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Proceedings of Symposium on Ultrasonic Electronics, Vol. 33 (2012) pp. 523-524
13-15 November, 2012

Acoustically Stimulated Electromagnetic Response in Bones

骨の音響誘起電磁応答

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1. Introduction

Bone is a connective tissue largely composed of collagen and inorganic mineral hydroxyapatite. Depending on the orientation of collagen fibers, two types of bone can be distinguished: outer cortical bone and inner trabecular bone. Bone mineral density obtained by X-ray or ultrasonic techniques [1] is normally used as an indicator of bone conditions, but the evaluation method of collagen quality is still in development.

We here focus on acoustically stimulated electromagnetic (ASEM) response originated from piezoelectricity of bone [2]. Since the origin of piezoelectric of bone is considered to be piezoelectricity of fibrous collagen crystals [3, 4], ASEM response may provide an indicator of collagen density or crystal orientation. The piezoelectric tensor is evaluated to be $d_{14} = 0.22$ [pC/N], $d_{15} = 0.043$ [pC/N], and $d_{31} = d_{32} \approx d_{33} = 0.0033$ [pC/N] for the C_∞, where the principal axis of the tensor is taken as the axis of bone. Temporal modulation of electric polarization is induced through the electromechanical properties when piezoelectric materials are irradiated with ultrasonic waves. According to classical electromagnetic (EM) field theory, time oscillation of electric polarization radiates EM fields into the surrounding media with the oscillation frequency. In recent years, we demonstrated detection of ASEM fields in a variety of materials with a tuned loop antenna placed on the near-field region [2, 5]. In this paper, we provide experimental results of ASEM measurements in piezoelectric bone and discuss its mechanism through X-ray computed tomography (CT).

2. Experimental Setup

In the ASEM measurements, rectangular 50ns wide pulses are applied at a repetition rate of 1 kHz by a pulser/receiver (Panametrics-NDT, 5077PR). To distinguish ASEM response from transducer noise, a target sample is placed in a focused zone at a distance (60mm) from 10 MHz transducer (Fig.1(a)) [2]. The ASEM signals are thus temporally separated at half of the echo delay time as shown in Fig.1(b). The signals are detected through a loop antenna tuned at a center frequency of 9.6MHz and amplified by 80 dB with low-noise preamplifiers (NF, SA-230F5). Two-dimensional (2D) images of ASEM response are obtained by mechanically scanning the focused ultrasonic beam. An X-ray CT scanner (Hitachi Aloka Medical, Ltd., LaTheta LCT-200) is used for structural analysis.

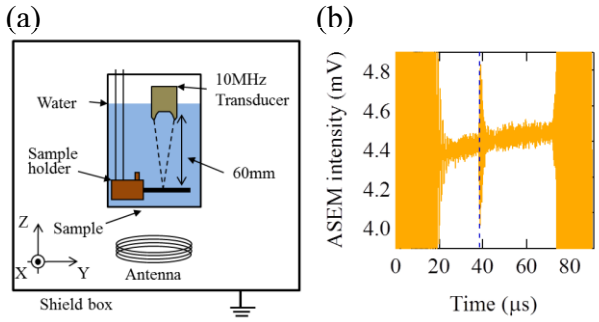

Fig. 1 (a) Schematic of the measurement set up. (b) Typical waveform of ASEM signals emitted from a bone. The signals are observed about 40 μs that is half of echo delay time.

Four rat femur specimens from two healthy rats are prepared for this study. No significant difference among the specimens is observed in X-ray CT and ASEM measurements.

3. Results and Discussion

We first represent typical X-ray CT results of our bone specimens. As seen in Fig.2, trabecular volume is lager but cortical-bone thickness is smaller in both ends of rat femur (epiphysis). On the other hand, trabecular volume is almost absent in the middle long part of femur (diaphysis). Mineral density of cortical bone exhibits a maximum peak on the hip joint side of diaphysis (Fig.2(d)).

