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Author(s)	Amin, Bilal; Elahi, Muhammad Adnan; Shahzad, Atif; Porter, Emily; O'Halloran, Martin
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A review of the dielectric properties of the bone for low frequency medical technologies

Bilal Amin[1,2], Muhammad Adnan Elahi[1,2], Atif Shahzad[2,3], Emily Porter[1,2] and Martin O'Halloran[1,2,3]

[1]Electrical and Electronic Engineering, National University of Ireland Galway, Ireland

[2]Translational Medical Device Lab, National University of Ireland Galway, Ireland

[3]School of Medicine, National University of Ireland Galway, Ireland

Abstract

The dielectric properties are key parameters that quantify the interaction between electromagnetic waves and human biological tissues. In particular, the development of electromagnetic-based medical technologies rely on knowledge of the dielectric properties of bone, specifically for applications such as electrical stimulation and bone health monitoring. Electrical stimulation is used in clinics to promote the healing of bone fractures, treating non-unions, congenital pseudarthrosis, bone regeneration and during bone implant procedures. The response of the bone to any external electrical stimulation is governed by the dielectric properties of the bone, which vary with the applied frequency of the stimuli. Bone mineral density is considered a key indicator of osteoporosis diagnosis, and is assumed to be related to the dielectric properties of the bone. Therefore, dielectric properties of bones may potentially be used to diagnose osteoporosis. The bone dielectric properties can be assessed non-invasively for bone health monitoring. Several research studies have reported dielectric properties of cortical and trabecular bones in recent literature. Since dielectric properties of bone determine the response of the tissue to therapies, it is important to compile and analyze the reported dielectric data in order to have a thorough understanding of these properties. It is established from the literature that the low frequency (10 Hz - 1 GHz) dielectric properties of bone are particularly important in diagnostic applications, as the correlation between the dielectric properties and bone mineral density is more significant than at higher frequencies. In this paper, the low frequency dielectric properties of the bone reported in the literature are compiled and quantitatively analysed. The results suggest that there is a significant inter- and intra-species variation in the reported dielectric data from human, bovine, porcine, and rat bone tissues. Moreover, the relationship between the dielectric properties and bone mineral density is inconsistent across the various studies, indicating that further research in this area is needed.

Keywords: Dielectric Properties, Bones, Electrical Stimulation, Osteoporosis, Bone mineral density.

1. INTRODUCTION

Electromagnetic (EM) wave reflection and propagation in biological tissues is characterized through the dielectric properties of the tissues (relative permittivity, and conductivity) [1]. The interaction of radio waves with biological tissues is an active research area that is well-reported in literature, starting from the early studies by Schwan and Foster in 1980 [2]. Some of the major applications of the dielectric properties of tissues include determination of the Specific Absorption Rate (SAR), dosimetry studies, design of EM-based medical devices [3], [4], design validation of wireless communication and on-body devices [5], [6]. The dielectric properties of tissues are both temperature and frequency dependent [7]. The dielectric properties are important parameters in the development of both novel EM diagnostic and therapeutic devices [6]. These types of devices include: time domain microwave radar for breast health monitoring [8], microwave ablation for treating liver, lung, kidney, bone and adrenal tumours [9], and microwave hyperthermia for breast cancer treatment [10].

The application of electrical stimulation in the treatment of bone diseases, such as repairing bone fractures or in bone surgeries for hip replacement, has been an active research area since 1977 [11–14]. Further, studies on animal bones have shown that when external electrical current is applied to the marrow of long bone, the bone is regenerated around the electrode [12–14]. In order to better understand the bone remodelling process during direct or induced electrical stimulation, characterisation of the electric field and current distribution in the bone is of vital importance, and this requires accurate knowledge of the bone dielectric properties [15].

In the literature, several studies have reported dielectric properties of bones at low frequency range [11], [16–26] and in microwave frequency range [21], [27–32]. A number of studies [18], [28], [31–33], suggest that bone health (in terms of bone mineral density (BMD)) can be predicted by dielectric properties of the bone. The relationship between the BMD and dielectric properties is reported in [14], [15], [16], [22], [27], [34], [35], [36]. However, the reported relationship between these parameters is not consistent across studies. Although most of the reported bone dielectric data is for *in vitro* properties, some recent studies [31], [37], [38] have also reported *in vivo* dielectric properties of the bone in the microwave frequency range, including [31] where a non-invasive microwave imaging technique was used to estimate the dielectric properties. There has been significant experimental work in bone dielectric characterization over the past four decades, but it is still difficult to understand and generalize the relationship between the dielectric and biophysical mechanical properties of bone. Therefore, an analysis of published dielectric data and an up-to-date literature review would play a significant role in understanding the relationship between the dielectric and biophysical properties of bone [39].

