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Paper

Near Real-time Measurement of Myocardial Contraction and Relaxation Based on High-frame-rate Ultrasound with a Graphical Processing Unit System

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Several speckle tracking methods have been proposed for noninvasive and quantitative evaluation of tissue motion. Since the low temporal resolution causes a large myocardial motion in the elevational direction and a large deformation, two-dimensional (2D) speckle tracking at a high frame rate is desirable for accurate estimation of myocardial contraction and relaxation. 2D speckle tracking at a high frame rate requires a high computational load, and the large suppression of calculation time is, therefore, essential for clinical use. In the present study, we investigate the minimum frame rate required for the estimation of myocardial contraction and relaxation. Furthermore, we employ a parallel computing principle using a graphical processing unit (GPU) system with 2,496 streaming processors to decrease the calculation time effectively. The employment of a parallel computing principle with a GPU system successfully decreased the calculation time to 1/50 of that using a desktop PC with a CPU. When the number of tracking points is 64, the calculation time was decreased to 28.7 s for the estimation during 1 s at a frame rate of 287 Hz, indicating that the proposed method with a GPU system has a potential to realize a near real-time estimation of myocardial contraction and relaxation.

Keywords : speckle tracking, myocardial contraction/relaxation property, two-dimensional (2D) displacement estimation, graphical processing unit (GPU)

1. Introduction

Cardiovascular disease is a major cause of mortality, and early diagnosis of the disease has become increasingly important because of the progress of the aging society. Ultrasonic diagnosis is an indispensable modality for diagnosis of cardiac diseases because it is noninvasive, cost effective, and easy to use. Diagnostic ultrasound is, therefore, widely used for diagnosis of the circulatory system, such as arteries[(1)-(3)] and the heart[(4)-(6)]. For the diagnosis of arteriosclerosis, the roughness of the blood vessels has been estimated using a highly accurate method for imaging the surface of a vessel[(7)-(9)]. Techniques for measuring the elasticity of a blood vessel using echoes from the radial artery have been studied[(10)-(12)]. For the evaluation of cardiac function, methods for visualization of hemodynamics[(13)-(15)] and tissue Doppler methods[(16)-(18)] have been reported. Two-dimensional myocardial displacement measurement[(19)(20)] and regional myocardial thickness variation rate measured by speckle tracking[(19)(21)] have been reported to be useful techniques; however, investigation of myocardial change from a contracted state to a relaxed state during one cardiac cycle is still challenging[(22)-(24)].

Since the low temporal resolution causes a large myocardial motion in the elevational direction and a large deformation[(25)-(27)], two-dimensional (2D) speckle tracking at a high frame rate is desirable for accurate estimation of myocardial contraction and relaxation[(28)(29)]. In our previous study, 2D displacements of the heart wall were estimated at a frame rate of 860 Hz and over using a wide transmit beam[(30)-(32)]. The high temporal resolution of the method is suitable for the accurate estimation of myocardial contraction and relaxation; however, a 2D speckle tracking method at a high frame rate requires a high computational load, and the large suppression of calculation time is, therefore, essential for clinical use.

Recently, graphics processing unit (GPU) systems have drawn large interest as a solution to the high computational load[(33)-(35)]. In the present study, we investigate the potential of the 2D speckle tracking method at a high frame rate using a GPU system in the measurement of myocardial contraction and relaxation. Our contributions are considered to be two-fold. First, we examine the minimum frame rate required for the estimation of myocardial contraction and relaxation. Second, we evaluate the potential of a GPU system in the high-frame-rate measurement of myocardial contraction and relaxation using a 2D speckle tracking method, where this application has not been considered in GPU investigations.

