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Communication

Dielectric properties of fluid-saturated bone: a comparison between diaphysis and epiphysis

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Keywords—*Bone conductivity, Bone impedance, Bone permittivity, Diaphysis, Epiphysis*

Med. & Biol. Eng. & Comput., 1988, **26**, 313–316

1 Introduction

THERE HAS RECENTLY been great interest in the study of the dielectric properties of bone due to the growing importance of electrical stimulation of osteogenesis in orthopaedic therapy. Several investigators have measured the dielectric properties of fluid-saturated bone as a function of frequency (ERIKSSON, 1976; CHAKKALAKAL *et al.*, 1980; KOSTERICH *et al.*, 1983; 1984; SINGH and SAHA, 1984; REDDY and SAHA, 1984; SAHA *et al.*, 1984). Up to now the measurements have been performed *in vitro* on mid-diaphyseal samples generally obtained from bovine or rat femurs. The results of these studies allow electrical modeling of bone and the correlation of bone permittivity and conductivity with its microstructure. The object of this study is to determine the dielectric characteristics in the proximal and distal epiphyses of femur and to compare them with those of the diaphyses.

2 Experimental method

2.1 *Specimen preparation*

A bovine femur was used to extract the samples to be measured. One sample was cut at each of the four positions indicated in Fig. 1. The samples in the three cuts of the epiphyses (CC, CC_1 and D) have thicknesses of 2·4–2·8 mm, areas of 61 mm^2 and were oriented so that their large surfaces were normal to the axial direction. Their locations are shown in Fig. 2. The sample from the diaphysis (F_a) had a thickness of 1·3 mm, an area of 29 mm^2 and was also orientated so that its large surfaces were normal to the axial direction, as shown in Fig. 3. The final dimensions were obtained by wet milling at low speed to avoid surface damage. After milling, and to remove the debris produced by machining without significantly affecting the bone marrow, the samples were briefly cleaned for 2 min in an ultrasonic bath in deionised water at room temperature. Once cleaned, the samples were immersed and kept in physiological solution until used for measurement.

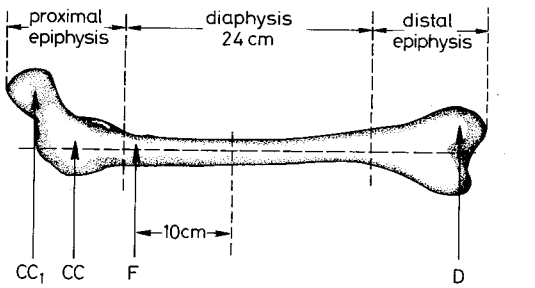

Fig. 1 *Positions of the samples cut from the diaphysis and the proximal and distal epiphyses of a bovine femur. The mid-diaphyseal plane is shown for reference*

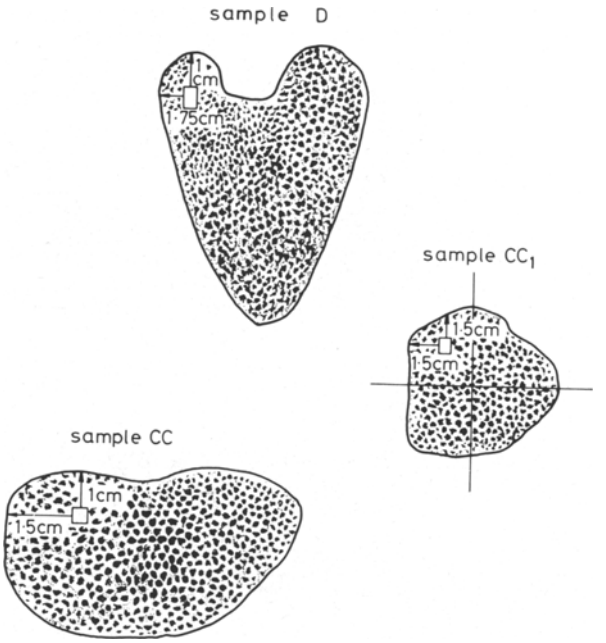

Fig. 2 *Location of the samples in the three cuts of the epiphyses. CC and CC_1 were from the proximal epiphysis and D was from the distal epiphysis. The planes shown are normal to the axial direction*