The objective of this paper is to present a comprehensive review of historical studies that have investigated the dielectric properties of bones, and to summarize the results in order to establish a clear relationship between the dielectric properties and bone health in the low frequency range (10 Hz - 1 GHz). A quantitative comparison of dielectric properties is performed across various experimental conditions, including study type (*in vivo*/*in vitro*), frequency range, biological source, bone type (cortical/trabecular), and measurement method.

The remainder of this paper is organized as follows: Section 2 presents the methods involved in reviewing all of the studies reporting the dielectric properties of bone; Section 3 presents a summary of the reported dielectric properties of bone, and investigates the relationship between bone quality and dielectric properties; Section 4 presents a discussion on the comparison of results from different studies, with an analysis on the variation in dielectric properties between different studies, and the variation of dielectric properties due to BMD; and finally, conclusions are drawn in Section 5.

2. METHODS

Fourteen studies on dielectric properties of bone completed in a 35 year period from 1983-2018 are reviewed in this paper. The inclusion criteria was such that all studies that reported or evaluated dielectric properties of bones and the relationship between bone dielectric properties and bone quality across the low frequency range (10 Hz - 1 GHz) were included. Across the frequency range of interest, all of the studies investigated *in vitro* dielectric properties of bones, and no study was found that reported the *in vivo* dielectric properties of bones. The bone samples were acquired from different species: seven studies reported dielectric properties of human bones; five studies reported the properties of bovine bones; one study reported the properties of porcine bones, and one study reported the rat bone properties. The techniques employed to measure the dielectric properties of bones also varied across different studies. The study reference, study type, frequency range, source of bone sample, and measurement technique of each reviewed study are tabulated in Table 1.

TABLE 1. Comparative description of reported studies

ε = relative permittivity; σ = conductivity; IA=Impedance Analyser; OECL=Open-ended coaxial line; r = Correlation Coefficient

Reference	Study Type	Frequency Range	Source	Measurement Technique	Dielectric Properties
Kosterich *et al.* [40]	*in vitro*	10 Hz - 100 MHz	rodent cortical bone	Platinum Electrodes, IA, Vector impedance meter	$\varepsilon = (6.4 \pm 2.4) \times 10^2$, $\sigma(S/m)$ = 13.3 ± 2.8 (at 10 kHz)

Reddy and Saha [22]	*in vitro*	1 kHz - 1 MHz	bovine cortical bone	Differential technique	ε_{axial} = 688 (at 10 kHz)
Mercato and Garcia [23]	*in vitro*	1 kHz - 1 MHz	bovine cortical bone	Differential technique	$\varepsilon_{distal\ epiphysis}$ = 29400 (at 1 kHz)
De Mercato and Sanchez [24]	*in vitro*	100 Hz, 10 kHz and 1 MHz	bovine cortical bone	Chlorided-silver metal Electrodes, Automatic IA	σ_{axial} = 66±7.3(μS/cm) to 107±2.5(μS/cm)
Gabriel *et al.* [21]	*in vitro*	10 Hz - 20 GHz	porcine cortical bone	IA, Network analyser OECL probes	ε = 1.0E+3 - 1.0E+1 $\sigma(S/m)$ = 1.0E-2 - 1.0E+1
Sierpowska *et al.* [18]	*in vitro*	100 Hz - 10 MHz	bovine trabecular bone	Stainless-steel Electrodes, LCR meter	ε = 290 ± 130, $\sigma(S/m)$ = 3.6 ± 1.4
Unal *et al.* [25]	*in vitro*	20 Hz - 2 MHz	bovine cortical bone	Text fixture, LCR meter	ε = 8; $\sigma(\mu S/m)$ = 0.1
Singh and Beharl [41]	*in vitro*	0.5 - 108 MHz	human cortical bone	Q meter, vector impedance meter	ε = 10 (at 10 MHz)
Saha and Williams [26]	*in vitro*	120 Hz - 10 MHz	human trabecular bone	Chlorided-silver metal Electrodes, LCR meter	ε = 33.06 ± 8.82 (at 10 MHz), $\sigma(mS/cm)$ = 3.6
Saha and Williams [42]	*in vitro*	120 Hz - 10 MHz	human cortical bone	Chlorided-silver metal Electrodes, LCR meter	ε = 308 ± 72, $\sigma(S/m)$ = 5.26 ± 2.22 (at 10 kHz)

