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Phantom experiments on separation of reflection and scattering components using ultrasonic synthetic aperture imaging
超音波開口合成法を用いた反射・散乱成分の弁別に関するファントム実験

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1. Introduction

In the early stage of atherosclerosis, endothelial cells on the internal surface of the arterial wall become damaged. This leads to detachment of endothelial cells and the degeneration of the internal elastic layer. As a result, the luminal surface of the arterial wall becomes rough. When ultrasound is irradiated towards this surface, signal components originating from scattering increases at the expense of signal components representing specular reflection, compared to the situation of the healthy smooth surface. Therefore, separation between specular reflection components and scattered components in the ultrasonic echo from the arterial wall potentially holds diagnostic information when such roughening occurs. In our previous work, the separation of the scattered and the reflected components in the echo signal was investigated by a method involving linear scanning and far-focused transmit beams [1]. In the present study, we aim to separate the reflection and scattering components by synthetic aperture imaging using spherically diverging waves and compare the separated signals representing these two components.

2. Principle

2.1. Synthetic aperture method

A synthetic aperture method using a spherically diverging transmit beam was used. To form a wave front that diverges from a virtual sound source placed at (x_f, z_f) behind the array, it is necessary to set proper time delays to the emitted pulses depending on the distance from the aperture center [2]. The transmission propagation distance r_t from the center of the aperture to the target point (x_t, z_t) is obtained by Eq. (1).

$$r_t = \sqrt{\left(x_t - x_f\right)^2 + \left(z_t - z_f\right)^2} - \left|z_f\right|. \qquad (1)$$

Similarly, the receiving propagation distance r_i from the target point to the i-th element of the aperture at $(x_t, 0)$ is obtained by

$$r_i = \sqrt{(x_i - x_t)^2 + {z_t}^2}. \qquad (2)$$

2.2. Method for differentiation of reflection and scattering components

In the present study, a method for separating the reflection and scattering components of the ultrasonic echoes was developed using a spherically diverging transmit beam. With respect to the target point (on a surface) in **Fig. 1**, the ultrasonic beam insonify the target from the $-\varphi$ direction and is reflected in the direction of φ. The arrival point of the reflection component is $(x_r, 0)$ and that of the backscattering component is $(x_b, 0)$.

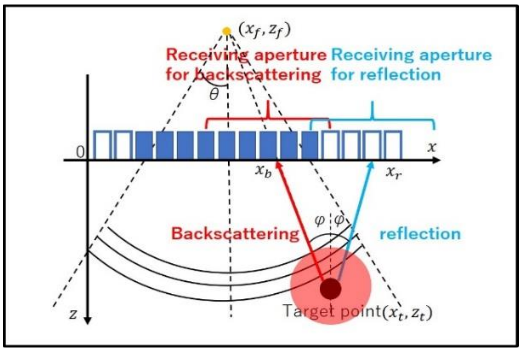

Fig. 1 Illustration of method for differentiation of reflection and backscattering components.

2.3. Receive propagation distance for plane sound source

In our previous study, the receive propagation distance was calculated by assuming the reflection originated from a point on a plat surface. However, as shown in **Fig. 2**, if the reflection component signal is considered, it is necessary to calculate the receive propagation distance as a reflection from a flat surface. In the present study, the receive propagation distance was calculated by assuming ultrasonic waves reflected from the target point as those from a plane (from now on denoted a "plane sound source"). As illustrated in **Fig. 2**, a spherical wave was emitted from a virtual point source behind the array. The ultrasonic wave reflected from the plane can be considered as a spherical wave from a point source, whose position is mirrored around the plane of reflection relative to the virtual source behind the array. In such a case, the receive propagation distance r_i is obtained by

$$r_i = \sqrt{\left(x_f - x_e\right)^2 + (2z_t + |z_f|)^2} - \frac{z_t + |z_f|}{\cos\varphi}. \quad (3)$$

