Angular Dependence of Ultrasonic Echo from Surface with Minute Roughness

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Abstract—Atherosclerosis is the main cause of circulatory diseases, and it is very important to diagnose atherosclerosis in its early stage. In an early stage of atherosclerosis, the luminal surface of an arterial wall becomes rough due to injury of the endothelium. Conventional ultrasonic diagnostic equipments cannot detect such micron-order surface roughness because their spatial resolution is, at most, 100 µm. In this study, for the accurate detection of surface roughness, ultrasonic beams were insonified from various angles relative to the surface of an object that has a micron-order asperity. Then, we focused on the angular dependence of echo amplitude and frequency characteristics. Using this method, it is shown that the angular dependence and frequency characteristics vary when an object has a surface roughness that cannot be detected by conventional B-mode imaging using linear scanning.

I. INTRODUCTION

Recently, the increases in the number of circulatory diseases such as myocardial and cerebral infarctions have become a serious problem. Therefore, it is important to diagnose atherosclerosis in an early stage because such circulatory diseases are mainly caused by atherosclerosis. Although the intima-media thickness is a useful marker for diagnosis of atherosclerosis [1], [2], [3], the initial step of atherosclerosis development was reported to be endothelial damage [4]. Therefore, for the diagnosis of atherosclerosis in an early stage, it is more effective to evaluate endothelial damage. For the evaluation of endothelial function, several methods have been reported including the measurement of changes in diameter [5] and intima-media elasticity [6] caused by flow-mediated dilation. In these methods, the measured changes in diameter or intima-media elasticity are caused by the response of the media to nitric oxide generated by the endothelium. Therefore, if the endothelium is injured, the response of the media to nitric oxide generated by the endothelium does not occur.

In the early stage of atherosclerosis, it was also reported that the luminal surface profile changes. The luminal surface of a clinically healthy artery is covered by a layer composed of endothelial cells and it is smooth. In the early stage of atherosclerosis, endothelial cells on the luminal surface are damaged [4], edema develops underneath the endothelium, endothelial cells are separated from the intima, and then the lumen of the artery has a micron-order surface roughness [7]. Therefore, for the detection of atherosclerosis in an early stage, it is necessary to detect a micron-order surface roughness on the luminal surface. In conventional ultrasonic diagnostic equipments, the lateral interval of ultrasonic beams is, at most, 100 µm, and the axial resolution of a B-mode image depends on the ultrasonic wavelength of 150 µm at 10 MHz because a B-mode image is constructed using the amplitude of the received echo. From these facts, the spatial resolution of a B-mode image obtained using conventional ultrasonic diagnostic equipment is, at most, 100 µm in both lateral and axial directions. Therefore, the surface roughness caused by atherosclerosis in an early stage cannot be detected by conventional B-mode imaging using ultrasonic diagnostic equipment. There are several studies on the ultrasonic detection of micron-order surface roughness. Sukmana et al. measured the surface roughness of sandpaper using air-coupled ultrasound, and showed that higher-frequency components in echo are attenuated when the surface of the object has a micron-order surface roughness [8], [9]. Arihara et al. measured the surface profile of an object made of silicone rubber in the micron-order using the phase of RF echo [10]. However, these methods are still not sufficient for accurate imaging of a surface with micron-order asperity.

In this study, various objects with different micron-order surface profiles were measured to obtain the angular dependences of ultrasonic echoes. Ultrasonic beams were insonified from various angles relative to the surface of an object that has micron-order asperity. Then, for the evaluation of micron-order surface roughness, we focused on the angle-dependent characteristics of echo amplitude and frequency characteristics [11].

II. MATERIALS AND METHODS

A. Data acquisition

Figures 1(a) and 1(b) show the schematic views of the experimental system and beam scanning, respectively. A linear-type ultrasonic probe (center frequency \( f_0 = 10 \text{ MHz} \), interval of aperture centers for transmitted beams \( L = 0.4 \text{ mm} \)) of conventional ultrasonic diagnostic equipment (Aloka SSD-6500) is used in this study. The number of electronically scanned beams, \( N \), is 30 per frame. Ultrasonic RF echoes are sampled at 40 MHz with a 16-bit resolution.