Saha and Williams [43]	*in vitro*	120 Hz - 10 MHz	human trabecular bone	Chlorided-silver metal Electrodes, LCR meter	ε = 601 ± 194, σ = 1.96 ± 0.93 (Lateral-medial Direction, at 10 kHz)
Williams and Saha [15]	*in vitro*	10 kHz, 100 kHz, and 1 MHz	human trabecular and cortical bone	Chlorided-silver metal Electrodes, LCR meter	$r = 0.4285$ between resistivity of human cortical bone and density measures
Sierpowska *et al.* [16]	*in vitro*	50 Hz - 5 MHz	human trabecular bone	Stainless-steel Electrodes, LCR meter	ε = 34.9 ± 4.7 (femur), 31.6 ± 7.7 (Tibia); $\sigma(S/m)$ = 0.085 ± 0.035 (femur), 0.101 ± 0.034 (Tibia)
Haba *et al.* [11]	*in vitro*	20 Hz	human trabecular bone	Impedance spectroscopy	ε = $(8.1 \times 10^6) \pm (5.2 \times 10^6)$

3. REVIEW OF DIELECTRIC PROPERTIES OF BONES

This section reviews each study that has investigated the dielectric properties of animal or human bones, along with studies that have examined the relationship between the dielectric properties of bones and bone quality (in terms of BMD) in the low frequency range (10 Hz - 1 GHz). The inter- and intra-species comparative analysis of dielectric properties of bones between different studies is presented in discussion section.

*A. **Dielectric properties of animal bone tissue***

This sub-section reviews all studies that have investigated dielectric properties of animal bones, presented in chronological order.

In 1983, Kosterich *et al.* [40] examined the dielectric properties of freshly excised and formalin fixed cortical femoral bone samples from rats across the frequency range of 10 Hz -

100 MHz. The bone sample size was six. An impedance analyser and a vector impedance meter were used to measure the complex impedance, with the bone samples placed between platinum electrodes. It was observed that the conductivity of fresh bone is 2-3 times higher than the conductivity of formalin fixed bone, and that the conductivity for both types of bone samples was independent of frequency below 100 kHz. It was observed in the study that, the conductivity of bone samples increases as power function of frequency. At 100 Hz, the average conductivity of six bone samples was found to be 12.6 mS/m and 4.8 mS/m for fresh and formalin fixed bone samples respectively. The average dielectric properties of six bone samples are tabulated in Table 2.

TABLE 2. Permittivity and conductivity values of rat bones at 37^oC

Frequency	**Conductivity mS/m (Fresh Bone)**	**Conductivity mS/m (Fixed Bone)**	**Permittivity (Fresh Bone)**	**Permittivity (Fixed Bone)**
100 Hz	12.6 ± 2.6	4.8 ± 0.7	$(3.8 \pm 2.0) \times 10^3$	$(1.6 \pm 0.5) \times 10^3$
1 kHz	12.9 ± 2.7	4.8 ± 0.7	$(1.0 \pm 0.5) \times 10^3$	$(7.7 \pm 1.0) \times 10^2$
10 kHz	13.3 ± 2.8	4.9 ± 0.7	$(6.4 \pm 2.4) \times 10^2$	$(4.2 \pm 0.5) \times 10^2$
100 kHz	14.4 ± 2.9	5.4 ± 0.6	$(2.8 \pm 0.3) \times 10^2$	$(1.9 \pm 0.3) \times 10^2$
1 MHz	17.3 ± 3.2	7.2 ± 1.1	$(8.7 \pm 1.3) \times 10^1$	$(8.1 \pm 1.2) \times 10^1$
10 MHz	23.7 ± 4.4	13.5 ± 2.3	$(3.7 \pm 0.5) \times 10^1$	$(4.0 \pm 0.7) \times 10^1$

Next, in 1984, Reddy and Saha [22] examined the dielectric properties of fluid-saturated cortical bovine bone across the frequency range of 1 kHz - 1 MHz. The bone sample size was five and the measurements were performed in all three principal directions (longitudinal, circumferential, and radial) of bone. A differential technique was used for dielectric properties measurement. The impedance was reported to be the lowest in the axial direction, whereas the specific resistivity in the radial direction was higher than that of the circumferential and axial directions. At 10 kHz, the values of specific resistance were found to be 54, 36, and 17 $k\Omega$ in radial, circumferential, and axial directions respectively. Similarly, at 10 kHz, the values of specific capacitance were found to be 21.4, 24.74, and 60.87 pF/cm in radial, circumferential, and axial directions respectively. The relative permittivity was found to be highest in the axial direction compared to radial and circumferential directions, as shown in Table 3.

In 1988, Mercato and Garcia [23] presented a comparative analysis between the dielectric

TABLE 3. Permittivity values of bovine cortical bones

Frequency	Axial Direction	Circumferential Direction	Radial Direction
100 MHz	74	30	23

properties of the proximal and distal epiphysis (The epiphyses are two extremes of tibia. The proximal epiphysis of tibia is near to knee and distal epiphysis is close to ankle) with diaphysis (the diaphysis is the central portion of bone between proximal and distal epiphyses) in a frequency range of 1 kHz - 1 MHz. The bone specimens were acquired from a bovine femur. The dielectric properties of bone samples were measured using the differential method. The measurement results indicated that the specific capacitance values in both epiphyses were larger than those obtained in diaphysis at any frequency. The relative permittivity was observed to be highest in the proximal epiphysis compared to distal epiphysis, and diaphysis, as shown in Table 4.

