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Frequency Dependence of Acoustically Stimulated Electromagnetic Response of Bones
骨の音響誘起電磁応答の周波数特性

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1. Introduction

Establishment of diagnostic method of osteoporosis is essential for prevention awareness in an aging society. In osteoporosis, the bone mineral density (BMD) is reduced, bone microarchitecture deteriorates, and the amount and properties of proteins (mainly collagen) in bone are altered. The BMD obtained by X-ray or ultrasonic techniques [1] is normally used as an indicator of bone conditions, but the noninvasive diagnostic method of osteoporosis resulting from other factors is still in development.

We here focus on acoustically stimulated electromagnetic (ASEM) response originated from piezoelectricity of bones [2,3]. Since the origin of piezoelectric of bone is considered to be piezoelectricity of fibrous collagen crystals [4], ASEM response may provide an indicator of bone quality such as collagen density or crystal orientation. In recent years, we demonstrated the detection of ASEM response in a variety of materials with a tuned loop antenna placed on the near-field region [2,3,5]. In the spatial mapping of the ASEM intensity in rat femurs, we found a maximum peak on the boundary between the diaphysis and the knee joint, suggesting the local anomaly of piezoelectricity [3]. However, in the piezoelectric materials, the near-field components of electric fields (rather than magnetic fields) may dominantly contribute to the ASEM signals through the capacitive coupling between the loop antenna (or the coil) and the sample. In this paper, to restrict the detected EM components to electric fields, we measure the ASEM response by using capacitively coupled metal-plate antennas. With the tuned antennas of different resonance frequencies, we show the frequency dependence of ASEM images in rat femurs and discuss the origin of the maximum peak near the knee joint side.

2. Experimental Setup

In the ASEM measurements, rectangular 50 ns 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 (60 mm) from 10 MHz transducer (Fig.1 (a)) [2]. The ASEM signals are thus temporally separated at half of the echo delay time ($\tau_{\mathrm{echo}}/2$) as shown in Fig.1 (b). The signals are detected through capacitively coupled narrow-band plate antennas (a cupper plate combined with a LC tank circuits) and amplified by 80 dB with low-noise preamplifiers (NF, SA-230F5). For measurements of the frequency dependence of the ASEM response, three narrow-band antennas of resonance frequencies of 9.6, 8.6 and 7.8 MHz are prepared with a bandwidth of 87 ± 9 kHz and an impedance of 50 ± 2 Ω. Two-dimensional (2D) images of ASEM response are obtained by mechanically scanning the focused ultrasonic beam with a diameter of 1 mm. An X-ray CT scanner (Hitachi Aloka Medical, Ltd., LaTheta LCT-200) is used for structural analysis. A rat femur specimen from a healthy rat is prepared for this study.

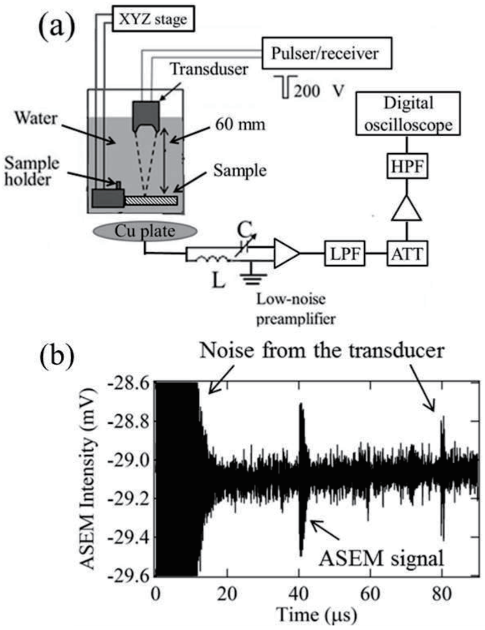

Fig. 1 (a) Schematic of the measurement setup. (b) Typical waveform of ASEM signals emitted from a rat femur. The signals are observed about 40 μs that is half of echo delay time.

