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Microwave Tomographic Imaging for Osteoporosis Screening: a Pilot Clinical Study

Zhou Tian [Student Member, IEEE], Paul M. Meaney [Member, IEEE], Matthew J. Pallone, Shireen Geimer, and Keith D. Paulsen [Member, IEEE]

Abstract

We are developing a microwave tomographic system for assessment of overall bone health. We hypothesize that as the mineralization of bone decreases due to the normal aging process and for more extreme situations such as osteoporosis, the dielectric property signature will also vary accordingly. To determine the merits of this approach, we have begun by performing initial exams of the heel to assess the level of image quality achievable. Early experience from our pilot study is encouraging and indicates that multiple planes of 2D images produce good representations of the 3D structural features within the heel.

I. INTRODUCTION

Osteoporosis is the most common bone disease in humans, and it represents a major public health problem as outlined in "Bone Health and Osteoporosis: A Report of the Surgeon General" [1]. The National Osteoporosis Foundation (NOF) has estimated that more than 10 million Americans have osteoporosis and an additional 33.6 million have low bone density of the hip. About one out of every two Caucasian women will experience an osteoporosis-related fracture in her lifetime, as will approximately one in five men [1]. Overall, hip fractures cause an excess mortality of 10 to 20 percent at 12 months, and up to 25 percent of patients with hip fractures require long term nursing home care [2].

Dual-energy x-ray absorptiometry (DXA) measurement of the hip and spine is the principal technology now used to establish or confirm a diagnosis of osteoporosis, predict future fracture risk and monitor patients by performing serial assessments [3]. Central DXA measurements of the hip or spine are currently the "gold standard" for serial assessment of bone mineral density (BMD). However, bone strength, which determines the fracture risk, is not derived solely from BMD [4]. It is also related to bone quality factors such as trabecular and cortical architecture, bone tissue composition, mineralization and rates of bone turnover [5].

Quantitative computed tomography (QCT) is more sensitive than DXA at detecting bone density differences or serial changes. Volumetric QCT can provide both densitometry and geometrical components either of the entire bone or its cortical and trabecular components separately, but it is costly and results in even greater radiation exposure than DXA. Calcaneal quantitative ultrasound (QUS) assesses two principle parameters: broadband ultrasound attenuation and speed of sound. QUS is less expensive, portable, non-ionizing, and does not require specially trained personnel; however, ultrasound cannot penetrate through bones very well in nature. There is no accepted threshold for a positive T-score of

the QUS index. A meta-analysis in 2006 concluded that QUS results using commonly used screening thresholds appeared to be insufficient for ruling in or out DXA-determined osteoporosis [6].

A new, noninvasive osteoporosis screening tool is need to look beyond bone mineral density and more at bone quality. Microwave imaging recovers dielectric maps (electrical permittivity and conductivity) of interrogated tissues. These properties essentially quantify the interactions of materials with external electromagnetic (EM) fields. For instance, studies have shown that collagen is a major source of the dielectric dispersion in bones, presumably due to counter-ion polarization effects. Bone consists of 20% collagen by weight, which is of critical importance to bone tensile strength [7]. At low frequencies (below 10 MHz), experiments performed on fluid-saturated bone by Chakkalakal et al. suggest that the dielectric properties of wet bone appear to be related to bone porosity [8]. In addition, strong correlations have been found between dielectric properties and mechanical properties (ultimate strength, Young's modulus, yield stress, etc.) in human trabecular bones over these low frequency ranges [9]. To the best of the author's knowledge, relationships between the microwave dielectric properties and mechanical properties or BMD of human bones have not been reported. Because of this diagnostic need and because of the potential of microwave imaging in this application, we are conducting a pilot clinical study to test the feasibility for bone imaging.

II. METHODS

A. Microwave Tomographic Imaging

Meaney et al. has previously developed a clinical prototype using microwave tomographic imaging (MTI) technology for breast imaging in 2000 [10]. To date, over 300 female volunteers have been imaged in over 500 exams with the first prototype and its successive system versions for neoadjuvant chemotherapy monitoring.