TABLE 4. Permittivity values of bovine femur at proximal, distal epiphysis and diaphysis of bovine cortical bones

Frequency	Extreme Proximal Epiphysis	Distal Epiphysis	Mid Region Proximal Epiphysis	Diaphysis
1 kHz	91049	85268	78948	68958

In 1991, De Mercato and Sanchez [24] examined the longitudinal variability of electric properties in three principal directions (radial, axial and tangential) along the diaphysis of bovine cortical femoral bone samples at three frequencies: 100 Hz, 10 kHz and 1 MHz. The bone sample size was nine. The dielectric properties were measured using an impedance analyser. It was observed that the conductivity and permittivity show significant variations along the diaphysis. The conductivity and relative permittivity values increased in magnitude near the epiphyses. The conductivity was found to be highest in the axial direction at all three measurement frequencies, intermediate in the tangential direction, and least in the radial direction. In conductivity, a variation of 47%, 53% and 59% was observed at different positions in axial, tangential, and radial directions respectively. The relative permittivity and conductivity values are tabulated in Table 5.

In 1996, Gabriel *et al.* [21] examined the dielectric properties of cortical and trabecular bone samples across the frequency range of 10 Hz - 20 GHz. Multiple measurement techniques were used. Specifically, an impedance analyser, network analyser, and OECL probes, were used to measure dielectric properties of bones. The bone samples were porcine. It was observed that the dielectric properties of trabecular bone are higher than those of cortical bone over the

TABLE 5. Permittivity and conductivity values of bovine cortical bone in three principal directions

Frequency	**Dielectric Properties**	**Axial Direction**	**Radial Direction**	**Tangential Direction**
1 kHz	Relative Permittivity	870	780	730
5 MHz	Conductivity ($\mu S/cm$)	73	40.2	54.5

investigated frequency range. However, this study only measured the dielectric properties of porcine cortical and trabecular bone samples.

In 2003, Sierpowska *et al.* [18] examined the dielectric properties of bovine trabecular bone samples across a frequency range of 100 Hz - 10 MHz. Electrical current was employed on samples through two round stainless-steel electrodes placed in a faraday cage with an LCR meter. The bone sample size was forty. This study also investigated the relationship between dielectric properties and Volumetric Bone Mineral Density (BMD_{vol}). The BMD_{vol} was measured by dividing the areal BMD with the sample thickness that was measured with a micrometre, where the areal BMD was measured by Dual energy X-ray absorptiometry (DXA). A strong positive linear correlation was observed between the BMD_{vol} and the dielectric properties $(r = 0.866)$. In this study, different sites of bovine femur were considered and it was observed that at f = 50 kHz the relative permittivity of femoral caput (FC) was highest (381) and the femoral greater trochanter was lowest (85). The corresponding BMD_{vol} in these sites were $0.586\ g/cm^3$ and $0.198\ g/cm^3$, respectively. At f = 50 kHz, the conductivity of femoral lateral condyle was found to be highest $(4.2\ S/m)$ and least in the femoral medial condyle.

Most recently, in 2018, Unal *et al.* [25] examined the relationship between the dielectric properties and the mechanical properties (toughness, strength and elastic modulus) across a frequency range of 20 Hz - 2 MHz. The measurements were performed on wet and increasingly dehydrated bovine cortical bones samples. The sample size was twenty-four. The dielectric properties of bones were measured using an LCR meter and a test fixture was used to place the bone samples. It was observed that the dielectric properties of bone vary as a result of dehydration of the bone. The authors found that the bound and unbound water components are major determinants of bone dielectric properties. It was observed in this study that the impact of unbound water on the dielectric properties is more significant than that of the bound water. The authors emphasized that their findings strongly suggest that dielectric properties of cortical bone may be used to identify the bone strength and toughness and hence further *in vivo* studies can be carried out.

B. Dielectric properties of human bone tissue

This sub-section reviews all studies that have investigated the dielectric properties of human bones. The studies are discussed in chronological order.

In 1984, Singh and Beharl [41] examined the dielectric properties of human cortical femur bone across a frequency range of 0.5 - 108 MHz. In the study, the parameters of resistivity, relative permittivity, dissipation factor, impedance, and phase angle were measured in bone to understand the mechanism of electrical osteogenesis (process of osteogenesis by using electrical stimulation). A Q-meter and vector impedance meter were used to measure the dielectric properties. The experiments revealed that the resistivity, relative permittivity, and impedance decrease as frequency increases. It was found that the resistivity and relative permittivity variations are least in the collagen, intermediate in the bone, and highest in the apatite. The comparative analysis of relative permittivity variation over observed frequency range for human bone, apatite, and collagen is shown in Figure 1.

