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Measurement of Angular Dependence of Ultrasonic Scattering from Wire Phantom Mimicking Myocardial Fiber

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The difference between a normal and a hypertrophic heart is whether the direction of regional myocardial fibers are homogeneously aligned along one direction. In order to investigate the angle dependence of ultrasonic scattering in relation to the fiber direction, we measured the ultrasonic echoes from a metal wire phantom, which mimics a bundle of myocardium fibers, as a function of the insonification angle. In this study, we focused on ultrasonic scattering properties in relation to the azimuth and elevation angles of insonification and reception. Experimental results showed that the amplitude of the reflected echo from the metal wire became maximum when the ultrasonic beam was insonified parallel to the fiber direction. In the case of such parallel insonification, echoes from the wire showed directivity like those from an interface. Such directivity was considered to contribute to the dependence of echoes on the azimuth angle. [DOI: 10.1143/JJAP.46.4897]

KEYWORDS: angle dependence, ultrasonic scattering, myocardial fiber

1. Introduction

Directions of myocardial fibers in a normal human heart wall change gradually from the epicardium to the endocardium and are homogeneously aligned in each plane that is parallel to the luminal surface of the heart wall.[1–3] However, in a heart wall affected by hypertrophic heart disease, the myocardial fiber direction becomes disarrayed.[4,5] Therefore, it is important to diagnose the myocardial fiber direction for differentiation of normal hearts from those affected by hypertrophic heart disease. It is expected that ultrasonic scattering from a heart wall can reveal such changes in the direction of myocardial fibers. Basic research based on backscattered echoes from the myocardium has been conducted for quantitative tissue characterization.[6]

In order to quantify the correspondence between the acoustic properties of an object and ultrasonic backscattering, ultrasonic backscattering from a reference phantom of known acoustic properties was measured with the influences of the measurement system being eliminated.[7,8] Baldwin and co-workers measured the ultrasonic myocardial attenuation while changing the angle of ultrasonic propagation relative to the myocardial fibers for quantitative ultrasonic cardiac tissue characterization.[1,6] By measuring ultrasonic backscattering from the myocardium at each insonification angle θ relative to the direction of the myocardial fibers, one can show that the ultrasonic attenuation in the myocardium is maximum when θ is zero (parallel) relative to the myocardial fibers and minimum when θ is 90° (perpendicular) relative to the fibers. In previous studies, it was found that ultrasound-integrated backscattering from the myocardium exhibits cyclic variation during one cardiac cycle.[9–12] One of the reasons is considered to be the change in the angle between the ultrasonic beam and the direction of myocardial fibers.[13] Recchia *et al.* measured the ultrasound backscattering from the inside of an excised canine myocardium specimen.[3] There was a strong relationship between the backscattering intensity and fiber orientation. They explained such an angular dependence using a mathematical model of the principal structure in a normal myocardium.[3] Holland *et al.* measured the angular dependence of the integrated backscattering from a bovine tendon.[14] Their results showed that the inherent anisotropy of the tissue structure influences the spectral properties of the ultrasound backscattering. They also investgated the effect of the angle dependence of ultrasound backscattering in the short-axis view of a mouse heart at end systole and end diastole.[15]

In this study, we focused on ultrasonic scattering properties in relation to the azimuth and elevation angles of insonification relative to the fiber direction. For this purpose, ultrasonic echoes from a wire phantom (with a diameter less than the wavelength) that mimics a bundle of myocardium fibers were measured as a function of the insonification angle.

2. Experimental Methods

The experimental setup is illustrated in Fig. 1. As shown in Fig. 1(a), two focused transducers were used for transmitting and receiving ultrasonic beams. The transmission and reception elevation angles are ϕ_1 and ϕ_2, respectively. In this paper, ultrasonic echoes from a wire phantom were measured at various angles, ϕ_1, ϕ_2, and azimuth angle θ. During the experiment, focal points of both transducers are required to be set at the same point on the phantom. By keeping the focal points at the same position, the object was revolved around that point to change the azimuth angle θ. Furthermore, the elevation angle ϕ was changed by moving the transducers along a circle with its center at the same point as the focal point on the phantom. To realize such operations, a custom-made apparatus was used. The measurement apparatus is shown in Fig. 1(b).

