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Anisotropy of Acoustically Induced Electric Polarization in Biological Tissues

生体組織における超音波誘起電気分極の異方性

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1. Introduction

It is known that bone structures are remodeled to adapt to the loads under which it is placed [1]. The idea has now been extended to soft fibrous tissues such as tendon and ligament [2]. These tissues are characterized by an abundance of tightly packed collagen fibers that give themselves its superior tensile strength [2]. The collagen structure is in bundles of parallel fibers along the direction of the force [2]. Therefore, assessing collagen orientation may serve as an index to evaluate locomotor pathology. For example, osteoporosis is a bone disease that increases the risk of fractures. Bone strength decreases when mineral density decreases or when the quality or structure of bone changes. The most common test for osteoporosis is dual-energy x-ray absorptiometry (DXA) that measures bone mineral density. However, the diagnostic method to evaluate bone quality has not yet been established.

Recently, we have demonstrated a unique

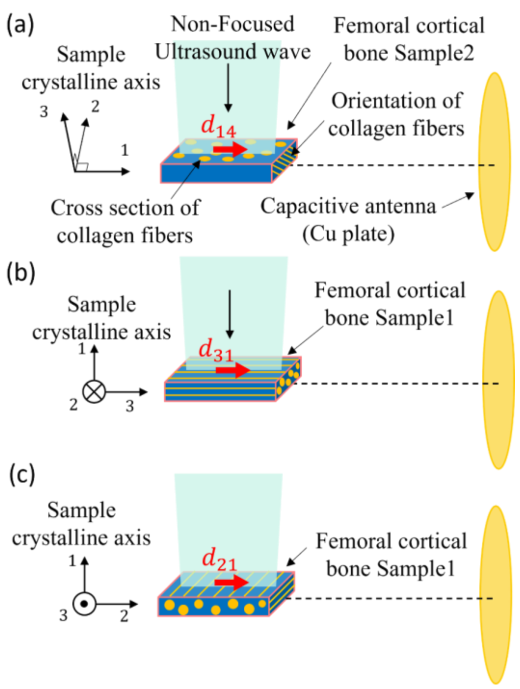

FIG. 1. Schematics of the geometric placements for the piezoelectric components, (a) d_{14}, (b) d_{31}, and (c) d_{21} measurements.

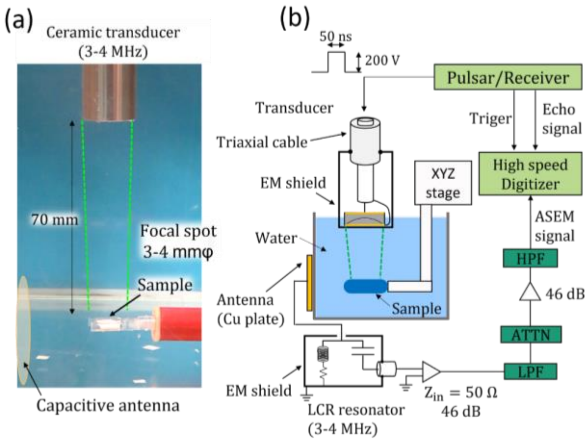

FIG. 2. (a) Photograph of the experimental setup. (b) Block diagram of the ASEM measurement system.

method to measure the stress-induced electric polarization of biological tissues [3,4]. This method is based on the generation and detection of acoustically stimulated electromagnetic (ASEM) response through electro- or magnetomechanical coupling of materials [5]. The first harmonic component of the acoustically induced electric polarization is detected by using a resonant capacitive antenna. The induced polarization which responds linearly to the applied acoustic stress was observed in Achilles tendon, aortic wall, and aortic valve, whereas it was small in adipose tissue and myocardium, indicating that fibrous tissues exhibit electromechanical coupling. The advantages of this method are that (i) spatial imaging of local electromechanical properties is obtained by scanning ultrasound beam, (ii) the stress-induced polarization of wet materials, even in living tissues, can be measured noninvasively.