3. Results and Discussion

We represent the X-ray CT and 9.6 MHz-ASEM image of our bone specimen (Fig. 2). The delay

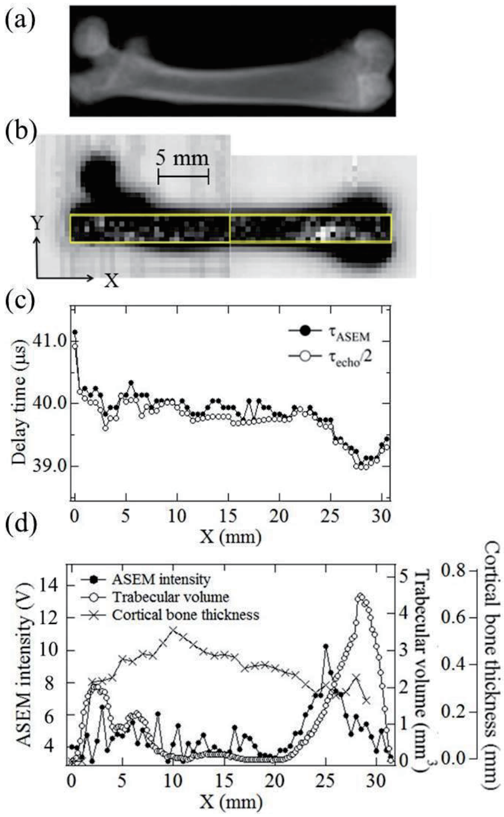

Fig. 2 (a) CT image of the rat femur specimen. (b) ASEM image at 9.6 MHz. The X-axis is defined as the axis along the diaphysis with the origin at the end of hip joint. The spatial mapping of the ASEM intensity is shown in the box surrounded by thick lines on the echo image. (c) Delay time of the ASEM and echo signals. (d) One-dimensional profile of trabecular volume, cortical bone thickness and the averaged ASEM intensity at individual X positions along the diaphysis.

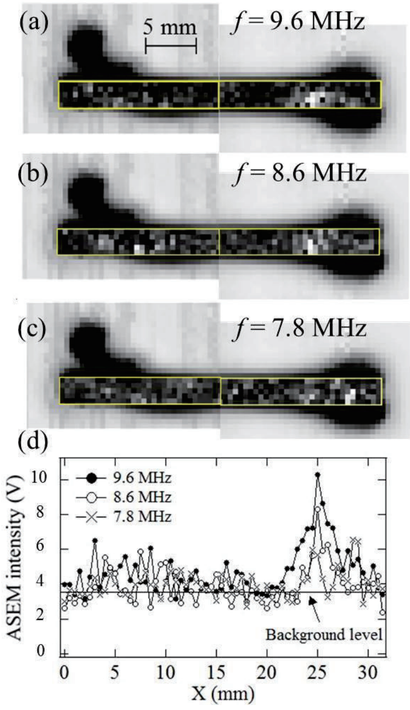

Fig. 3 (a)-(c) ASEM images at 9.6, 8.6 and 7.8 MHz. (d) One-dimensional profile of the averaged ASEM intensity and the thickness

time of the ASEM signals ($\tau_{\rm ASEM}$) corresponds to $\tau_{\rm echo}/2$ (Fig.2 (c)), where a delay time of 160 ns in low- and high-pass filters is considered to be included in the $\tau_{\rm ASEM}$. Furthermore, the ASEM signals are observed even in diaphysis without trabecular bones. Therefore, we conclude that the signals detected here are the ASEM response from the cortical bone rather than from inner trabecular bones. As is the experiments using a loop antenna [3], the ASEM intensity exhibits a maximum on the knee joint side of diaphysis.

One simple interpretation is that the ASEM intensity is enhanced by a thickness-mode mechanical resonance in cortical bone. The resonant thickness is estimated to be about 0.18*n* (*n*: integer) at 9.6 MHz [6]. As seen in Fig. 2 (d), the cortical bone thickness is about 0.32 mm, comparable to the resonant thickness of *n*=2, on the knee joint side of diaphysis. The frequency dependence of the ASEM intensity is obtained (Fig. 3) but in the lower-frequency measurements no increase in the ASEM intensity is observed at the smaller X positions in the region of the thicker cortical bone. Thereby, the specific peak is not explained only by the simple thickness mode. The earlier studies indicate that the piezoelectricity shows the maximum around the knee joint side of diaphysis in a human femur [7]. Further studies of the detail frequency spectra and the anisotropy of ASEM response are required to clarify the origin of the anomaly on the knee joint side.

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