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Fast Ultrasonic Imaging of the Heart
心臓の高速超音波イメージング

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1. Introduction

Ultrasonography is a valuable method for non-invasive diagnosis of living organs, such like the heart, by measuring cross-sectional images of the organs in real time. By real-time imaging of the heart, abnormal macroscopic motion and shape can be diagnosed. Furthermore, ultrasonic Doppler technique realizes quantitative measurements of blood flow and motion of the heart wall. As described above, diagnostic ultrasound significantly contribute to diagnosis of the heart. In addition to the conventional ultrasonic diagnostic techniques described above, recently it was reported that measurements of the transient of myocardial contraction and relaxation and the propagation of the heart-wall vibration caused by the closure of valves during a short period (about 10 ms) are useful for assessment of myocardial function[1,2]. However, these measurements require a very high frame rate larger than 500 Hz that cannot be realized by conventional ultrasonic diagnostic equipment. In this study, a method was investigated to realize a high frame rate imaging of the heart at a frame rate over 500 Hz.

2. Principles

In conventional sector scanning, the ultrasonic field is focused both in transmit and receive (**Fig. 1**(a)). Therefore, the frame rate is determined by dividing the pulse repetition frequency by the number of scan lines. On the other hand, the use of unfocused beams in transmit can increase the frame rate. By creating multiple focused receiving beams in one unfocused transmitting beam (Fig. 1(b)), the number of transmits, which is required to obtain the same number of scan lines as that in conventional sector scanning, can be reduced. In this study, plane waves were transmitted in at most 15 directions (at a lateral field of view of 90 degrees) at angle intervals of 6 degrees, and 16 focused receiving beams were created in each transmit beam at angle intervals of 0.375 degrees (parallel beam forming[3)]). This procedure enables high frame rate imaging over 400 Hz at a typical pulse repetition frequency of 6 kHz (maximum observable range: about 13 cm).

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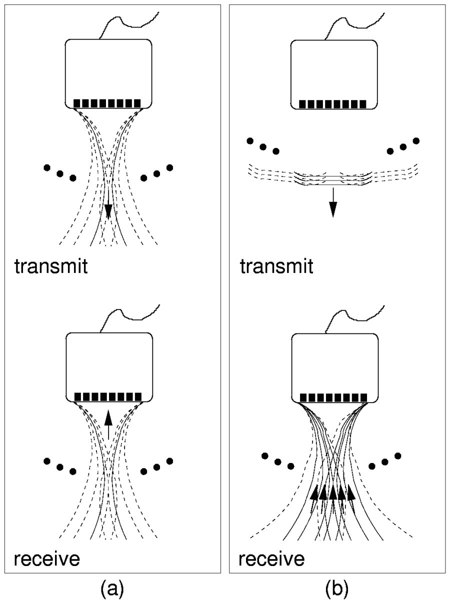

Fig. 1 Illustration of scan sequence. (a) Conventional sector scan. (b) Parallel beam forming.

3. Measurement of Emitted Sound Field

Ultrasonic field emitted from a 3.75-MHz sector-type probe (UST-52101, Aloka, Co., Ltd., Tokyo, Japan) was measured with a hydrophone (H025-002, Toray Engineering, Co., Ltd, Tokyo, Japan). **Figures 2**(a), 2(b), and 2(c) show ultrasonic RF signals received by the hydrophone placed at 50 mm, 100 mm, and 130 mm away from the sector-type probe, respectively. Ultrasonic signals received by the hydrophone were acquired by an oscilloscope (TDS220, Tektronix Japan, Co., Ltd., Tokyo, Japan) at a sampling frequency of 500 MHz. Figure 2(d) shows lateral profiles of the maximum sound pressure. In sector scanning, the lateral width Δx, which is scanned by one transmission, is proportional to the distance in the range (depth) direction. At z = 50 mm, $\Delta x = 2 \cdot 50 \tan(3 \text{ degrees})$ = 5.2 mm. As shown in Fig. 2(d), the lateral width Δw at half maximum of squared sound pressure is wider than Δx at z = 50 mm. However, Δw of about 12 mm at z = 100 mm is close to Δx of 10.5 mm. Therefore, the measurable depth would be limited to be less than 100 mm.

