Vector impedance meter	$\sigma_r = 12.9 \pm 2.7\ (\Omega\text{-cm})^{-1}$ (fresh) $\sigma_r = 4.8 \pm 0.7\ (\Omega\text{-cm})^{-1}$ (fixed)	Special cell suitable for radial direction only.
Reddy and Saha[86] (1983)	Wet bovine femur	AC (10 kHz), Differential technique	ρ_r* = 54 k Ω-cm, ^{C}sp,§ r = 21.4 pf-cm^{-1} ρ_c† = 36 k Ω-cm, ^{C}sp, c = 24.74 pf-cm^{-1} ρ_l‡ = 17 k Ω-cm, ^{C}sp, l = 60.87 pf-cm^{-1}	

* r = radial
† c = circumferential
‡ l = longitudinal
§ sp = specific

TABLE 5. Dielectric Properties of Compact Bone Tissues

Reference	*Source and Condition*	*Measurement Techniques*	*Dielectric Properties*	*Comments*
Shamos and Lavine[102] (1964)	Dry femur	at 1 kHz, LCR meter	$\epsilon' = 9.2$	Direction dependent
Marino *et al.*[72] (1967)	Human bone (62%, r.h.) (dry)	at 1 kHz, bridge method	$\epsilon' = 16$, $\epsilon'' = 2.8$ $\epsilon' = 6$, $\epsilon'' = 0.1$	Values adopted from Figs. 3(A) and 4
Lakes *et al.*[64] (1977)	Bovine bone (78%, r.h.)	at 1 kHz, impedance bridge	$\epsilon' = 100$ $\tan\delta \simeq 1$	Electric field perpendicular to the bone axis
Reinish and Nowick[93] (1979)	Human bone (60%, r.h.)	Direct coupled low-frequency bridge	$\epsilon' = 30$ (at 1 kHz) $\epsilon'' = 18$ (kHz)	Four-point measurement
Kosterich *et al.*[62] (1983)	Rat femur (fresh) (fixed)	AC (1 kHz) Impedance analyzer and vector impedance meter	$\epsilon' = (1.0 \pm 0.5) \times 10^3$ $\epsilon' = (7.7 \pm 1.0) \times 10^2$	Cell suitable for only radial direction measurement
Reddy and Saha[86] (1983)	Wet bovine bone	AC (1 kHz), differential technique	$k'_l = 2060$ $k'_r = 590$ $k'_c = 823$ $k''1 = 10.8 \times 10^4$ $k''_r = 3.3 \times 10^4$ $k''_c = 5.02 \times 10^4$ $\tan\delta_l = 52.30$ $\tan\delta_r = 56.38$ $\tan\delta_c = 60.93$	

and at the extremities but also a continuous process of remodeling of the internal structure. Frost[41–43] has studied the microscopic aspects of such remodeling and has shown that a continuous destruction of existing bone and replacement with new bone goes on in the skeleton regardless of the age of the person. He has also measured the rate of this internal remodeling, which is most active at one year of age but slows down markedly during adulthood, being lowest at about age 30.

In the normal adult skeleton, a balance exists between bone resorption by osteoclasts and bone formation by osteoblasts. This results in continual turnover in bone substance but no appreciable change in bone mass or significant change in bone structure. Under some circumstances, however, they become unbalanced and one or the other process dominates. This happens, for example, in senile osteoporosis in which bone formation lags behind bone breakdown. Consequently, bone becomes thin and its density decreases, making the material more fragile and thus more liable to fracture.

It is not known which mechanism triggers the bone cells to initiate remodeling. Several authors have hypothesized that disuse osteoporosis is triggered due to the lack of strain-related potentials (SRP) in bone.[8,9] It is quite likely that the electrical properties of bone play an important role in this remodeling activity and bone growth.[8,9] For instance, in 1962 Bassett and Becker[9] proposed that stress-induced bioelectric potentials were the command signal in the operation of Wolff's law, and these signals controlled bone cell activity and the orientation of their macromolecular by-products.

Age. Many authors have studied the structural and chemical changes that occur with age in bone.[5,20,57–59,113] Jowsey[57–59] observed that young individuals show a high percentage of both bone formation and resorption, indicating a high turnover rate. Arnold *et al.*[5] found that the trabecular structure is considerably more irregular in individuals in the 50s and 60s when compared with the orderly pattern found in children. The authors have pointed out in the previous section that electrical properties of bone are related to bone's microstructure. As microstructure and density of bone are dependent on age, a relation between the age of the bone under study and its electrical properties is likely to exist. Swanson and Lafferty[113] observed an increase in conductivity with an increase in the age of the rat tibia. They found that this increase in conductivity corresponds to the age-dependent increase in the inorganic portion of the bone density. In another study, Marino and Becker[71] studied the piezoelectricity in bone as a function of age and reported that the average value of the piezoelectric constant d_{14} in femurs from three-week-old calves was 58% of the value of similar specimens obtained from three-year-old bulls. These results further indicate that mature bone exhibits a higher piezoelectric constant.[71]