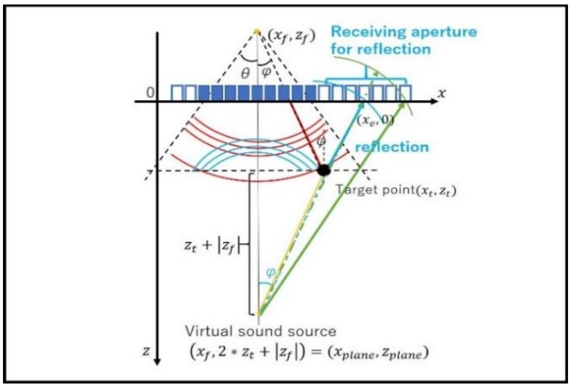

Fig. 2 Illustration of calculation of receive propagation distance for virtual sound source.

2.4. Experimental setup

In the experiments, a linear array transducer with 192 elements and an element pitch of 0.1 mm was used. The center frequency of the transducers was 7 MHz. Ultrasound echoes received by individual transducer elements were sampled at a sampling frequency of 31.25 MHz. The sound velocity was assumed to be 1482 m/s in the receive beamforming. One smooth and three rough planar reflector phantoms with sizes of 10 × 10 cm were used. These phantoms were made of a liquid urethane casting elastomer fabricated with three types of sand papers with different degrees of roughness [3]. The four phantoms were denoted smooth, p100, p60, and p40, with the latter being the roughest. The distance from the phantoms to the transducer was 10 mm.

3. Results and Discussion

Figs. 3(a)-(d) shows the maximum amplitude values in each of the 193 scanlines obtained by conventional synthetic aperture imaging, reflection component, scattering component, and reflection component by assuming a plane sound source, respectively. The orange lines in **Fig. 3** shows the average of the maximum amplitude values over all scan lines. The data of **Figs. 3**(b)-(d) were normalized with the maximum amplitude value in the conventional method.

Fig. 4 shows the average and standard deviation of the maximum amplitude values over all scan lines. The average and standard deviation of conventional synthetic aperture imaging do not tend to be proportional to the surface roughness. On the other hand, the average and standard deviation of reflection components obtained by assuming a plane sound source were proportional to the surface roughness. Also, the difference between the averages for the reflected and scattered components were proportional to the surface roughness.

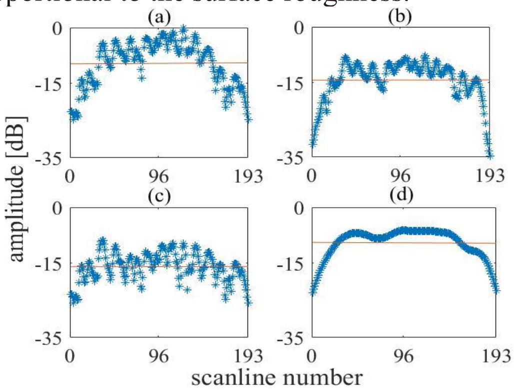

Fig. 3 The amplitude profiles obtained with p100 phantom using (a) conventional synthetic aperture, (b) reflection component, (c) scattering component and (d) reflection component by assuming a plane sound source.

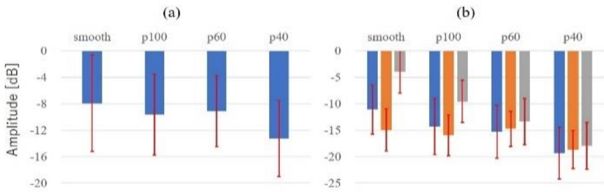

Fig. 4 Means and standard deviations of echo amplitudes over all scan lines by (a) conventional synthetic aperture imaging and (b) reflection emphasized image (blue), scattering emphasized image (orange) and reflection emphasized image with assumption of a plane sound source (gray).

4. Conclusions

In the present study, the reflection and scattering components were separated by synthetic aperture imaging in phantom experiments and, then, the echo signals in the images generated from the corresponding components were compared. The results confirmed that the average and standard deviation of the reflection component obtained by assuming a plane sound source as well as the difference on the averages between the reflected and scattered components were proportional to the surface roughness.

References

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