The method using steering the ultrasonic beam proposed by Nakagawa et al., [12] as shown in Fig. 1(b), is used in this study. Using this method, the direction of all ultrasonic beams can be designed so as to pass through a point of interest \( O_j \). As shown in Fig. 1(b), all beams pass through point \( O_j \) at the
surface of the object. When an ultrasonic beam is insonified from the position $a_i$ of the aperture center $i$ the beam angle $\theta_i$ is expressed as follows:

$$\theta_i = \tan^{-1} \left( \frac{L \cdot \left( i - \frac{N-1}{2} \right)}{l} \right).$$  \hspace{1cm} (1)

The distance $l$ from the surface of the probe to the surface of the object is set to be 9.4 mm, and then the maximum beam angle $\theta_{\text{max}}$ is 32.6°.

Furthermore, the ultrasonic probe is used to scan the object by changing its position $x_j$ using a stage in order to measure RF echo from multiple points of interest $\{O_j\}$ on the surface along the $x$-direction. At each position $x_j$ in $j$-th frame ($j = 1, 2, \ldots, M$), all beams pass through a point $O_j$, which is set at the surface of the object. The position $x_j$ is changed by 5 $\mu$m per frame for 2 s (frame rate: FR=434 Hz, speed of stage motion: 2.17 mm/s).

Figure 1. (a) Experimental system for measurement of an object surface. (b) Schematic diagram of beam scanning.

**B. Analysis of angular dependence**

Figure 2 shows RF echo from a point scatterer at each beam angle $\theta_i$. The amplitude of each RF echo is normalized by the acoustic pressure that corresponds to the maximum 16-bit discrete value.

In this measurement, the distance from the point of interest to the receiving position varies as the beam angle $\theta_i$ changes. Thus, the axis of time $t_i$ for each ultrasonic beam should be corrected by the difference in propagation distance. The propagation time $t_i$ at a position $a_i$, where the ultrasonic beam is transmitted, is given by

$$t_i = \frac{2l}{c \cdot \cos \theta_i},$$  \hspace{1cm} (2)

where $c$ is the sound speed in water. As shown in Fig. 2, the waveform of RF echo is not distorted and the wavefront of the echo at each ultrasonic beam aligns in the case that the object is a point scatterer. Thus, received RF echoes at various beam angles are plotted as a function of the beam angle $\theta_i$ and the time $t$, which is corrected by the difference in propagation time.

![Fig. 1](image1)

![Fig. 2](image2)

![Fig. 3](image3)

**C. Objects**

Four metal plates that have different surface roughnesses obtained by polishing with sandpaper were measured. Figure 3 shows the surface profiles $h(x_i)$ at lateral position $x_i$ of
objects Nos. A-D measured by a profilometer using a fine needle. Figure 4 shows the conventional linear scanning B-mode images of objects Nos. A and D. As shown in Fig. 4, the surface profile $h(x_i)$ in the micron-order, as shown in Fig. 3, cannot be detected by the conventional B-mode imaging using linear scanning.

In this study, the root mean squared (RMS) roughness $R_q$, which is the standard deviation of the surface height $h(x_i)$, is used for the statistical evaluation of surface roughness. The RMS roughness $R_q$ is obtained as follows:

$$R_q = \sqrt{\frac{1}{N} \sum_{i=0}^{N-1} \left(h(x_i) - \bar{h}(x)\right)^2},$$

where $N$ is the total number of lateral positions $\{x_i\}$ and $\bar{h}(x)$ is the average height of the surface profile. Figure 3 also shows $R_q$ of each object used in these measurements.

### III. Experimental Results

Figures 5(a) and 5(b) show RF echoes from object No. A ($R_q = 0.206 \mu m$), which has the most smooth surface among the measured objects in these experiments, and from object No. D ($R_q = 4.131 \mu m$), which has the roughest surface, respectively. In these experiments, the distance $l$ from the surface of the probe to the surface of the object was set to be 9.4 mm, and the maximum beam angle $\theta_{\text{max}}$ was 32.6$^\circ$.