In the MTI system, the 16 monopole antennas are positioned in a 15.2 cm diameter circular array (Figure 1) with each antenna being able to function as both transmitter and receiver. Microwave signals are broadcast sequentially from one antenna at a time and received by the complement of 15 antennas. When a homogeneous object, with different dielectric properties than the coupling liquid, is illuminated within the imaging region, it distorts the field pattern in terms of reflection, scattering and absorption. If the object is heterogeneous, the normal case for biological materials, it further complicates the propagation. (We tailor the coupling bath to minimize the difference between its dielectric properties and the overall properties of the target to more precisely reveal the internal structures of the object. The antenna array can move vertically so that multiple 2D cross sections at different heights can be imaged. In addition, the even- and odd-number sets of antennas can move independently so that 3D full volumetric data can be acquired (for 3D imaging which is currently being investigated). Data is acquired over a range of frequencies (500MHz-2500MHz), after which microwave images are reconstructed offline using an iterative Gauss-Newton method. The hardware of the MTI system is shown in Figure 2.

Figure 3 shows an E-field simulation of an in-plane transverse electric (TE) wave at 1GHz using Comsol Multiphysics software (COMSOL, Inc., Burlington, MA, USA). The black dot indicates the microwave signal source. The microwave propagates through a background media ($\epsilon_r=5.41$, $\sigma=0.05\text{S/m}$) and is distorted by the testing object ($\epsilon_r=59.47$, $\sigma=1.08\text{S/m}$, indicated by the arrow). The distortion is formed because the testing object has different dielectric properties than the background (the coupling bath in our case). Dielectric properties consist of permittivity (ϵ_r) and conductivity (σ). Permittivity reflects the extent to which localized charge distributions can be distorted through polarization by an external

field, while conductivity is a measure of the ease with which delocalized electric charge can migrate through the material under the field's influence [11].

B. MTI for Osteoporosis Screening

In osteoporosis, bone mass decreases and pore size increases. The lost bone mass is replaced by a mixture of bone marrow (high dielectric properties) and fat (low dielectric properties). We hypothesize that the corresponding changes in dielectric properties in this remodeling process can be used to evaluate the condition of bone health. We have conducted ex vivo experiments on saline saturated bone specimens to investigate the relationship between dielectric properties and BMD. We have also initiated MTI heel scanning to assess the level of image quality achievable (Figure 4). The heel was chosen as the imaging target because the calcaneus is composed mainly of trabecular bone and is weightbearing making it quite similar to more critical injury-prone sites such as the spine and hip. Trabecular bone is generally sensitive to mass changes due to its higher turnover and larger surface area compared with cortical bone. Because minor bone changes are usually only detectable over long time periods, we deliberately chose human volunteers with either a recent lower leg or foot injury, who would experience fairly large mineralization changes over a short time period because of the non-weight-bearing recovery protocol. During the study, we imaged patients just after having either a cast or boot removed (typically worn from 6-10 weeks depending on the recovery protocol) and at 6 - 10 weeks afterwards. At the first session the patients were imaged with x-ray CT, MTI and QUS (Figure 5). This allowed for comparison between contralateral controls of all three modalities. At the second visit, we performed MR, MTI and QUS measurements. In this case, only contralateral comparisons could be performed for the MTI and QUS modalities. The CT images were not repeated at the second date due to excessive exposure concerns. The MR images were performed to aid with soft prior imaging studies where internal structural information is required. The QUS measurements were used to both confirm contralateral measurements at the first session and also for longitudinal analysis. In the case of the CT and MTI images, we performed standard region of interest (ROI) analyses which we have utilized in previous breast studies.

To facilitate image co-registration between modalities, a custom fixture was used in all MTI, CT and MR scans. An optical scanning system has recently been developed and will be integrated into the system shortly which can recover accurate renderings of the heel surface while inside the MTI tank. The geometry profile will help reduce co-registration errors between the various imaging modalities.

III. RESULTS

To the best of the author's knowledge, the first in vivo microwave images (with 1cm spacing between two slices) of human heel are shown in the first row of Figure 6. The corresponding CT images, reconstructed with Mimics software v13.1 (Materialise US, Ann Arbor, MI, USA), are shown in the second row. It should be noted that the CT coronal slice thickness is 0.39mm for this system. From previous studies, we estimate that the effective slice thickness for the microwave images to be on the order of 2cm. Volume-based comparisons will be performed in future analyses utilizing our full 3D reconstructed images.