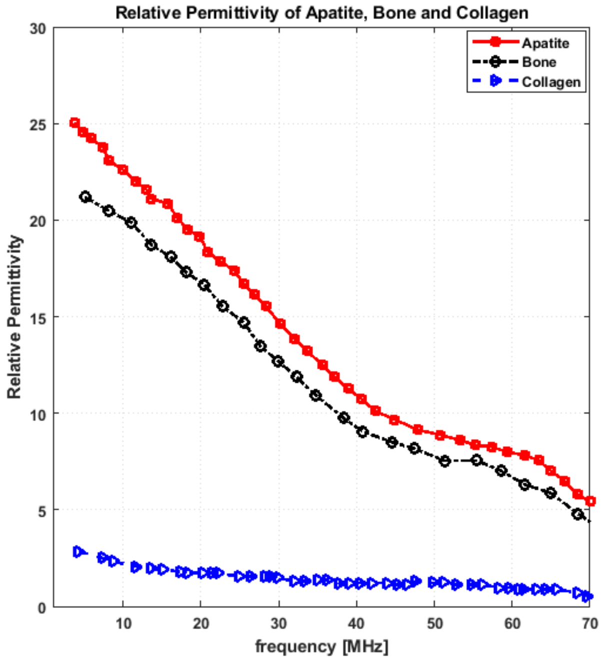


Fig. 1. Comparison of relative permittivity for human bone, apatite, and collagen [41].

In 1986, Saha and Williams [26] examined the electrical (resistivity and specific capacitance) and dielectric properties of wet human trabecular bone as a function of frequency (120 Hz - 10 MHz) and direction. The bone samples were acquired from the distal tibia of three patients (two male, one female). To measure the dielectric properties of bone samples in all three principle directions (longitudinal, circumferential, and radial), an LCR meter was used. The bone samples were placed between chlorided-silver electrodes. The mean resistivity of 30 trabecular bone specimens at 100 kHz in the longitudinal, anterior-posterior, and lateral-medial direction were 500 ohm-cm, 613 ohm-cm, and 609 ohm-cm respectively, whereas the mean specific capacitance of these bone samples at 100 kHz in the longitudinal, anterior-posterior, and lateral-medial direction were 8.64 pF/cm, 615.25 pF/cm, and 14.64 pF/cm, respectively. It was observed that the dielectric properties are significantly dependent on frequency; however, resistivity and impedance are not highly frequency dependent. The dielectric properties showed an anisotropic behaviour, since the values for the longitudinal direction differ from those obtained in the other two orthogonal directions. However, the values of the properties for the anterior-posterior direction and the lateral-medial direction show significant correlation.

In 1992, Saha and Williams [42] examined the electrical and dielectric properties of wet human cortical bone. The bone samples were acquired from the distal tibia of a 54 year old male. An LCR meter was used to measure the dielectric properties of the bone samples in all three principal directions. The bone samples were placed between chlorided-silver metal electrodes. The mean resistivity value of 10 cortical bone samples at 100 kHz in the axial, circumferential, and radial directions were 1.55 kΩ-cm, 15.79 kΩ-cm, and 21.5 kΩ-cm respectively; whereas the mean specific capacitance of these bone samples at 100 kHz in the axial, circumferential, and radial directions were 33.81 pF/cm, 9.98 pF/cm, and 9.83 pF/cm, respectively. The resistivity was found to be highest in the radial direction and lowest in longitudinal direction. Conversely, the specific capacitance was found to be highest in the longitudinal direction and lowest in the radial direction. The dielectric properties were measured in the radial direction, and it was reported that the dielectric properties of rat bones measured in [40] have larger values, compared to the dielectric properties of wet human cortical bone measured in this study.

In 1995, Saha and Williams [43] reported a comparative study on the dielectric properties of wet human cortical and trabecular bone samples across the frequency range of 120 Hz - 10 MHz. The study was performed on bone samples acquired from the distal tibia of three patients (two male, one female). The electrical and dielectric properties of cortical and trabecular bones were measured in three principal orientation of bones. An LCR meter was used to measure the dielectric properties of bone samples. The bone samples were placed between chlorided-silver metal electrodes. It was observed that the resistivity of human cortical bone is approximately 3.1 times higher than that of trabecular bone in the longitudinal direction and 25 times higher in the transverse direction. A similar trend was observed in the relative permittivity also. The relative permittivity of cortical bone was found to be approximately 3.9 times higher than that of the trabecular bone in the longitudinal direction, and 0.65 times higher in the transverse direction. The dielectric properties of both cortical and trabecular bone samples in all three directions at 10 kHz are tabulated in Table 6.

