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High-frame-rate ultrasound imaging for assessment of cardiovascular function

Hideyuki Hasegawa (Univ. Toyama)

1. Introduction

Medical ultrasound imaging is widely used in clinical situations for cross sectional imaging of living organs and assessment of their function such as blood flow noninvasively. Clinical diagnostic ultrasound systems provide a real-time capability while the imaging frame rate is limited to several tens frames per second. Although such an imaging frame rate is still significantly superior to those of other medical imaging modalities such as CT (computed tomography) and MRI (magnetic resonance imaging), a higher imaging frame rate would be beneficial for functional imaging of dynamically moving organs such as heart and blood vessels. Nowadays high-frame-rate ultrasound, which enables an extremely high imaging frame rate of over ten thousand frames per second, has been widespread in research works and clinical trials for functional imaging of living organs while it is difficult in most cases to provide functional information in real-time.

We developed an imaging system, which realized an imaging frame rate of 10,000 frames per second at maximum[1)]. In high-frame-rate ultrasound imaging, unfocused transmit beams are used in transmit to illuminate the imaging field of view at once, and a large number of receiving focal points are placed at the same time to obtain an ultrasound image in every transmit-receive event. Typically plane and diverging waves are used for linear-array and phased-array imaging to visualize regions in square and sector formats, respectively[2,3)]. In this paper, methods for high-frame-rate ultrasonic imaging and its applications to cardiovascular functional measurements are described.

2. Methods

2.1. Beamforming for high frame rate imaging

To obtain an ultrasonic image, the echo signal from every spatial point in the imaging field of view needs to be estimated. In conventional medical ultrasonic imaging (focused-beam imaging), a focused transmit beams is used and thus only a narrow region along the axis of the transmit beam is illuminated. Therefore, basically one or a few scan lines are created by placing multiple receiving focal points along the transmit beam. Since an ultrasonic image is composed of a large number of scan lines, a lot of transmit-receive events are required to obtain scan lines required to construct an ultrasonic image. On the other hand, focusing both in transmit and receive improves spatial resolution and suppression of sidelobes.

In high-frame-rate ultrasonic imaging, a region, which is wider than that in focused-beam imaging, is illuminated with an unfocused transmit beam, e.g., plane and diverging waves in linear-array and phased-array imaging, respectively[2,3)], to reduce the number of transmit-receive events required to construct an ultrasonic image. Using such a procedure, an ultrasonic image can be produced by only one transmit-receive event, resulting in an extremely high imaging frame rate of over 10,000 frames per second.

Although the above-mentioned beamforming process achieves an extremely high imaging frame rate, spatial resolution and image contrast are degraded due to the lack of focusing in transmit. Such degradations in resolution and contrast can be reduced by coherent compound of echo signals obtained from multiple transmit-receive events[4)]. The coherent compound technique is inspired by synthetic aperture imaging and performed using steered plane waves in linear-array imaging[4)] and linearly translated[3)] or steered[5)] diverging waves are used. Although resolution and contrast are improved by increasing the number of transmit beams to be compounded, the imaging frame rate is decreased. Therefore, the number of transmit beams is chosen depending on applications by considering which is prioritized between image quality and imaging frame rate.

2.2. Methods for functional imaging of cardiovascular system

For assessment of functional cardiovascular imaging such as blood flow imaging, the motion of a target needs to be estimated from received echo signals. The autocorrelation method[6)] is a widely-used motion estimator, which estimates the target motion using the phase shift of the received echo signal. The computation load of the autocorrelation method is small and the method is used in various applications such as real-time color flow imaging. Although the autocorrelation method is effective for motion estimation, the method can estimate the component of the target motion only in the direction of ultrasonic propagation because it uses the phase of the received echo signal.

E-mail: hasegawa@eng.u-toyama.ac.jp

To overcome such a problem that the autocorrelation method can estimate only the axial motion of a target, the vector Doppler method was developed to estimate a velocity vector by measuring axial velocities from multiple directions[7,8]. Although the autocorrelation method can be used for the vector Doppler method, the direction of ultrasonic propagation needs to be determined to estimate velocity vectors accurately. In the conventional vector Doppler method, the beam steering angle, which is assigned in the beamforming process, is used for estimation of velocity vectors. However, the ultrasonic wavefront is disturbed due to interferences of scattered waves. Therefore, we developed a method for determining the direction of the ultrasonic wavefront by estimating the wave vector using the phase of the received echo signal[9]. The errors in estimation of velocity vectors were reduced significantly by estimating the direction of the wavefront corresponding to ultrasonic propagation.

As described above, velocity vectors can be estimated by the vector Doppler method. However, the method requires a relatively wide aperture to cross multiple beams at steering angles that are sufficient for estimating velocity vectors with acceptable errors. Therefore, it is difficult to apply the vector Doppler method to cases when a narrow aperture is required, i.e., phased-array imaging. In such cases, the block matching method is commonly used for estimation of velocity vectors[10].

2.3. Acquisition system

Nowadays it is common to use a programmable ultrasound system, which can control transmission and reception of ultrasound signals with a large number of elements. We developed a custom-made ultrasound system with 256 transmit-receive channels (RSYS0016, Microsonic). The system can store the ultrasonic echo signals received by individual elements. The acquired signals are analyzed off-line.

3. Results

In this article, measurement of flow velocity vectors is shown as an example of functional imaging of the cardiovascular system. **Figure 1** shows an in vivo example on a carotid artery of a 48-year-old subject. In the B-mode image in Fig. 1(a), echoes from blood cells are significantly weaker than those from surrounding tissues. To suppress the echoes from surrounding tissues and analyze echoes from blood cells, a clutter filter using singular value decomposition[11,12]. Figure 1(b) shows flow velocity vectors estimated by the vector Doppler method[9] in cardiac diastole. Even in a healthy subject without atherosclerotic plaque in the measured region, flow disturbances are visualized by flow velocity vectors in the upper right part of the artery in Fig. 1(b).

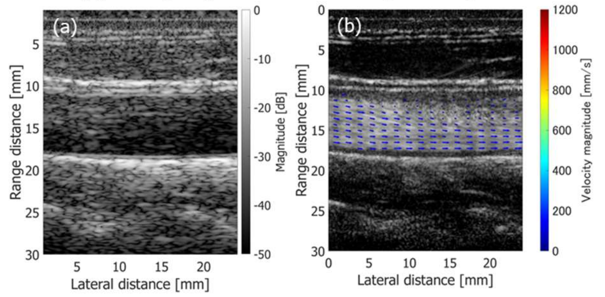

Fig. 1: In vivo example on 48-year-old healthy subject. (a) Normal B-mode image. (b) Clutter-filtered B-mode images. (c) Estimated flow velocity vectors overlaid on clutter-filtered B-mode image.

3. Conclusions

This article briefly describes the fundamental principle of high-frame-rate ultrasound imaging and applications for cardiovascular functional imaging.

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