Assuming that the acoustically induced polarization of biological tissues is attributed to piezoelectricity as observed in inorganic crystals, the anisotropic properties should be determined by the crystal symmetry. The uniaxial collagen crystals presumably have the C_6 symmetry, which is associated with the piezoelectric tensor [6]:

$$\begin{matrix} 0 & 0 & 0 & d_{14} & d_{15} & 0 \\ 0 & 0 & 0 & d_{15} & -d_{14} & 0. \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{matrix}$$

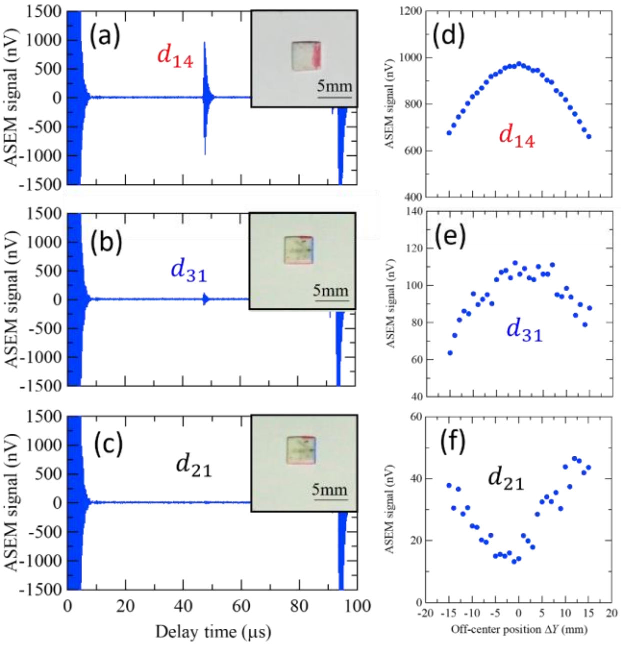

FIG. 3. Typical time traces of ASEM signals in the (a) d_{14}, (b) d_{31} and (c) d_{21} measurement settings. The one-dimensional profiles of the signal amplitude plotted against the off-center position for the (d) d_{14}, (e) d_{31} and (f) d_{21} measurement settings.

If a large number of these crystals are oriented to the same direction in the acoustically excited area, the induced polarization will follow the above piezoelectric tensor. This implies that the anisotropic properties may be an index for evaluating the quality or structure of fibrous biological tissues. In this paper, we confirmed that the acoustically induced polarization of fibrous tissues follows the piezoelectric tensor with the uniaxial symmetry.

2. Experimental Setup

Two fragment samples with different cross sections for the collagen fiber direction were prepared from a bovine femoral cortical bone [Fig. 1]. The samples are set in a plastic sample holder and submerged in a glass tank of deionized water [Fig. 2(a)]. The block diagram of the experimental setup is shown in Fig. 2(b). An appropriate distance between the sample and transducer (70 mm in this experiment) allows us to separate the pulsed ASEM response from the EM noise generated by the transducer temporally [4]. The ASEM signal is detected by a resonant capacitive antenna (Cu circular plate) tuned to the frequency of the ultrasound waves [3].

The direction of polarization can be identified by scanning the sample along the surface of the Cu circular plane. If electric polarization is perpendicular to the surface of the circular plate, the charge induced in the plate is expected to be the maximum when the sample is positioned at the central axis of the plate as seen in Fig.2. In contrast, if electric polarization is parallel to the surface of the circular plate, the charge induced in the plate is almost cancelled out. Because the ASEM signal amplitude is proportional to the induced charge in the plate [5], the direction of polarization is determined from the one-dimensional profile of the signal amplitude for the off-center position in the Cu circular plate.

3. Results

Figure 3 shows the time traces of the ASEM signals and the profiles of the signal amplitude for the off-center position for the d_{14} d_{31} and d_{21} measurements. The signal amplitude for the d_{14} component is about one order of magnitude larger than that for the d_{31}components. No characteristic profile with a maximum was observed in the d_{21} measurement setting [Fig.3(f)], indicating that the [010] polarization due to the d_{21} component is negligibly small. Though not shown here, the similar results of piezoelectric tensor are also obtained in Achilles tendon.

The nonzero values of d_{14} and d_{31} are consistent with the piezoelectric tensor for the uniaxial symmetry of collagen crystals. The fact that the d_{14} for shear response is the main component was reported in dry bone and tendon [6].

4. Conclusion

We have studied the anisotropic properties of the acoustically induced electric polarizations in biological fibrous tissues. The polarization is explained by the piezoelectric tensor with the uniaxial symmetry of collagen crystals. Thereby, the orientation of collagen can be evaluated by measuring the anisotropic properties of ASEM response.

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