Next, let us show results of ASEM

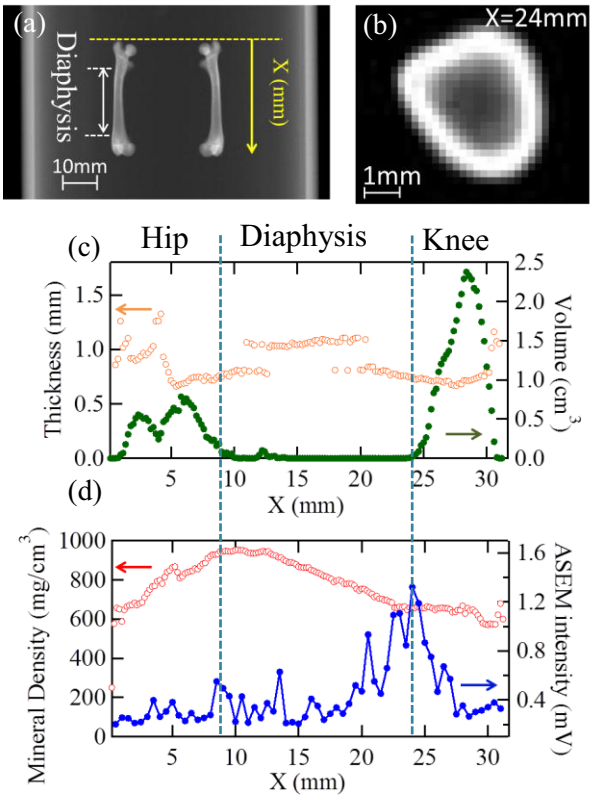

Fig. 2 (a) X-ray CT image of rat femur specimens. The X-axis is defined as the axis of bone with the origin at the end of hip joint. (b) Cross sectional image at x=24 mm. (c) X-dependence of cortical bone thickness and trabecular volume. (d) X-dependence of mineral density of cortical bone and ASEM intensity.

measurements. Spatial mapping of ASEM intensity is shown in Fig.3. The origin of ASEM fields is attributed to the cortical bone rather than inner trabecular bone because the signals are predominantly observed in diaphysis (Fig.2 (c)). This is also supported by the analysis of delay time of pulsed ASEM signals. The most striking feature of our experimental results is that ASEM intensity exhibits a maximum on the knee joint side of diaphysis. The similar feature is observed in both right and left femur and also in specimens of different healthy rats.

We now discuss the reason why stronger EM fields are generated from the knee joint side of diaphysis. One simple interpretation is that ASEM intensity is enhanced by thickness-mode mechanical resonance in cortical bone. The resonant thickness is estimated to be about $0.18n$ (n: integer) [6]. As seen in Fig.2 (c), however, the thickness on the opposite side (hip side) of diaphysis is comparable to that on the knee joint side. The feature is thus not simply explained by specific structural properties.

From a simple calculation of near-field

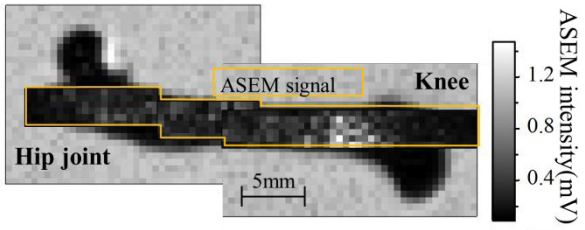

Fig.3 Ultrasonic image of a rat femur. The spatial map of ASEM intensity is shown in the area surrounded by thick lines on the standard echo image

components of EM fields induced by thickness modes of cortical bone, the signal voltage is proportional to a piezoelectric constant, $e_{31}/c_{11} = d_{3i}c_{i1}/c_{11}\,(i = 1\,\text{to}\,3)$, where c_{ij} is stiffness tensor. We thus note piezoelectric properties of cortical bone. Figure 2 (d) suggests an inverse correlation between mineral density and ASEM intensity along the long axis of bone. Namely, the ASEM intensity increases as the ratio of hydroxyapatite decreases (as the ration of collagen density increases). Therefore, the feature would be well interpreted by the fact that piezoelectricity of bone originates from collagen.

4. Conclusion

We have investigated rat femurs by a unique method to detect EM fields stimulated by ultrasonic waves (ASEM method). Stronger signals are observed in cortical bone on the knee side of diaphysis, suggesting that the collagen-rich region is probed by the ASEM method.

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