2. Materials and Methods

2.1 Parallel Beamforming for the Signal Acquisition at a High Frame Rate Parallel beamforming is a technique that realizes the acquisition of RF signals at a high frame rate[(28)(29)]. This technique employs few wide transmit beams in a frame, and many narrow receive beams are generated for each transmit beam,

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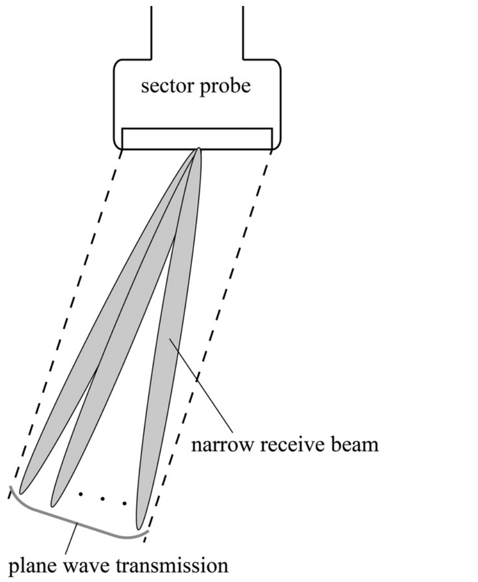


Fig. 1. Illustration of one transmit-receive procedure in parallel beamforming using plane wave transmission.

as shown in Fig. 1. Typically, the frame rate, f_{FR}, is determined by the pulse repetition frequency, f_{PRF}, and the number of transmit beams in a frame, N_{T}.

$$f_{\mathrm{FR}} = f_{\mathrm{PRF}} / N_{\mathrm{T}}. \quad \cdots\cdots (1)$$

Therefore, the employment of few transmit beams widely improves temporal resolution that suppresses the effects of a myocardial motion in the elevational direction and a deformation on motion estimation.

2.2 Calculation of 2D Tissue Motion using Normalized Cross-correlation Function The normalized cross-correlation between ultrasound RF signals is one of the most common speckle tracking techniques for the estimation of tissue motion. The normalized cross-correlation function between a tracking point at l-th lateral position and d-th axial position in the n-th frame, $\mathrm{P}_{l,d,n}$, and a calculation point in a search area in the $(n+\Delta n)$-th frame, $\mathrm{Q}_{l+m,d+k,n+1}$, was given by

$$\gamma_{l,d}(n,m,k) = \frac{1}{A} \sum_{i=(1-N_{\mathrm{WL}})/2}^{(N_{\mathrm{WL}}-1)/2} \sum_{j=(1-N_{\mathrm{WD}})/2}^{(N_{\mathrm{WD}}-1)/2} \{ w(i,j)^2 r(n,i+l,j+d)$$

$$\cdot r(n+\Delta n, i+l+m, j+d+k) \}, \quad \cdots\cdots (2)$$

$$A = \xi(n,i,j)\xi(n+\Delta n, i+m, j+k), \quad \cdots\cdots (3)$$

$$\xi(n,i,j) = \sqrt{\sum_{i=(1-N_{\mathrm{WL}})/2}^{(N_{\mathrm{WL}}-1)/2} \sum_{j=(1-N_{\mathrm{WD}})/2}^{(N_{\mathrm{WD}}-1)/2} \{ w(i,j) r(n,i+l,j+d) \}}, \quad \cdots\cdots (4)$$

where m and k are respectively the lateral and axial shifts of $\mathrm{Q}_{l+m,d+k,n+1}$ from $\mathrm{P}_{l,d,n}$, N_{WL} and N_{WD} are respectively the correlation kernel widths in the lateral and axial directions, $w(i,j)$ is the correlation kernel function, and $r(n,i,j)$ is the RF signal at i-th lateral position and j-th axial position in the n-th frame.

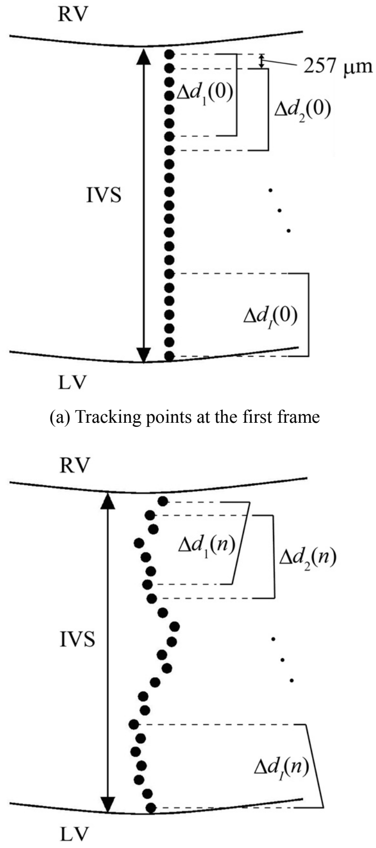
The correlation kernel should be designed based on the ultrasound speckle size that depends on the ultrasound beam width and pulse length[30][31]. In the present study, the correlation kernel were defined using the −20 dB width of the lateral ultrasound beam, B_{L}, and that of the envelope in the axial direction, B_{D}. The correlation kernel function was given by

