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3D Ultrasound Imaging by Synthetic Transmit Aperture Beamforming Obtained with a Spherically Curved Array Transducer

半球型アレイトランスデューサの送信開口合成による３次元超音波イメージング

Eiki Hayashi[1 ‡], Naoya Kanno[1], Ryo Shintate[1], Takuro Ishii[1], Ryo Nagaoka[2], and Yoshifumi Saijo[1] ([1]Graduate School of Biomedical Engineering, Tohoku Univ; [2]Graduate School of Science and Engineering for Research, Univ. of Toyama.)

林瑛己 [1 ‡]，菅野尚哉 [1]，新楯諒 [1]，石井琢郎 [1]，長岡亮 [2]，西條芳文 [1] ([1] 東北大院 医工, [2] 富山大院 理工)

1. Introduction

Imaging of micro-structures in the skin is important for elucidating the detailed properties of the tissue altered due to skin diseases and aging. On this topic, photoacoustic (PA) imaging has attracted much attention in recent years as a modality that can provide high-contrast micro vascular images in the skin layers. Essentially, the imaging modality acquires photoacoustic (PA) waves generated at particles that are irradiated with laser pulses and emit acoustic waves based on the "photoacoustic effect"[1], and has an ability to selectively visualize the particles. We have developed a PA imaging system equipped with a custom spherically curved array transducer to achieve three-dimensional PA images with both high spatial and temporal resolution, and have successfully visualized skin microvessels[2]. However, the obtained images lacked morphological information around the vessels. Since ultrasound (US) imaging has the potential to complement the limitation, the optimal US imaging sequence for the spherically curved array transducer has to be determined. In this study, we designed a US imaging method for the spherical transducer using the synthetic transmission aperture (STA) scheme and evaluated the imaging quality of the proposed method.

2. Materials and Methods

2.1 Spherically curved array transducer

A 256-ch spherically curved array transducer was custom-designed and fabricated. As shown in **Fig. 1**, the transducer was 42.4 mm in diameter with an opening angle of 90° and a spherical radius of 30 mm. It also had a hole of 10.4 mm in diameter at the center for laser irradiation. Each element was a square shape of approximately 2.2 × 2.2 mm. From a preliminary experiment that

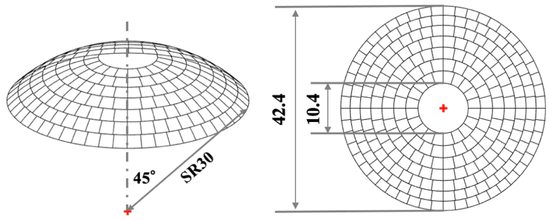

Fig. 1. Dimensions of the spherically curved array transducer. SR: spherical radius.

transmits acoustic pulses to a metal plate, the center frequency of the transducer was measured to be 11.5 MHz with a fractional bandwidth of approximately 62 % (8-15.5 MHz). It is noted that the specification of the transducer was originally designed for maximizing its sensitivity for the PA waves and this study used the same transducer for US imaging in order to achieve duplex PA-US images as a goal of our project.

2.2 Synthetic transmit aperture (STA) method

As a scheme of ultrasound transmissions, STA method [3] was used to enhance image resolution. Because of the hemispherical geometry of the transducer surface, each element transmits a beam that intersects the geometric focus of the array **(Fig. 2)**, and the echoes are received by all the elements. This process is repeated for all N elements, resulting in N x N echoes. Focusing is corrected by calculating the delay time, which depends on the geometric distance from the transmitting element to the imaging point and the distance back to the receiving element. The round trip delay is then

$$\tau_{m,n} = \frac{1}{c}[(r - r_m) + (r - r_n)] \quad (1)$$

$$\tau_i = \sqrt{(x_p - x_i)^2 + (y_p - y_i)^2 + (z_p - z_i)^2} \quad i = m, n \quad (2)$$

where r is the focal length (distance from each element to the geometric focal point), r_m and r_n are the distances from the image points to the transmitter

eiki.hayashi.p5@dc.tohoku.ac.jp

and receiver elements, respectively, c is the speed of sound, and (x_p, y_p, z_p), (x_m, y_m, z_m) and (x_n, y_n, z_n) are the coordinates of the image pixels and transmitter and receiver elements, respectively. In the case of an array of N elements, the image pixels of (x_p, y_p, z_p) can be expressed by

$$A_{STA}(x_p, y_p, z_p) = \sum_{m=1}^{M} \sum_{n=1}^{N} y_{m,n}\left(\frac{2r}{c} - \tau_{m,n}\right) \qquad (3)$$

where $y_{m,n}$ is the echo signal and $\tau_{m,n}$ is the delay time calculated in Eq. (1).