First received 25th June and in final form 21st September 1987

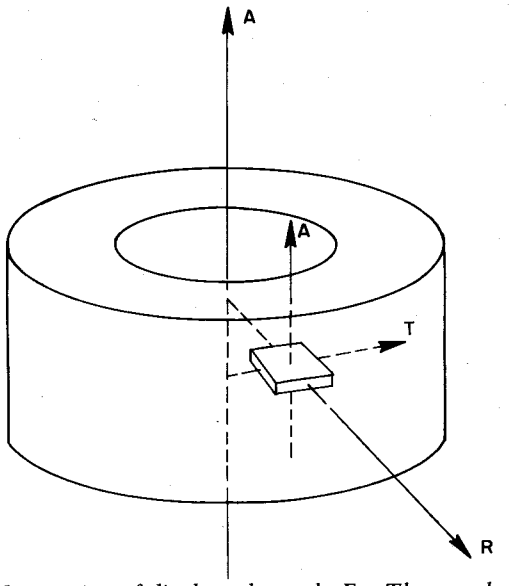

Fig. 3 *Orientation of diaphyseal sample F_a. The sample is from the mid position between the periosteal and the endosteal surfaces and its large area is normal to the axial direction. A = axial direction; R = radial direction; T = tangential direction*

2.2 *Measurement system*

Measurements of the dielectric properties were carried out using a parallel combination of the bone sample and a reference impedance, following the differential methodology previously used by other investigators (REDDY and SAHA, 1982; 1984; SAHA *et al.*, 1984). In other studies, bone saturation was achieved by complete immersion of the sample in physiological solution and using this solution as the means of contact between the sample and the electrodes. Because contacting through the solution is the main source of polarisation effect errors, in the present work bone saturation was achieved without immersing the sample in the solution. The contact was made directly, by means of a conductive jelly, between silver electrodes and the sample surfaces, in order to avoid the solution's polarisation effects and the possible measurement errors due to contacting the sample. Although chlorinated silver electrodes were not used, the electrodes' surfaces were plated with silver conductive paint before each measurement to avoid the cumulative effect of their polarisation. The electrodes contact the samples on their large surfaces, so that the applied electric field is in the direction of the bone axis.

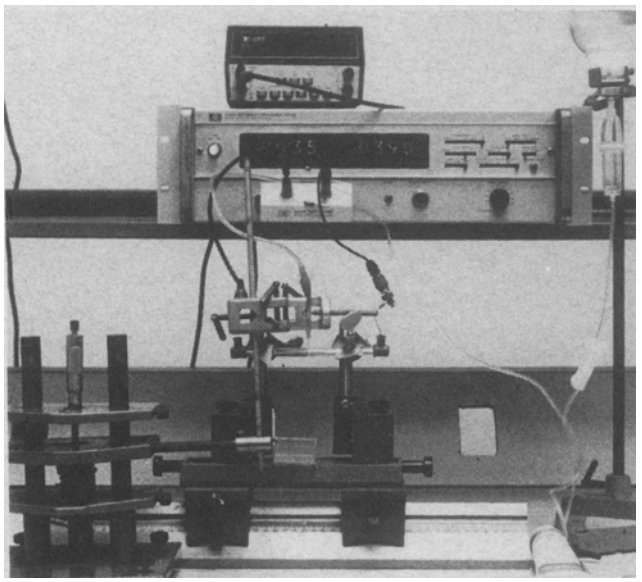

Fig. 4 *Measurement system showing the inch worm screw driven sample holder, containing the electrodes, the physiological solution reservoir and the micrometer-approaching mechanism of the capillary used to keep the sample saturated*

To maintain the sample in a saturated condition, a capillary, connected to a reservoir containing physiological solution (0.9 per cent NaCl in H_2O, pH = 6·10), was placed vertically above the sample in direct contact with it. The measurement system and the arrangement to keep the sample saturated are shown in Fig. 4. Capacitance and conductance measurements of the parallel combination sample reference impedance were performed, using an automatic capacitance bridge, at frequencies of 1 kHz, 10 kHz, 100 kHz and 1 MHz. The measuring signal was 200 mV (RMS) at 1 kHz and 100 mV (RMS) at 10 kHz, 100 kHz and 1 MHz.