For the first slice of the permittivity images, the heel cross section appears as a triangle with a low property zone in the middle corresponding to the calcaneus (marked with red arrow) and the higher property areas to the surrounding soft tissue (high water content tissue has higher dielectric properties). The widening soft tissue area to the right corresponds to the area extending to the underside of the foot and the narrowing portion to the left corresponding to the back of the ankle zone. As the slices progress further down to the apex, the heel progressively disappears (Figure 7).

IV. CONCLUSION

We have begun imaging the heels of injured patients to assess whether we can acquire quantitative images of the heel that may be meaningful in the context of assessing overall bone health. Early results suggest that our sets of 2D images at multiple planes convey meaningful information about the heel structure and property distribution. The image resolution is sub-centimeter and can be improved with frequency increase. We are in the early stages of comparing the images of injured and control (contralateral) heels to assess whether the recovered properties are sensitive to changes of bone loss. We are also progressing to full 3D images of the heel where we will be able to recover more complete renderings of the dielectric property distributions. These tests are the first steps towards developing a system that will provide diagnostically relevant bone health information.

REFERENCES

1. U. General. A report of the Surgeon General. Department of Health and Human Services; 2004. Bone Health and Osteoporosis.
2. Watts N, Lewiecki E, Miller P, Baim S. National Osteoporosis Foundation 2008 Clinician's Guide to Prevention and Treatment of Osteoporosis and the World Health Organization Fracture Risk Assessment Tool (FRAX): what they mean to the bone densitometrist and bone technologist. *Journal of Clinical Densitometry*. 2008; 11(4):473–477. [PubMed: 18562228]
3. Kanis J, Melton L, Christiansen C, Johnston C, Khaltav N. Perspective: the diagnosis of osteoporosis. *Journal of Bone and Mineral Research*. 1994; 9(8):1137–1142. [PubMed: 7976495]
4. Turner C. Bone strength: current concepts. *Annals of the New York Academy Science*. 2006; 1068:429–446.
5. Bouxsein M. Bone quality: where do we go from here? *Osteoporosis International*. 2003; 14(suppl. 5):S118–27. [PubMed: 14504716]
6. Nayak S, Olkin I, Liu H, Grabe M, Gould M, Allen I, Owens D, Bravata D. Meta-analysis: accuracy of quantitative ultrasound for identifying patients with osteoporosis. *Annals of internal medicine*. 2006; 144(11):832. [PubMed: 16754925]
7. Kosterich J, Foster K, Pollack S. Dielectric permittivity and electrical conductivity of fluid saturated bone. *IEEE Transactions on Biomedical Engineering*. 1983:81–86. [PubMed: 6832795]
8. Chakkalakal D, Johnson M, Harper R, Katz J. Dielectric properties of fluid-saturated bone. *IEEE Transactions on Biomedical Engineering*. 1980:95–100. [PubMed: 7353901]
9. Sierpowska J, Hakulinen M, Toyra J, Day J, Weinans H, Jurvelin J, Lappalainen R. Prediction of mechanical properties of human trabecular bone by electrical measurements. *Physiological measurement*. 2005; 26(2):119.
10. Meaney P, Fanning M, Li D, Poplack S, Paulsen K. A clinical prototype for active microwave imaging of the breast. *IEEE Transactions on Microwave Theory and Techniques*. 2000; 48(11): 1841–1853. Part 1.
11. Pethig R. Dielectric and electrical properties of biological materials. *Electromagnetic Biology and Medicine*. 1985; 4(2)

Fig. 1.
Microwave antennas of the microwave tomographic imaging system.

Fig. 2.
Photo of the microwave tomographic imaging system.

Fig. 3.
E-field simulation of in-plane TE wave at 1GHz. The black dot indicates the source, and the black circle outlines the testing object.

Fig. 4.
Illustration of MTI scan on human heel. White rods indicate the antenna array.
Reconstructed with Mimics 13.1.

Fig. 5. Examination on human heel with different modalities. Upper left: MTI; upper right: CT; lower left: MRI; lower right: QUS.

Fig. 6. Upper: permittivity images of a human heel at 1300MHz in two different planes; Lower: corresponding CT images in the same planes.

Fig. 7.
Stack of 2D permittivity images of human heel at 1300MHz with 1cm spacing.