Both transducers for transmission and reception were single-element concave transducers (Tokimec 7Z10I-PF30-C-K445). The focal distances of the transducers are 30 mm and the center frequency is 7.0 MHz. The wire phantom was placed in a water tank, as shown in Fig. 1(b), and fixed onto the center of the cylindrical pedestal. The azimuth angle θ of insonification relative to the fiber direction was changed by rotating the pedestal. There was a hole of 20 mm diameter at the center of the top of the pedestal in order to receive only the signal reflected from the object. A sine wave of one cycle

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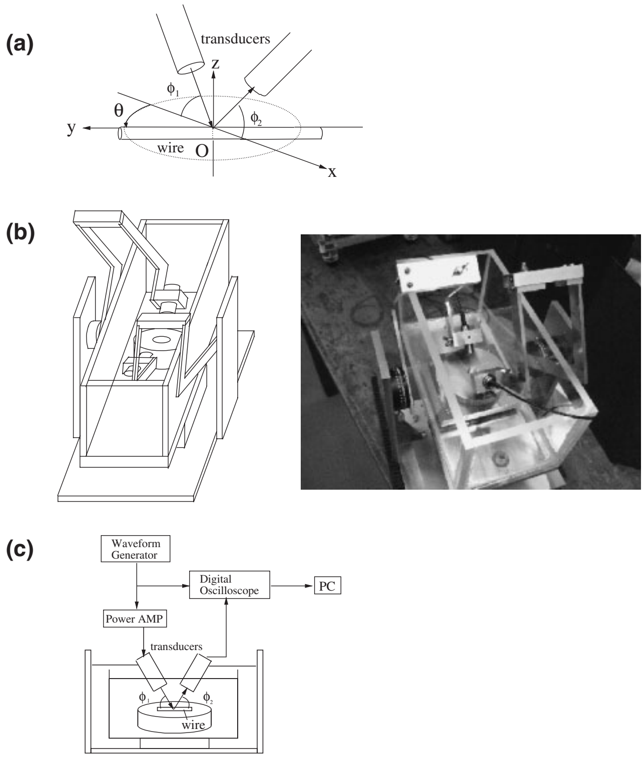

Fig. 1. Illustrations of (a) the measurement, (b) custom-made apparatus, and (c) experimental setup.

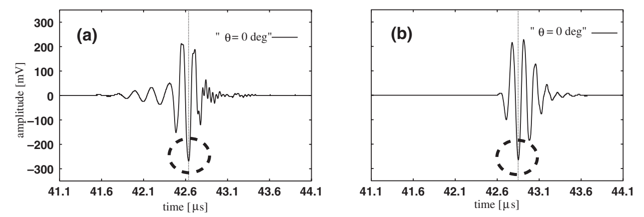

Fig. 2. Examples of the received signals from the wire ($\theta = 0°$). (a) $\phi_1 = \phi_2 = 30°$. (b) $\phi_1 = \phi_2 = 50°$.

was applied to the transmitting transducer. The signal reflected from the object was received by the receiving transducer. The digitized data were acquired after averaging the reflected signals 128 times using a digital oscilloscope (Tektronix TDS220).

The diameter of a human myocardial fiber (10–15 μm)[5] is thinner than the wavelength of ultrasound (400–500 μm) used in ultrasonic diagnostic equipment. Therefore, ultrasonic echoes from human myocardium fibers are scattered waves. The phantom used in this study was a copper wire of about 170 μm in diameter. The wavelength of insonified ultrasound was 214 μm. Thus, ultrasonic echoes were also scattered waves.

3. Results

Figure 2 shows the received RF signals when the ultrasonic beam was insonified parallel to the wire ($\theta = 0°$) at two settings of the elevation angles ($\phi_1 = \phi_2 = 30$ and $50°$). As shown in Fig. 2, the peak value was measured at each setting of the azimuth and elevation angles.

Figure 3 shows the angular dependence of the maximum amplitude of the reflected signals at each azimuth angle, θ.

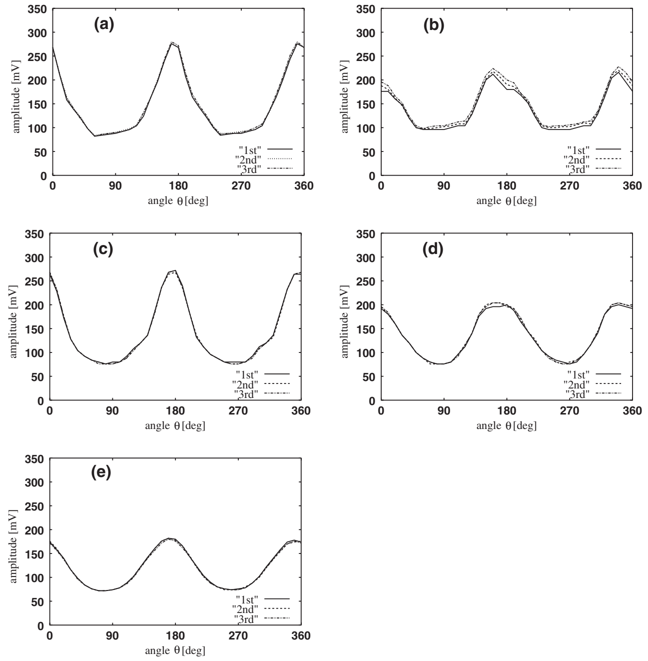

Fig. 3. Maximum amplitude of the received signals at each azimuth angle θ. (a) $\phi_1 = \phi_2 = 30°$. (b) $\phi_1 = \phi_2 = 40°$. (c) $\phi_1 = \phi_2 = 50°$. (d) $\phi_1 = \phi_2 = 60°$. (e) $\phi_1 = \phi_2 = 70°$.