3 Results

The following parameters were obtained for each of the samples: specific capacitance, resistivity, relative permittivity, dielectric loss factor, dissipation factor, specific impedance and phase angle. From the values of the resistivity ρ and of the specific capacitance C_s the other parameters can be calculated, modelling the bone sample as a parallel circuit of a capacitance and a conductance,

relative permittivity k':

$$k' = C_s/\varepsilon_0 \tag{1}$$

dielectric loss factor k'':

$$k'' = 1/\varepsilon_0 \omega\rho \tag{2}$$

dissipation factor tan δ:

$$\tan \delta = k''/k' = 1/\omega\rho C_s \tag{3}$$

specific impedance Z_s:

$$Z_s = \rho - j/\omega C_s \tag{4}$$

phase angle θ:

$$\theta = \text{arc tan } (-\rho\omega C_s) \tag{5}$$

where ε_0 is the permittivity of free space and ω the angular frequency of the test signal.

Measurements on the four samples were repeated five times to reduce the probability of measurement error. Although the largest dispersion in both capacitance and conductance measurement results was observed at 1 kHz, they were repeatable within ±3 per cent at any frequency. Because all measurements were carried out at frequencies of 1 kHz and higher, and at relatively small current densities, the possible errors induced by the electrode polarisation impedance should be comparatively smaller than the measurement errors themselves. The results as a function of frequency, from 1 kHz to 1 MHz, are presented in Figs. 5–12. The electrical parameters shown were calculated

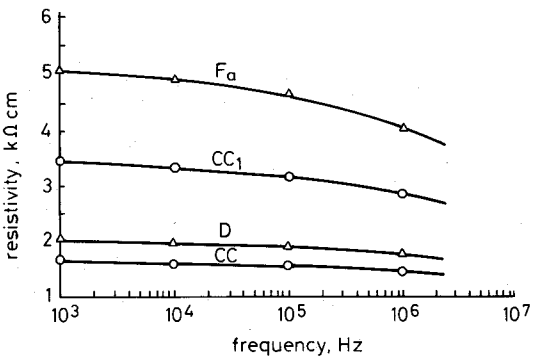

Fig. 5 *Electrical resistivity against frequency of samples F_a in the diaphysis, CC and CC_1 in the proximal epiphysis and D in the distal epiphysis*

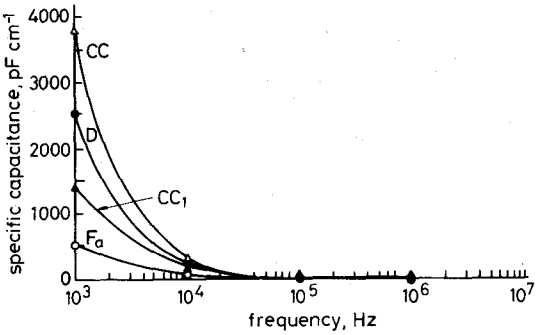

Fig. 6 *Specific capacitance against frequency of samples F_a in the diaphysis, CC and CC_1 in the proximal epiphysis and D in the distal epiphysis*

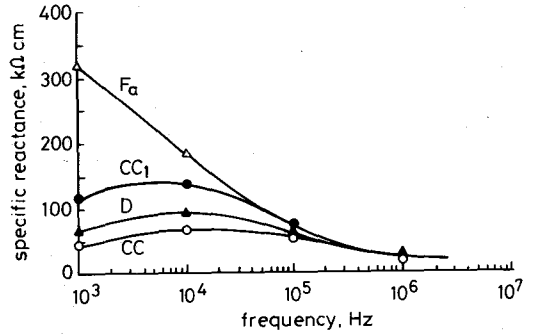

Fig. 7 *Specific reactance against frequency of samples F_a in the diaphysis, CC and CC_1 in the proximal epiphysis and D in the distal epiphysis*

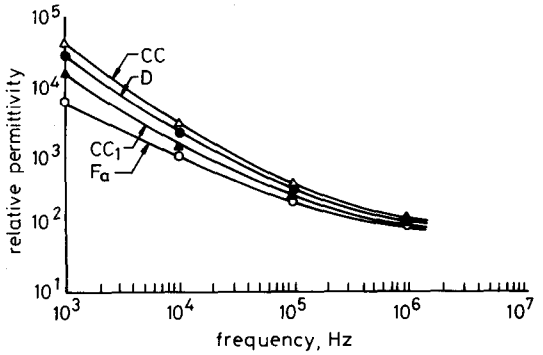

Fig. 8 *Relative permittivity against frequency of samples F_a in the diaphysis, CC and CC_1 in the proximal epiphysis and D in the distal epiphysis*

