Investigating human bone microarchitecture and dielectric properties in microwave frequency range

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***Abstract*— Dielectric properties of bones are proposed to monitor bone quality. However, no study has investigated the relationship between bone dielectric properties and microarchitecture of bone, which is of paramount importance for bone quality assessment. This paper reports the first *in-vitro* investigation of relationship between dielectric properties of human trabecular bone (n = 45) and its microarchitecture parameters (trabecular number, trabecular thickness and trabecular spacing). The objective of the study was to investigate the difference between osteoporotic (n = 23) and osteoarthritis (n = 22) patients in terms of microarchitectural parameters and dielectric properties and to examine any relationship between microarchitectural parameters and dielectric properties. A significant difference was observed between osteoporotic and osteoarthritis patients in terms of microarchitecture parameters. The trabecular number and trabecular thickness were found to be significantly high for osteoarthritis patients in comparison to osteoporotic patients. The percentage difference for trabecular number and trabecular thickness between both patients group was found to be 27% and 31% respectively. Trabecular spacing was lower in osteoarthritis patients compared to osteoporotic patients. Similar differences were also observed between both patients group in terms of dielectric properties. More importantly, the dielectric properties were significantly higher for osteoarthritis patients than osteoporotic patients with a percentage difference of 42% and 32% at 900 MHz in terms of relative permittivity and conductivity respectively. These preliminary findings support the idea of using dielectric properties to as a method to differentiate bone quality.**

***Index Terms*—trabecular microarchitecture, dielectric properties, bones, osteoporotic, osteoarthritis.**

I. INTRODUCTION

The interaction of electromagnetic (EM) waves with human biological tissues is mainly characterized by dielectric properties (namely relative permittivity and conductivity) of biological tissues [1]. The knowledge of these dielectric properties forms basis of a number of diagnostic and therapeutic medical devices [2], [3]. These devices include microwave imaging for breast health monitoring, microwave ablation for treating liver, lung and adrenal tumors and hyperthermia for breast cancer treatment [4],[3],[5]. Electrical stimulation is widely employed in diagnosis and treatment of bone diseases such as fixing bone fracture and during bone surgeries [6]. Osteoporosis is a major bone disease caused by demineralization of bones and results into deterioration of trabecular bone microarchitecture [7],[8]. This loss of microarchitecture leads to bone fractures [9]. In clinical practice, bone mineral density (BMD) is considered as a key potential indicator for detection of osteoporosis and is obtained via Dual X-ray Absorption (DXA) scan [10], [11]. DXA scan uses the standard X-ray doses, therefore frequent DXA scans can cause long term health risks and it does not diagnose osteoporosis correctly as it only measures bone quantity, not quality; even variations in bone size can skew BMD scores [12], [13]. Some studies have suggested that dielectric properties of bones can potentially be used to detect osteoporosis, since it was observed that the dielectric properties of bones are influenced by different levels of BMD [14], [15]–[17]. However, limited studies have investigated a correlation between bone dielectric properties and bone quality in terms of BMD [7]. Three of the total four studies on relationship between dielectric properties and BMD reported a negative correlation, while one reported a positive correlation [14], [15], [18], [19]. Further, only one of these four studies measured *in vivo* dielectric properties of human bones and the sample size was limited to two healthy volunteers. Therefore, no definite conclusion can be drawn from these results. Moreover, no study has previously measured dielectric properties of diseased human bone samples. Therefore, more studies with larger sample size are required to establish accurate knowledge of bone dielectric properties, particularly for diseased bone samples varying in bone quality.

The specific research question of this study was, whether change in trabecular bone microarchitecture is linked to change in dielectric properties. The study used forty-five bone samples from osteoporotic and osteoarthritis patients. These samples were expected to have different trabecular microarchitecture as they belong to patients with different disease types. The trabecular bone microarchitecture of osteoarthritis patients is more compact and dense as compared to osteoporotic patients, [20]. Osteoporosis weakens bone microarchitecture, however, osteoarthritis patients have comparatively compact and dense microarchitecture. These two patient populations provide bone samples with varying bone quality. The analysis of microarchitecture of these bone samples was performed by CT scan and then dielectric properties were measured *in-vitro* using

open-ended coaxial probe across microwave frequency range of 0.5 - 8.5 GHz. Both microarchitectural parameters and dielectric properties were compared between osteoarthritis and osteoporotic patient population. Statistical analysis of results was performed to analyse statistical significance of results.