Disease states. Various bone diseases affect the bone microstructure and its chemical composition.[43,59,78,109,114] In order to understand the possible role of the electrical parameters at the onset of these changes, and thereby use electrical stimuli possibly to reverse them, it is important to discover the correlation between the diseased-bone structure and the electrical behavior of the bone samples. These data are also of interest in view of the recent use of electrical fields to control disuse osteoporosis in animals.[60,73] Such information will indicate whether or not the electrical properties are related to the pathologic condition. However, at present, little information is available on the electrical properties of diseased bone. Some results have been published on the electromechanical coefficient of diseased bone.[71] Marino and Becker[71] reported that the value of d_{14} was low for the specimen prepared from neoplastic lesion in bone. Further study is urgently needed to characterize the electrical properties of bone samples from various metabolic disorders.

OTHER RELATED PHENOMENA

Other effects related to bioelectricity in bone are due to mechanically induced charge separation. It is evident from the studies on the electrical and electromechanical properties of bone that transduction of mechanical to electrical energy may arise intrinsically by one or more mechanisms operating in concert.[8] Electrical potentials may arise in materials with at least five different properties: piezoelectricity, pyroelectricity, ferroelectricity, semiconductor (solid-state), and electret.[8] Electrical response in a crystal due to a mechanical stress is called piezoelectricity, and this effect in bone was first reported by Fukada and Yasuda[44] in 1957.

The pyroelectric effect may be defined as the production of electric polarization as a result of change in temperature. This effect may play a role in both the processes of morphogenesis and the physiologic functions of many living organisms.[6] Lang[65] reported the pyroelectric coefficient for dry bovine femur to be 0.036 ± 0.021 coulomb/cm^2°.

Ferroelectricity occurs in a material as the result of the presence of spontaneous polarization and is caused by the realignment in the orientation of spontaneous electric dipoles under the action of an external electric field. El Messiery *et al.*[36] reported the ferroelectric properties in bone by studying first the ferroelectric hysteresis loops of a sample and then the amount of electrical energy stored in the unit volume.

The electret effect is defined as the charge retention capacity in a material, and this property in bone has been reported by a few investigators.[4,74] Mascarenhas[74] reported that the dried bone was able to store charge to the order of a nanocoulomb/cm^2. Andrabi and Behari[4] observed that a bone was able to store a measurable amount of polarization charge. These authors further noted that dry bone samples were able to retain the charge even after five months. Most of the previously mentioned properties have not been studied in detail, except the electromechanical effect, which has most physiological significance. The electromechanical effect and its relation to electrical properties are described below.

ELECTROMECHANICAL EFFECT AND ITS RELATION TO ELECTRICAL PROPERTIES

Electromechanical effect has been studied extensively and intensively both in dry and in living bone since the first report of Fukada and Yasuda in 1957.[1,3,7,9,11,18,19,30,31,35,50,54,-55,82,83,91,102-105,116-118] The large interest in studying electromechanical effects in bone was generated because of their possible role in bone growth and remodeling processes.[7,48,49] Various theories have been proposed by different workers to explain the origin of electromechanical effects in bone. These include classical piezoelectricity,[44,104] gradient theory,[116,117] streaming potential theory,[3,38] and the combination of both the classical piezoelectricity and streaming potential theories.[3,50,55,83]

Recent investigations indicate that the origin of strain-related potentials (SRP) cannot be explained fully in terms of the classical piezoelectricity theory for both dry and wet bone.[3,50,55,83] Two competing mechanisms (piezoelectricity and streaming-potential theories) have been suggested by some authors to explain the origin of electrical signals produced by the bending of physiologically moist bone.[50,83] These authors[50,83] further suggest that streaming potentials dominate piezoelectricity in wet bone in bending deformation. The need for two different mechanisms to explain electromechanical effects in wet bone has been attributed to the influence of the fluid occupying the pores.[3,50,55,83] It has already been noted that the dielectric and electric properties are different for dry and wet bone.[29,62,86] Since the dielectric properties also influence the measurement of electromechanical properties of bone, characterization of the dielectric properties is important in a study of the electromechanical behavior of bone.[50,55,56,118]

DISCUSSION

The objective of the current paper was not only to summarize the presently available data on the electrical properties of bone but also to elucidate the many variables such as orientation, frequency, moisture content, temperature, and microstructure of the bone samples, which affect the electrical properties. Various methods of measurement and their limitations have also been discussed. Several areas that need further study have been identified. It is evident that much further work is needed before a complete understanding of the electrical behavior of bone is obtained. Such knowledge will be an important step toward the development of an optimum modality of electrical stimulation for osteogenesis. The rather extensive bibliography will facilitate initiation of future studies, particularly by scientists who may be new to this area.

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