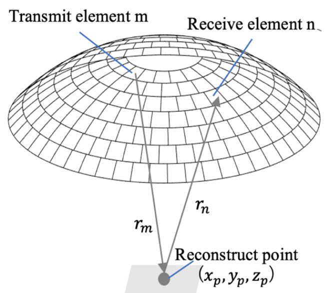

Fig. 2 Synthetic transmit aperture (STA) method

2.3 Wire phantom experiment

To investigate the spatial resolution and the effect of artifacts, we imaged a copper wire with a diameter of 100 µm placed in water at a depth of 30 mm, which is the geometrical focal point of the transducer. The US signals were collected by a programmable acquisition system (Vantage 256 systems, Verasonics). The transmission frequency was 12.5 MHz and the sampling frequency was 62.5 MHz. Two methods of US imaging scheme were used: 1)conventional method (transmitting from a single element and receiving at all elements), 2) STA method described in 2.2. The acquired US signals were processed and analyzed in MATLAB (MathWorks, Natick, USA). C-mode and B-mode images were generated from both methods and the axial and lateral resolutions were evaluated by calculating full width at half maximum (FWHM) of the copper wire in the images.

3. Result and Discussion

Fig. 3 shows the imaging result of the copper wire in C-mode (**Fig.3 (a, c)**) and B-mode (**Fig. 3 (b, d)**) images to compare with the conventional and the STA methods. These results showed that STA method could image the wire more uniformly and smoothly than the conventional method. Also, the lateral (**Fig. 4(e)**) and axial (**Fig. 4(f)**) profiles were compared between the two methods. The FWHM in the axial and lateral directions of the conventional methods were 128 and 172 µm, respectively, while those values of STA methods were 155 and 184 µm, respectively.

4. Conclusion

In this paper, we introduced a STA approach for US imaging using a spherically curved array transducer, and the imaging quality was compared with the single element transmission method. While the axial and lateral resolutions of STA images were relatively low compared with the conventional method, the proposed method achieved uniform and smooth images. It was suggested that the STA method would be effective for US imaging using the spherically curved array transducer.

References
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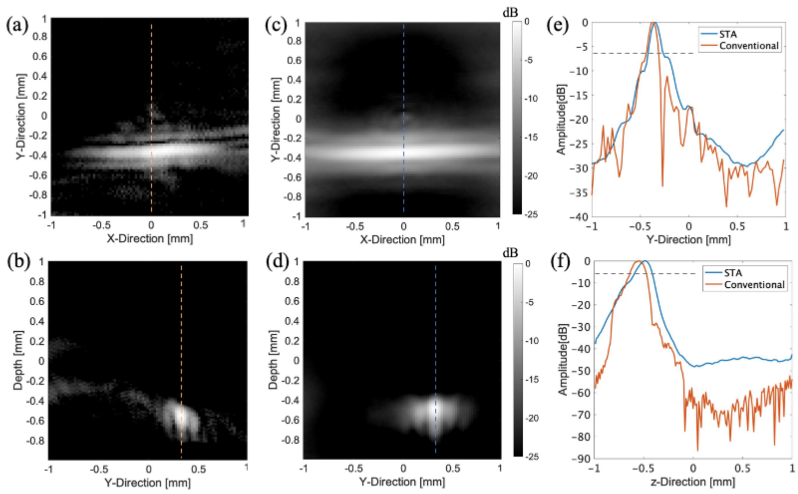

Fig. 3 US Imaging result of cooper wire, (a), (b) C-mode and B-mode image by conventional method. (c), (d) C-mode and B-mode image by STA method. (e), (f) The comparison of the envelope along the dotted line in C-mode image and B-mode image.