$$w(i,j) = \exp\left[-\left(\frac{i^2}{2{\sigma_{\mathrm{L}}}^2} + \frac{j^2}{2{\sigma_{\mathrm{D}}}^2} \right) \right], \quad \cdots\cdots (5)$$

$$\sigma_{\mathrm{L}} = B_{\mathrm{L}} / \Delta l, \quad \cdots\cdots (6)$$

$$\sigma_{\mathrm{D}} = B_{\mathrm{D}} / \Delta a, \quad \cdots\cdots (7)$$

where Δl and Δa are the lateral and axial intervals of ultrasound RF data, respectively.



(a) Tracking points at the first frame

(b) Tracking points at the n-th frame

Fig. 2. Estimation of myocardial contraction and relaxation from the distance change between two tracking points.

2.3 Estimation of Myocardial Contraction and Relaxation

Figure 2 shows the proposed process to estimate the myocardial contraction and relaxation from the change in distance between two tracking points. First, the tracking points were set along a scan line in the IVS at the time of the Q-wave in the electrocardiogram. Second, the position of each tracking point was tracked using the 2D speckle tracking method. The myocardial expansion $S_i(n)$ around the i-th tracking point at the n-th frame is given by

$$S_i(n) = \Delta d_i(n) - \Delta d_i(0), \quad \cdots\cdots (8)$$

$$\Delta d_i(n) = \left| \mathbf{d}_{i+W}(n) - \mathbf{d}_{i-W}(n) \right|, \quad \cdots\cdots (9)$$

where $\mathbf{d}_i(n)$ denotes the position vector of the i-th tracking point, $\Delta d_i(n)$ denotes the distance between the two position vectors, and W is a constant. In the present study, the obtained myocardial expansion $S_i(n)$ was averaged temporally to suppress high-frequency noise components by

$$\overline{S}_i(n) = \frac{1}{N_C} \sum_{k=(N_C-1)/2}^{(N_C+1)/2} S_i(n+k), \quad \cdots\cdots (10)$$

where N_C is an odd number that denotes the number of frames used for the temporal averaging.

2.4 Reduction of Calculation Time by Employing Appropriate Frame Rate For the estimation of myocardial contraction and relaxation using 2D speckle tracking, a high frame-rate data acquisition can suppress the effect of myocardial motion in the elevational direction and a large deformation. Therefore, a high frame rate acquisition is desirable for accurate estimation. However, the computational load in a cardiac cycle is proportional to the frame rate, and a low frame rate acquisition is desirable to reduce the calculation time.

2.5 Reduction of Calculation Time using the GPU System Since the two-dimensional speckle tracking required massive calculation time, a parallel signal processing algorithm using a GPU system was employed. The computational load for two-dimensional speckle tracking per one frame using a CPU is given by

$$O_{\mathrm{CPU}}(N_{\mathrm{WL}} N_{\mathrm{WD}} N_{\mathrm{SL}} N_{\mathrm{SD}} N_{\mathrm{L}} N_{\mathrm{D}}), \quad \cdots\cdots (11)$$

where $N_{\mathrm{WL}} N_{\mathrm{WD}}$ is the number of points in a correlation window required to calculate a cross-correlation value, $N_{\mathrm{SL}} N_{\mathrm{SD}}$ is the number of calculation points in the search area, and $N_{\mathrm{L}} N_{\mathrm{D}}$ is the total number of tracking points in the heart wall.