TABLE 6. Relative permittivity and conductivity values of trabecular and cortical bone samples in three orthogonal directions at 10 kHz

Human Trabecular Bone		
Direction	**Conductivity (mS/cm)**	**Relative Permittivity**
Longitudinal	2.31 ± 1.01	574 ± 371
Anterior-posterior	1.83 ± 0.69	594 ± 154
Lateral-medial	1.96 ± 0.93	601 ± 194
Human Cortical Bone		
Direction	**Conductivity (mS/cm)**	**Relative Permittivity**
Axial	66.2 ± 15.3	1.267 ± 66.3
Circumferential	7.0 ± 2.7	307 ± 61.6
Radial	5.3 ± 2.2	308 ± 111

In 1996, Williams and Saha [15] investigated the relationship of electrical properties of wet cortical and trabecular human bones with the wet, dry, and ash tissue densities. The bone samples were acquired from human distal tibia. The measurements were performed at the frequencies of 10 kHz, 100 kHz, and 1 MHz. As in the previous studies, the properties were measured using an LCR meter with chlorided-silver metal electrodes. In order to prevent dehydration, the measurements were carried out in a humidity chamber at near 100% relative humidity. A significant positive correlation ($r = 0.617$, at 100 kHz) was reported between dielectric properties of trabecular bone and density measures (wet, dry and ash bone tissue densities). Similarly, a positive correlation was observed between the specific capacitance of trabecular bone and density measures, whereas a weak correlation ($r = 0.4285$) was found between the resistivity of human cortical bone and density measures. It was observed that no correlation existed between resistivity of trabecular bone and density measures.

In 2005, Sierpowska *et al.* [16] examined the effect of dielectric properties variation on human trabecular bones acquired from different anatomical sites, across a frequency range of 50 Hz - 5 MHz. Trabecular bone samples were obtained from the distal femur and proximal tibia from thirteen human knee joints. The dielectric properties were measured by applying electrical current to samples through two round stainless-steel electrodes placed in a Faraday cage using an LCR meter. It was observed that the difference between the relative permittivity for femoral and tibial bone samples at 1.2 MHz was 9.5% approximately. However, the difference in conductivity at 1.2 MHz was approximately 16% between femoral and tibial bone samples.

In 2017, Haba *et al.* [11] examined the dielectric properties of trabecular and sub-chondral human femoral head bone of 20 patients who underwent a total hip replacement due to hip osteoarthritis. The dielectric properties of the bone samples were measured over 0.10 Hz - 10 kHz using impedance spectroscopy. The two electrodes were gold plated brass plates. A non-linear correlation between BMD and dielectric properties was reported in this study. It was suggested that electrical impedance spectroscopy can be applied for *in vivo* measurements of dielectric properties.

4. DISCUSSION

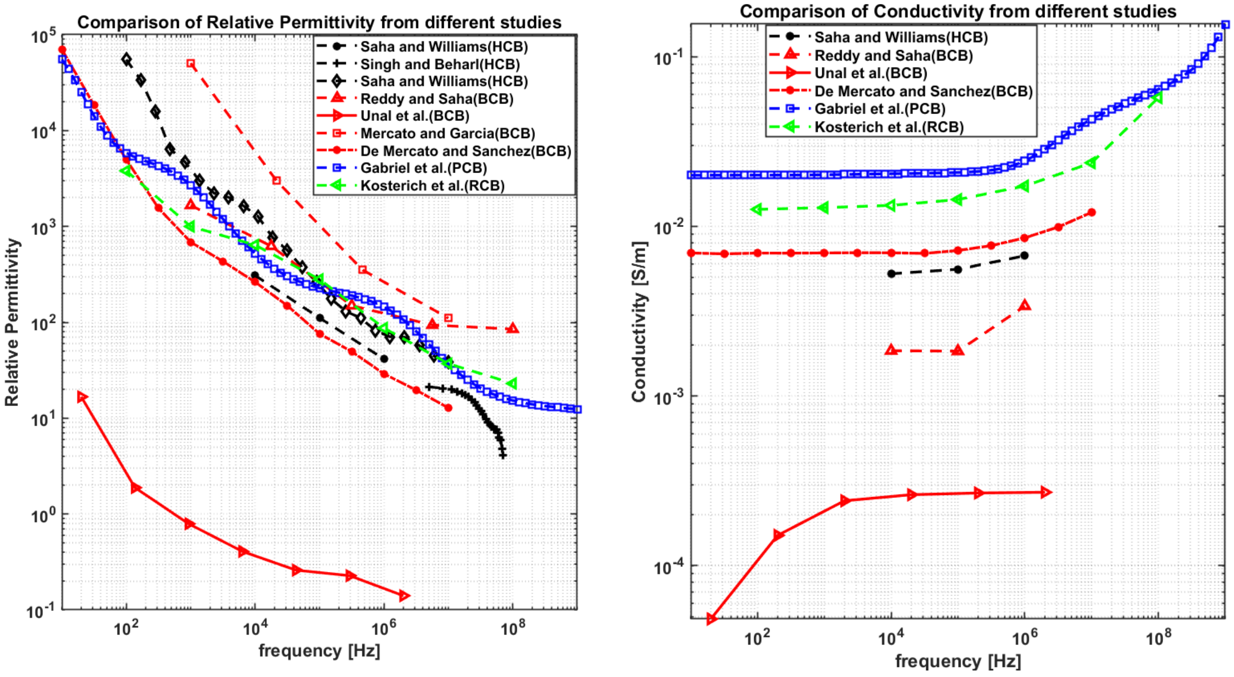
In this section, the variations in dielectric properties of both trabecular and cortical bones and the relationship between the bone dielectric properties and bone quality (in terms of BMD) in the low frequency range is discussed.