II. Methodology

Sample collection

This study was performed on twelve patients (seven osteoporotic patients and five osteoarthritis patients). Donations of human femoral heads were obtained under ethical approval and informed written patient consent. The patients were undergoing through total hip replacement surgeries. The mean age of osteoporotic patients was 70.5 ± 8 years and for osteoarthritis patients the mean age was 73.4 ± 1 years. Trabecular bone samples were obtained from femoral head of each patient. Based on availability of bone samples from each patient the total sample size from both sets of diseased patients was forty-five (n = 45, osteoporotic bone samples n = 23, osteoarthritis bone samples n = 22). The average dimensions of measured bone samples were (12.7 ± 1.4) mm × (5 ± 0.5) mm × (5 ± 1) mm (length × width × depth).

In order to prevent loss of moisture from bone samples after surgical extraction, the samples were put into phosphate buffered saline (PBS) and were frozen at -20 °C, until measurements were performed. This preservative procedure is same as used in previous studies of bone dielectric properties [13],[14].

Microarchitecture parameters measurement

To obtain the microarchitecture parameters of bone samples such as trabecular number (Tb.N), trabecular thickness (Tb.Th), and trabecular spacing (Tb.Sp), each bone sample was microCT scanned at 17.2 μm voxel size (Scanco μCT100, Energy Intensity: 70kVp, 114 μA, 8 W, using 0.1mm aluminum filter to minimize beam hardening, integration time: 500msec). Using vendor software, volumes of interest (VOIs) were contoured manually from each bone core and thresholded (using a single global threshold of 355 mgHA/cm^3 for all cores). The contoured images were segmented to create a binary image, isolating bone tissue. Manufacturer supplied evaluation scripts were run on segmented VOIs to quantify Tb.Th, Tb.N and Tb.Sp. In order to ensure the consistency between microCT scans, the equipment was weekly calibrated by using hydroxyapatite phantoms. After microCT scan, the bone samples were also tested mechanically under compression and refrozen. The compression may have slightly altered the microarchitecture of bone samples, which would not skew TbTh, but may slightly alter TbN and TbSb. However, bone content remained same and all bone cores received same treatment.

Dielectric properties measurement

Prior to dielectric measurements, the bone samples were taken out of PBS and brought to room temperature. The surface of each bone sample was cleaned to avoid any contribution of PBS to dielectric properties measurement. The Open-ended coaxial probe measurement technique was employed in frequency range of 0.5 – 8.5 GHz over 101 linearly spaced points. The Keysight E5063A vector network analyzer (VNA) was connected with the Keysight slim form probe 85070E. A standard three-load one-port calibration (Air, Short and Deionized water) was used to calibrate the measurement equipment. The calibration of the measurement equipment was verified by measuring dielectric properties of 0.1 M NaCl solution (saline) [23]. The combined uncertainty of the measurement equipment was found to be 0.61% and 2.54% for relative permittivity and conductivity, respectively. A total of four measurement locations were chosen for each bone sample (two at the top and two at the bottom) to account for within sample variations and three measurements were performed at each measurement location of the sample. The temperature of each sample was recorded before measurement and was found to be 22 ± 0.1 °C.

III. Results And Discussion

Fig. 1-3 compare trabecular microarchitectural parameters between osteoporotic and osteoarthritis patients. The trabecular number from both sets of patients are shown in Fig. 1. It can be observed that the values of trabecular number for osteoarthritis patients are higher as compared to values for osteoporotic patients. The percentage difference in terms of trabecular number was found to be 27% between both patients groups. A two-tail *t-test* was performed to find statistical significance of the difference between microarchitectural parameters of osteoporotic and osteoarthritis patient's bone samples. A *p-value* < 0.01 was obtained for each of the microarchitectural parameter suggesting statisticall significance of the differences. Hence, the above results confirm that the patients suffering from osteoporosis have less compact trabecular number compared to osteoarthritis patients as expected.