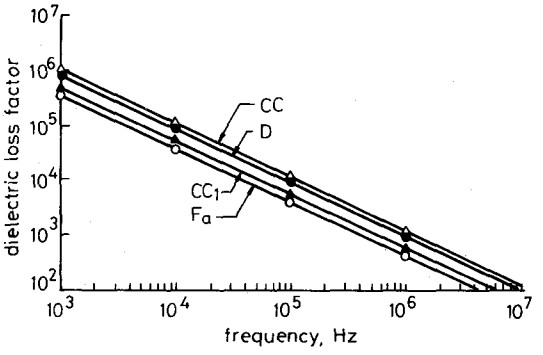

Fig. 9 *Dielectric loss factor against frequency of samples F_a in the diaphysis, CC and CC_1 in the proximal epiphysis and D in the distal epiphysis. The loss factor includes both the dielectric relaxation process and the ionic conductivity contributions*

from capacitance and conductance measurements using the above equations. The graphs corresponding to samples from the diaphysis and both epiphyses are presented together for comparison purposes.

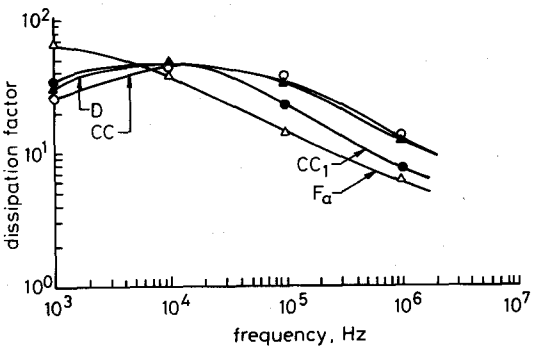

Fig. 10 *Dissipation factor against frequency of samples F_a in the diaphysis, CC and CC_1 in the proximal epiphysis and D in the distal epiphysis*

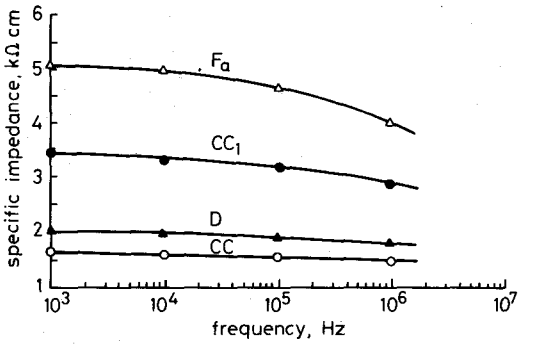

Fig. 11 *Specific impedance against frequency of samples F_a in the diaphysis, CC and CC_1 in the proximal epiphysis and D in the distal epiphysis*

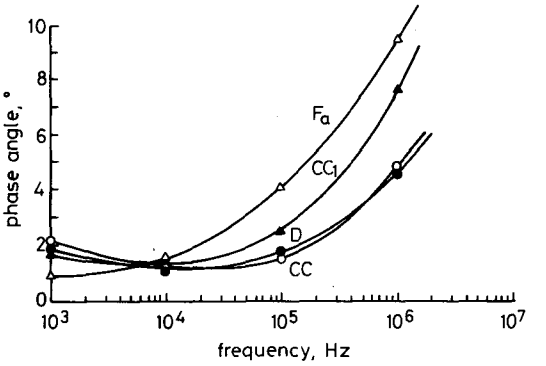

Fig. 12 *Negative phase angle against frequency of samples F_a in the diaphysis, CC and CC_1 in the proximal epiphysis and D in the distal epiphysis*

4 Discussion and conclusions

Fig. 5 shows that above approximately 10 kHz the dielectric relaxation phenomena begin to become important, as is evidenced by the increase in electrical conductivity at higher frequencies. This increase is larger for diaphyseal sample F_a and for sample CC_1, which corresponds to the head of the proximal epiphysis. From the results of Fig. 5 it can be seen that the values of resistivity obtained in both epiphyses (samples CC_1, D and CC), at any frequency, are smaller than those obtained in the diaphysis (sample F_a). Conversely, Fig. 6 shows that the values of specific capacitance obtained in both epiphyses, at any frequency, are larger than those obtained in the diaphysis.