The huge calculation time was reduced using the graphical processing unit (GPU) system with 2,496 streaming processors (K20c, NVIDIA Tesla; OS: 6.4, 64 bits, CPU: Intel core i7-3770). Programming languages used in the present study were C and CUDA, where CUDA is one of the compute unified device architectures. As shown in Fig. 3, each block in GPU system was assigned to the respective tracking points and each thread was assigned to the respective calculation point in the search area. Since each thread calculates a cross-correlation value given by Eq. (2), the theoretical computational load per thread is given by

$$O_{\mathrm{Thr}}(N_{\mathrm{WL}} N_{\mathrm{WD}}). \quad \cdots\cdots (12)$$

In the present study, the number of threads is given by

$$N_{\mathrm{Thr}} = N_{\mathrm{SL}} N_{\mathrm{SD}} N_{\mathrm{L}} N_{\mathrm{D}}. \quad \cdots\cdots (13)$$

When the number of streaming processors used in a GPU system is larger than that of threads, all threads are calculated simultaneously by the streaming processors of the same number. Therefore, the calculation time depends on the computational load of a thread. In contrast, the number of streaming processors is smaller than that of threads, the number of threads calculated simultaneously is the same as that of the streaming processors, and the threads are calculated in turn. Therefore, the computational load for 2D speckle tracking per one frame using a GPU system is given by

$$\begin{cases} O_{\mathrm{GPU}}(N_{\mathrm{WL}} N_{\mathrm{WD}}) & \text{if } N_{\mathrm{Thr}} < N_{\mathrm{Str}} \\ O_{\mathrm{GPU}}(N_{\mathrm{WL}} N_{\mathrm{WD}} N_{\mathrm{Thr}} / N_{\mathrm{Str}}) & \text{else} \end{cases}, \quad \cdots\cdots (14)$$

where N_{Str} is the number of streaming processors used in a GPU system.

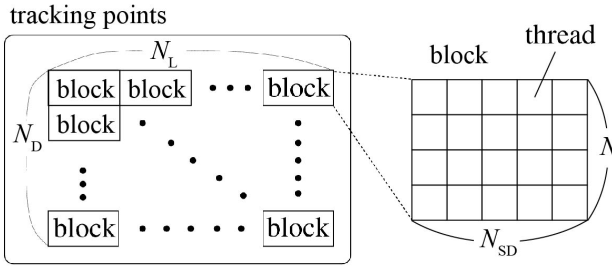


Fig. 3. Parallelization of the processing for calculation of the two-dimensional correlation function. Each block in GPU system was assigned to the respective tracking points. Each thread in a block calculates a cross-correlation value between a tracking point and a calculation point in a search area.

3. Results

3.1 Experimental Setting In the present study, plane waves were transmitted to seven different directions using a 3.75-MHz sector probe with 96 elements equipped to a diagnostic ultrasound system (Alpha10, Hitachi-Aloka Medical, Japan), where the angular interval of transmit directions was 6°. Since the number of transmit beams in a frame, N_{T}, is 7 and the pulse repetition frequency f_{PRF} was 6,020 Hz, the frame rate, f_{FR}, was 860 Hz. 16 narrow receive beams were generated for each plane wave transmission. Therefore, the total number of receive beams was 112 and their angular interval was 0.375°. As described above, the ultrasound measurement using parallel beamforming achieved a high frame rate measurement with sufficient spatial resolution.

The −20 dB widths in the lateral and axial directions at a depth of 40 mm, B_{L} and B_{D}, were 2.48 and 1.96 mm, respectively. Since the sampling frequency was 15 MHz and the sound velocity was set to 1,540 m/s, the axial interval of RF data, Δa, was 51.3 μm. The lateral interval of RF data at the interventricular septum (IVS) was 330 μm, because the angular interval was 0.375° and a typical depth of IVS was about 50 mm.

The initial distance of adjacent tracking points was set to 257 μm, as shown in Fig. 2. Since the myocardial expansion was calculated by Eq. (9) and W was set to 3, the initial distance of two tracking points, $\Delta d_i(0)$, was 1.54 mm. The temporal averaging parameter N_{C} in Eq. (10) was set to 7. We investigated the estimation accuracy of the proposed method under the conditions of frame rate f_{FR} = 860, 430, 287, and 172 Hz. This investigation was conducted by employing Δn = 1, 2, 3 and 5 in Eq. (2). The calculation time was evaluated by changing the number of tracking points $N = N_{\mathrm{L}} N_{\mathrm{D}}$ (N = 2, 4, 8, 16, 32, 64, 128, 256).