A. *Variations in dielectric properties of bones*

This sub-section discusses the variation of dielectric properties across the low frequency range for all reported studies to-date for both trabecular and cortical bones.

1) ***Variations in dielectric properties of cortical bone****:* The relative permittivity and conductivity of cortical bone samples in the low frequency range are plotted in Figure 2(a) and Figure 2(b) respectively. The data in the literature is reported across different frequencies, therefore, for the comparison, a common frequency point (10 MHz) is chosen in order to evaluate the variation in the data. A comparative analysis indicates that:

1) There is a significant variation in the relative permittivity of the cortical bone (mean ± standard deviation (SD) = 40.93 ± 35.63) across different species (human, porcine, bovine, and rat), which is also in-line with the BMD variation reported in [44].
2) The relative permittivity of the bovine cortical bone (52.86 ± 54.59) is significantly higher than that of the human cortical bone (29.33 ± 8.62). Considering the higher BMD of bovine compared to human, a positive correlation between the relative permittivity and BMD can be inferred, which is also in-line with the findings of [15], [18].
3) The variation in the relative permittivity of human cortical bone (SD = 8.62, 29%) is lower than the variation in bovine cortical bone (SD = 54.59, 103%). The dielectric properties reported by Unal *et al.* [25] are found to be significantly low in comparison to the literature. The underneath reason of this difference may be due to; different measurement procedure, sample preparation, bone composition, porosity of bone sample, age and anatomical location of bone.



(a)

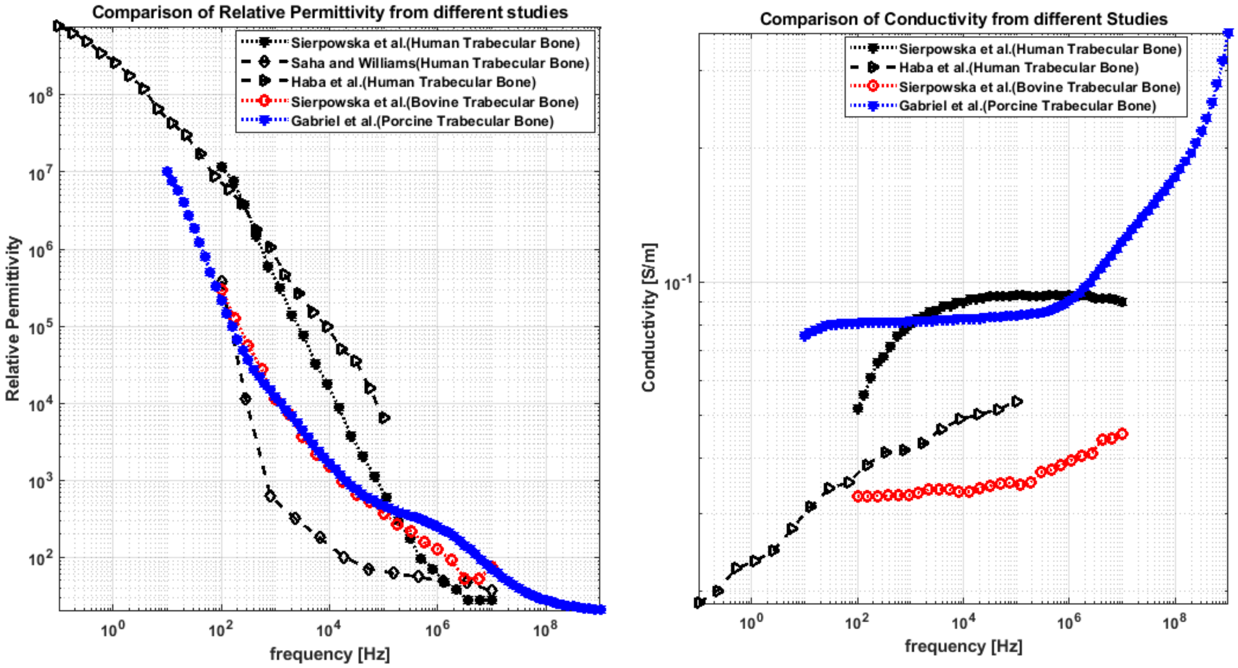
(b)

Fig. 2. Comparison of dielectric properties of cortical bone from reported studies. The graph shows a comparison between dielectric properties of bones sourced from different species (human, bovine, porcine and rat).The dielectric properties reported for Unal *et al.* are for wet bone sample. HCB = Human Cortical Bone; BCB = Bovine Cortical Bone; PCB = Porcine Cortical Bone; RCB = Rat Cortical Bone.