As shown in Fig. 5(a), in the case of the smooth surface, the amplitude of RF echo at the beam angle $\theta = 20^\circ$ is low and that at the beam angle $\theta = 30^\circ$ cannot be detected. On the other hand, in the case of the rougher surface, the amplitude of RF echo at the beam angle $\theta = 30^\circ$ can be detected as shown in Fig. 5(b). From these results in Fig. 5, it is found that the echo amplitudes in the range $\theta \geq 20^\circ$ increase as the surface of the objects becomes rough.

![Conventional B-mode images of objects No. A (a) and No. D (b).](image)

The angular dependences of ultrasonic echoes from four different objects that have different surface roughnesses, as shown in Fig. 3, were measured and the power spectra of RF echoes at the corresponding beam angles $\{\theta_i\}$ were acquired. In these experiments, the experimental system is similar to the system shown in Fig. 1. The angular dependences of RF echo were measured by moving the ultrasonic probe automatically using a stage. RF echoes were acquired during 4 mm movement at 10 $\mu$m intervals (the number of measurement points $\{x_i\} = 400$).

Figure 6 shows the averaged power spectra of RF echo at each beam angle $\theta$ for each object shown in Fig. 3. As shown in Fig. 6, for the beam angle $\theta$ of about $0^\circ$, the power spectra shown in Figs. 6(a)-6(d) are similar whereas the surface roughness $R_q$ differs. However, in the case of $\theta \geq 20^\circ$, the center frequency component increases as surface roughness increases.

Figure 7 shows the power spectra shown in Fig. 6 for the temporal frequencies from 5 to 10 MHz. As shown in Figs. 7(c)-7(e), the power spectra at about the center frequency ($f = 7.5$ MHz) increase as surface roughness $R_q$ increases when the beam angle $\theta$ is greater than $20^\circ$. From these results, in this study, the power of RF echo, $P(\theta)$, is obtained as follows:

$$P(\theta) = E_t \left[ \left( V_0(t) - \bar{V}_0(t) \right)^2 \right],$$

where $V_0(t)$ is the RF echo signal at the time $t$ and $\bar{V}_0(t)$ is its average. Figure 8 shows the change in the power $P(\theta)$ of RF echo at the corresponding beam angles $\theta$ for all objects. In Fig. 8, the power $P(\theta)$ of RF echo is normalized by the power $P(0^\circ)$ at $\theta = 0^\circ$. As shown in Fig. 8, the normalized power $P(\theta)/P(0^\circ)$ of RF echo in the region of $\theta \geq 20^\circ$ increases as the surface roughness $R_q$ increases.

The relationship between the surface roughness $R_q$ and the normalized power $P(\theta)/P(0^\circ)$ of RF echo is shown in Fig. 9. From Fig. 9, it is found that the increase in the surface roughness $R_q$ causes the increase in the power of RF echo in the region of $\theta \geq 20^\circ$.

![Average power spectra of RF echo at each beam angle $\theta_i$ for each object shown in Fig. 3.](image)
IV. CONCLUSION

In this study, the angular dependence of ultrasonic echoes was measured by steering the ultrasonic beam. Objects that have a micron-order surface roughness that cannot be detected by conventional B-mode imaging using linear scanning were used in these measurements. Using the proposed method, it was found that the spatial distribution of echo amplitudes and the frequency characteristics of echoes differ as the surface profile differs. Furthermore, using the proposed method, it was shown that the increase in the RMS surface roughness $R_q$ causes the increase in the power of RF echo in the region with $\theta \geq 20^\circ$. These results provide a possibility that a micron-order surface roughness can be quantitatively evaluated using the angular dependence of ultrasonic echo, particularly using a large beam steering angle that is not commonly used in conventional ultrasonic diagnostic equipment.

Fig. 9. Relationship between the surface roughness $R_q$ and the normalized power $P(\theta)/P(0^\circ)$ of RF echo in the range $\theta \geq 20^\circ$.

REFERENCES