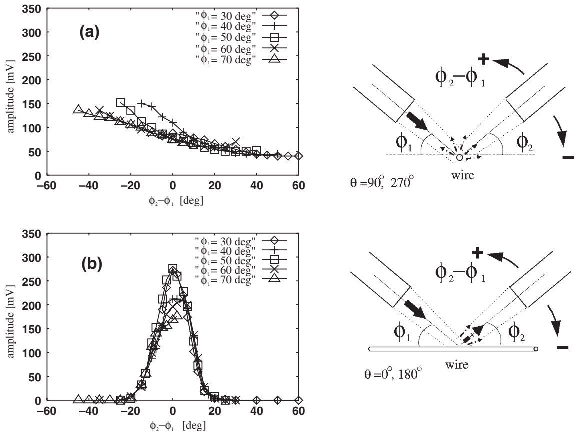

Fig. 4. Maximum amplitude of the received signals at each angle difference ($\phi_2 - \phi_1$) between receiving and insonification elevation angles, ϕ_1 and ϕ_2. (a) $\theta = 90°$. (b) $\theta = 0°$.

The amplitude of the reflected signal changed with azimuth angle, θ. Although the pedestal was rotated three times, reproducible measurements were achieved with respect to the azimuth angle, θ. At the same elevation angle ($\phi_1 = \phi_2$), the amplitude became maximum when the ultrasonic beam was insonified parallel to the wire ($\theta = 0$ and $180°$). On the other hand, when the ultrasonic beam was insonified perpendicularly to the wire ($\theta = 90$ and $270°$), the amplitude tended to be the smallest.

Figure 4 shows the maximum amplitude of the received signals at each difference between elevation angles ($\phi_2 - \phi_1$). The azimuth angle θ was kept at 90° in Fig. 4(a) and $\theta = 0°$ in Fig. 4(b), respectively. Amplitude profiles and amplitudes showed similar tendencies at each insonification elevation angle ϕ_1.

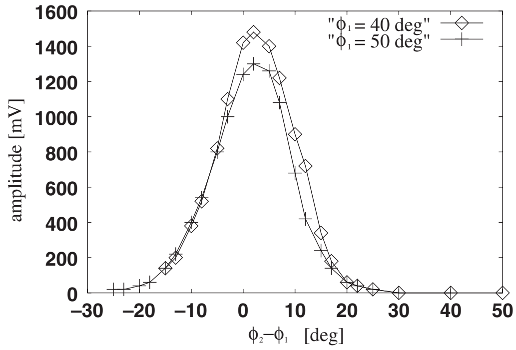

Fig. 5. Maximum amplitude of the received signals from an aluminum plate at each angle difference ($\phi_2 - \phi_1$).

In the case of insonification perpendicular to the wire ($\theta = 90^\circ$), the amplitude does not change greatly with respect to ($\phi_2 - \phi_1$), and decreases as the angle difference ($\phi_2 - \phi_1$) increases. On the other hand, in the case of insonification parallel to the wire direction ($\theta = 0^\circ$), amplitudes become maximum when the angle difference ($\phi_2 - \phi_1$) is 0°. When the absolute value of the angle difference is more than 20 degrees, the amplitude is almost zero.

Figure 5 shows the echo amplitude from a flat aluminum plate measured by a similar procedure as that in the case of Fig. 4(b). Echoes from the aluminum plate are maximum when the angle difference ($\phi_2 - \phi_1$) is 0°. When the absolute value of the angle difference is greater than 20°, the amplitudes are again almost zero. These results suggest that the wire acts as an interface in the case of parallel insonification ($\theta = 0^\circ$).

4. Conclusions

In this study, in order to investigate the angle dependence of ultrasonic scattering from a wire, we constructed an experimental system that allows us to change the elevation and azimuth angles. The amplitude of the reflected signal from the wire changed with azimuth angle, θ.

The maximum amplitude of the received signals at each angle difference, ($\phi_2 - \phi_1$), did not change greatly with insonification elevation angle, ϕ_1, in the case of insonification perpendicular to the wire ($\theta = 90^\circ$). On the other hand, in the case of insonification parallel to the wire ($\theta = 0^\circ$), the wire acts as an interface. Such a difference in amplitude profiles with respect to the angle difference between transmitting and receiving elevation angles provides a clue to the cause of the dependence of echo on the azimuth angle.

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