*2) **Variations in the reported dielectric properties of trabecular bone:*** The relative permittivity and conductivity of trabecular bone over the low frequency range are shown in Figure 3(a) and Figure 3(b) respectively. The available studies did not allow the same choice of frequency as in part A, so for the comparison 10 kHz is chosen to calculate the variation in the data. The comparative analysis indicates that:

1) There is a significant variation in the relative permittivity of the trabecular bone (mean ± standard deviation (SD) = 23904 ± 42180) between different species (human, bovine and porcine).
2) There is a significant variation in the relative permittivity of the human trabecular bone. The mean and standard deviation from different studies is found to be 38777 ± 52238.
3) The relative permittivity values of porcine and bovine trabecular bone samples show less variation, the mean percent difference between relative permittivity values of porcine and bovine trabecular bone samples is 20%.

It is assumed that the intra-species differences between the bone dielectric properties are mainly due to the type of sample (i.e., the anatomical location), measurement technique and age of specie, however the inter-species differences between the bone dielectric properties are due to bone samples acquired from different species (bovine, porcine, human, rat).



(a) **(b)**

Fig. 3. Comparison of dielectric properties of trabecular bone from reported studies. The reported studies exhibit variation in results, and the dielectric properties of trabecular bones of human, bovine, porcine and rat all vary from each other.

B. Relationship between the Dielectric Properties of Bone and Bone Mineral Density

This sub-section examines the relationship between the bone dielectric properties and BMD, as a platform for new medical device development to potentially diagnose and monitor osteoporosis. A total of three studies reported on the relationship between BMD and dielectric properties, two of which involved human bones [15] and [11] and one which involved animal bones [18]. The comparative analysis indicates that:

1) Dielectric properties of bone appear to vary monotonically with BMD [18], [31]. It is well reported in the literature that the BMD varies with age [45], [46], thus it can be deduced that the dielectric properties of bones may also vary with age [31].

2) Two of the three studies reported a positive linear correlation between the dielectric properties and the BMD, while one reported a non-linear correlation.

To summarize, Sierpowska *et al.* [18] found a strong positive linear correlation between BMD and dielectric properties ($r = 0.866$) at 50 kHz for bovine trabecular bone samples. Consistent with Sierpowska, Williams and Saha in [15] found a correlation of $r = 0.617$ between the dielectric properties and BMD at 100 kHz. Both studies are in agreement with each other, however the difference between the correlation coefficients may be due to the difference in species, as Sierpowska *et al.* [18] investigated the relationship for bovine trabecular bone samples and Williams and Saha [15] investigated the same for human distal tibia. In contrast to the two above studies, Haba *et al.* [11] found a non-linear correlation between dielectric properties and BMD for human trabecular bone samples. The authors stated that the difference was likely due to the difference of bone samples from osteoarthritis human patients, unlike the above studies that utilized healthy bone samples. BMD values were not reported in this study and the change of dielectric properties was expressed in terms of percentage change of mineralization.

5. CONCLUSION

In this paper, the first comprehensive review of the low frequency dielectric properties of bone has been presented. The focus of this review was to analyze and summarize the existing dielectric data in a structured, quantitative way such that the conclusions could inform the development of novel low frequency medical devices. Specifically, the variation in measurement techniques and reported data in literature has been examined, and relationship between the dielectric properties and bone health (in terms of BMD) has been analyzed.

Significant inter- and intra-species variation in the dielectric properties was observed in the reported data. The intra-species variation can be associated with the difference in the bone type, measurement technique, and sample handling. The studies examining the relationship between BMD and dielectric properties found contradictory results. Two studies reported a positive linear correlation between BMD and the dielectric properties; however, one study found a non-linear correlation. Hence, significant future work is required to establish the relationship between BMD and dielectric properties over the low frequency range, especially since BMD is a key potential indicator in osteoporosis detection.

The reviewed studies vary in terms of measurement technique, the bone species source, and the anatomical location. These variations account for significant differences in the results reported. The analysis presented here suggests that extensive work is required in order to truly understand the dielectric and electrical behaviour of bones. Such work would help the medical device industry to develop devices for electrical stimulation during osteogenesis, for orthopaedic surgeries, and for osteoporosis detection.

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