Furthermore, Δx would be reduced when a transmit beam is steered. The lateral width, Δw_θ, at steering angle θ is expressed as $\Delta w_0 \cos\theta$. Therefore, the lateral field of view would be also limited. At a depth of 100 mm, steering angle θ_{max} at which Δx is same as Δw_θ is obtained as follows:

$$\theta_{max} = \cos^{-1}\left(\frac{\left.\Delta x\right|_{\text{at 100 mm}}}{\left.\Delta w_0\right|_{\text{at 100 mm}}} \right) \approx 30 \text{ deg}.$$

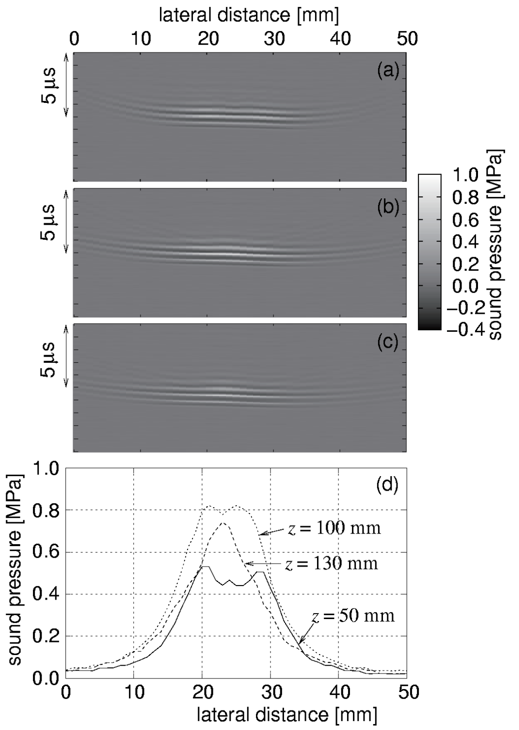

Fig. 2 Sound fields measured by a hydrophone. Hydrophone was placed at (a) 50 mm, (b) 100 mm, and (c) 130 mm. (d) Lateral profiles of the maximum sound pressure at corresponding depths.

4. Imaging of a Phantom

Figure 3 shows a B-mode image of a phantom which mimics biological tissue (403GS, Gammex, Inc., Middleton, WI, USA). Plane waves were transmitted in 11 directions at angle intervals of 6 degrees. This number of transmission and a pulse repetition frequency of 6028 Hz realized a frame rate of 548 Hz. Due to the inhomogeneity and limited width of a transmit beam, undesirable fluctuation in the image occurred in the region outside the white dashed line. As shown in Fig. 3, although the field of view was limited, the phantom was imaged at a frame rate of 548 Hz which is much higher than that achieved by conventional sector scanning.

5. *In Vivo* Imaging of a Human Heart

Figure 4 shows a B-mode image of a heart of a 23-year-old healthy male. Plane waves were transmitted in 7 directions at angle intervals of 6 degrees. By reducing the number of transmission, an extremely high frame rate of 1020 Hz was achieved. As shown in Fig. 4, although the field of view was limited, the heart could be imaged with a good quality at an extremely high frame rate.

6. Conclusion

In this study, high frame rate imaging of the heart over 1000 Hz was realized using parallel beam forming. To enlarge the field of view, transmit beam should be optimized by further investigations.

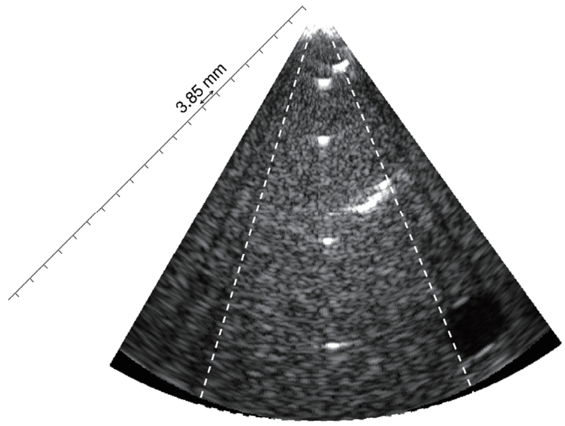

Fig. 3 B-mode image of a phantom measured at a frame rate of 548 Hz.

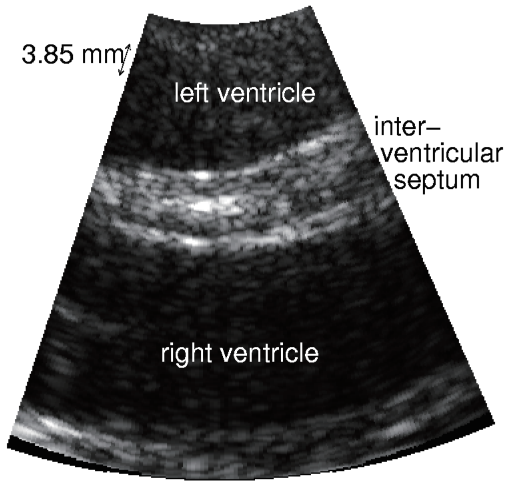

Fig. 4 B-mode image of a heart of a 23-year-old healthy male measured at a frame rate of 1020 Hz.

References

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