Extending the microarchitectural analysis, the trabecular thickness of both set of patients is compared in Fig. 2. Since patients suffering from osteoporosis have weak and less compact trabecular microarchitecture, thus the thickness of trabeculae reduces as well [24]. It can be observed from Fig. 2 that the trabeular thickness of ostearthritic patients is also higher as compared to trabecular thickness of osteoporotic patients. The percentage difference is found to be 31%. The trabecular spacing was observed to have inverse relationship with the disease compared to trabecular number and trabecular thickness. Since, osteoporosis deteriotes the trabecular microarchitecture, thus the spacing between trabeculae increases [25]. Thus it can be observed from Fig. 3 that the trabecular spacing is higher for osteoporotic patients compared to trabecular spacing of osteoarthritis patients. The percentage difference is found to be 33%.

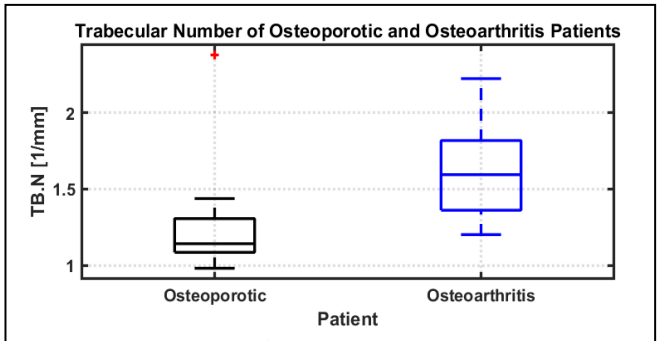


Fig. 1. Trabecular Number of Osteoporotic (black box) and Osteoarthritis Patients' (blue box) bone samples. The red markers are outliers in data.

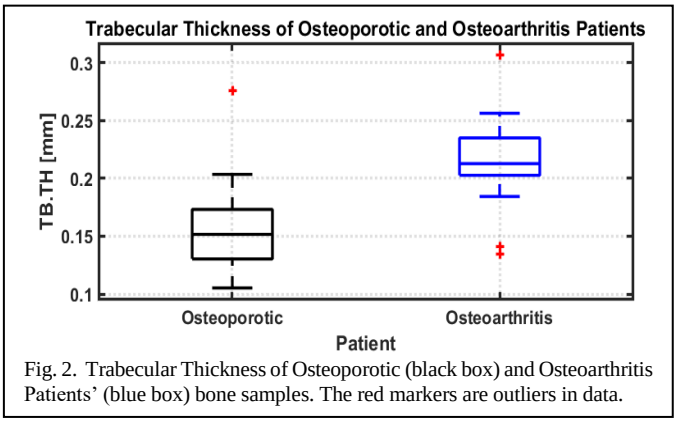


Fig. 2. Trabecular Thickness of Osteoporotic (black box) and Osteoarthritis Patients' (blue box) bone samples. The red markers are outliers in data.

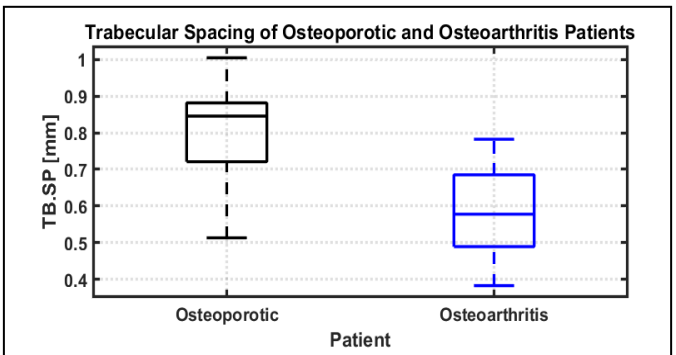
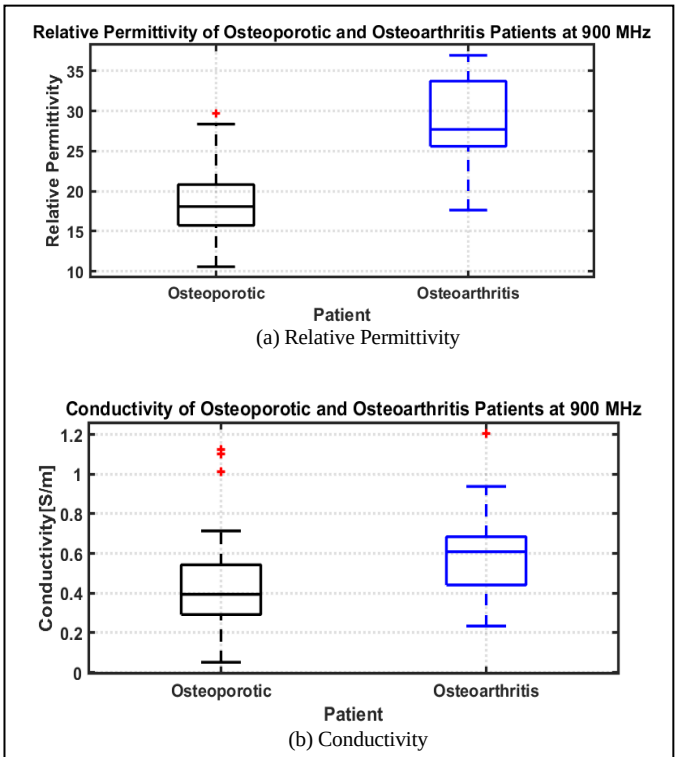