With respect to the resistivity, the values obtained in sample CC of the proximal epiphysis and D of the distal epiphysis are less than half of the values obtained in the diaphyseal sample F_a (Fig. 5). Similarly, the resistivity of sample CC_1, which corresponds to the region of the head of the proximal epiphysis, is less than three-quarters of that of sample F_a in the diaphysis. Nevertheless, the resistivity of this region (sample CC_1) is also about twice the

resistivity of sample CC and significantly larger than in sample D. The preceding indicates that, of the three samples considered in the epiphyses, sample CC_1 presents resistivity values closest to those of the diaphyseal sample F_a.

As bone electrical conductivity is a consequence of the microstructure of the bone tissue, the above results reflect the fact that the structure in the epiphyses is different from that in the diaphysis. This well known fact has been repeatedly confirmed by microscopic observations. It is also noted that this difference tends to lessen as the head of the proximal epiphysis is approached, i.e. of the three samples of the epiphyses considered, the bone structure at the head of the proximal epiphysis (sample CC_1) is more like the structure of the diaphysis, from an electrical point of view. Considering the cancellous nature of the proximal epiphysis, the fact that a much higher resistivity was measured in sample CC_1 than in sample CC cannot be attributed exclusively to the different orientation of the trabeculae in those samples, which is given by the directions of the axis of applied stress to the head and of the bone axis. Even taking into account the angle between these two axes, the resistivity in the direction of applied stress at CC_1 would still be considerably higher than that at CC. Consequently, the different resistivities should be attributed mainly to structural differences between the two regions of the proximal epiphysis.

These differences are also partially revealed by the specific capacitance values obtained for the four samples, as shown in Figs. 6 and 8. The lowest values of capacitance in Fig. 6 correspond to the regions where the bone is more compact, represented by diaphyseal sample F_a and sample CC_1 of the head of the proximal epiphysis. In this case, the permittivity of the diaphysis, at any frequency, is smaller than that of the epiphyses. The values obtained at the head of the proximal epiphysis are again closest to those of the diaphysis, indicating the greater similarity between their microstructures.

These results are not surprising taking into account the porous nature of bone tissue in the epiphyses and its compact nature in the diaphysis and considering that the measured electrical conductivity is mainly due to the liquid content. The fact that lower values for the permittivity of the diaphysis were obtained, relative to those of the epiphyses, agrees with the general theory of chaotic mixtures of a matrix with an inclusion. Here the physiological solution is the inclusion in a solid bone matrix. The theory predicts that the permittivity should increase as the content of the inclusion increases. This kind of behaviour is evident from Fig. 8, if one recalls the structural differences between the diaphysis and the epiphysis. Nevertheless, the microstructure is not the only cause of the difference between the permittivities measured in the diaphysis and the epiphyses, as, in contrast to diaphyseal bone, epiphyseal bone also contains marrow and fats that affect the matrix permittivity. As expected, for increasing frequency the effect of the polarisation of the liquid in the mixture becomes less significant. The permittivity values indicate that, as in the case of the resistivity, the proximal epiphysis has a more compact structure at its head.

The specific reactance of the four samples is shown in Fig. 7. In spite of the fact that the reactance of CC_1 is closer than that of the two other epiphyseal samples (CC and D) to the reactance of the diaphyseal sample F_a, the form of the observed variation is similar in the three samples of the epiphyses due to their similar porous nature. Fig. 11 shows the specific impedance of the samples. Because of the high liquid content these curves are almost identical to those of the resistivity (Fig. 5), at the frequencies considered. Only in the diaphysis (F_a) and at frequencies above 100 kHz does the specific impedance become slightly lower than the resistivity owing to the more compact nature of bone tissue in the diaphysis, which makes the relative contribution of the matrix to the total impedance more significant at higher frequencies.

The measurement of the electrical characteristics of bone allows us to differentiate its structural nature in each one of its parts. The results of this preliminary study could help in the electrical modelling of bone and in the correlation of bone permittivity and conductivity with the different microstructure of bone existing at its various regions. Because it appears that electrical phenomena in bone are a direct consequence of its nature and physical structure, the present comparison could further the understanding of the structural differences between the diaphyseal and epiphyseal regions of a femur from an electrical point of view. However, based on the results obtained in this study it is evident that, to better characterise the electrical properties of the epiphyses, further work is needed that will take into account the trabeculae orientation and the influence of the bone constituents on the permittivity of the bone matrix.

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