Fig. 3. Trabecular Spacing of Osteoporotic (black box) and Osteoarthritis Patients' (blue box) bone samples.



(a) Relative Permittivity

(b) Conductivity

Fig. 4. Box plots of relative permittivity and conductivity for Osteoporotic (black box) and Osteoarthritis Patients' (blue box) bone samples. The red markers are outliers in data.

The relative permittivity and conductivity of each bone sample obtained from osteoporotic and osteoarthritis patients are shown in Fig. 4 in terms of box plot. It can be observed from Fig. 4 that the relative permittivity of bone samples obtained from osteoarthritis patients are higher as compared to osteoporotic patients. At 900 MHz the percentage difference between both sets of patients is found to be 42% and 32% in terms of relative permittivity and conductivity, respectively. Similar results were obtained on other frequency points as well. A two-tail *t-test* was performed to find statistical significance of difference between dielectric properties of osteoporotic and osteoarthritis patient's bone samples. The *t-test* was performed at 900 MHz, 2.42 GHz, 4.02 GHz and 6.02 GHz. A *p-value* < 0.01 was calculated at each of the above mentioned frequency points and difference at each frequency was found to be statistically significant. The frequency points were selected based on comparsion of our findings to what reported in literature. The spread of values in relative permittivity is less for osteoporotic patients compared to osteoarthritis patients as observed in box plots of each patient. This difference in dielectric properties can be attributed to the fact that the trabecular microarchitecture of osteoarthritis patient is much more compact and dense compared to osteoporotic patient's trabecular microarchitecture. The dense trabecular microarchitecture of bone indicates higher degree of mineralization due increased amount of bone present [26], [27] and difference in mineralization results in dielectric properties variation. As the trabecular spacing increases between trabecular bones, the empty spaces are filled with yellow marrow that mostly constitutes fats, resulting in lower overall dielectric properties of bone. The findings of this analysis supports the fact that the change in trabecular bone microarchitecture is linked to change in dielectric properties. The results suggest that the higher trabecular number and trabecular thickness result in the higher relative permittivity and conductivity.

IV. Conclusion

In this study the relationship between dielectric properties of human trabecular bones and trabecular microarchitecture was analyzed. The study reports significant differences between osteoporotic and osteoarthritic patients in terms of trabecular number, trabecular thickness and trabecular spacing. The measurement results reveal significant percentage difference between microarchitecture parameters of both sets of patients. Similarly, significant differences were observed in terms of relative permittivity and conductivity at observed frequency points. The results suggest that differences in microarchitecture parameters are reflected in dielectric properties as well. The mean dielectric properties (conductivity and relative permittivity) of osteoarthritic trabecular bone are higher in magnitude than osteoporotic trabecular bone from the human femoral head. Hence, dielectric properties can be potentially used to classify bones of different microarchitecture. These findings motivate the design and development of a microwave imaging based device to measure *in-vivo* dielectric properties of bone.

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