3.2 Myocardial Contraction and Relaxation in IVS The proposed method was applied to the heart of a 23-year-old healthy male. Figure 4 shows a B-mode image in the longitudinal section plane of the left ventricle of the heart. Figure 5 shows the myocardial contraction and relaxation in IVS. As shown in Fig. 5, myocardial contraction of the apex side was followed by that of the basal side in the IVS. This result was consistent with those in the previous study[32]. Furthermore, as shown in Fig. 5, the myocardial expansion on the left ventricular side in the IVS was significantly larger than that on the right ventricular side. This phenomenon may originate from the fact that the left ventricle ejects blood into the aorta with large pulse pressure.

3.3 Appropriate Frame Rate for the Estimation of 2D Myocardial Contraction and Relaxation in IVS In the present study, we investigated the estimation accuracy of the proposed method under the conditions that the frame rate f_{FR} = 860, 430, 287, and 172 Hz. Figure 6 shows the lateral displacement of a tracking point estimated by the proposed method. The estimated

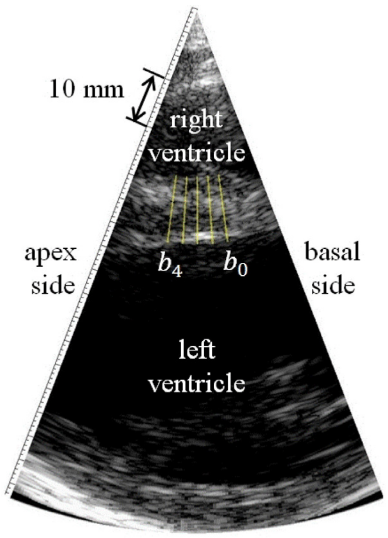


Fig. 4. B-mode image of the heart wall of a 23-year-old healthy male. The tracking points are set along the 5 yellow lines in the IVS.

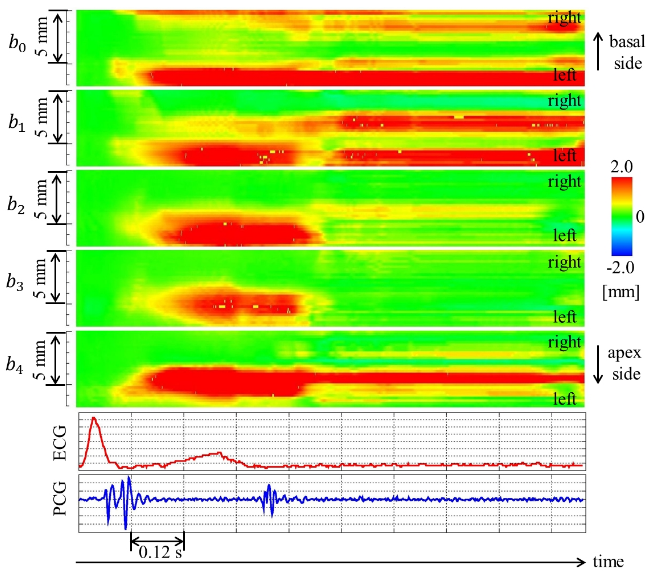


Fig. 5. Myocardial expansion in the IVS estimated at the frame rate of 860 Hz. Color bar shows the distance change of two tracking points, where the initial distance is set to 1.54 mm.

lateral displacements under the conditions of f_{RF} = 860, 430, and 287 Hz were similar. In contrast, the estimated displacement of f_{RF} = 172 Hz was about 1 mm different from those of $f_{RF} \geq 287$ Hz during the latter half of a cardiac cycle. This result shows that the appropriate frame rate was about 287 Hz for the accurate and near real-time estimation of 2D myocardial contraction and relaxation in IVS.

3.4 Efficiency of a GPU System in the Measurement of Myocardial Contraction and Relaxation In order to evaluate the effect of the parallelization using a GPU system, we compared the calculation time by changing the number of tracking points. Table 1 shows the calculation time for estimation of the myocardial contraction and relaxation using a desktop PC with a single CPU and the GPU system. The calculation time of a desktop PC with a single CPU was almost proportional to the number of tracking points N. On the other hand, the efficiency of a GPU system increased significantly as the number of tracking points increased, and when N was equal or larger than 128, the employment of a GPU system successfully decreased the calculation time to 1/50 of that using a desktop PC with a single CPU. When the number of tracking points N was set to 64, the GPU system acquired 10 frames/s. In contrast, a desktop PC with a CPU acquired only 0.22 frames/s. These results show that the GPU system employed in the present study is suitable for a near real-time processing.

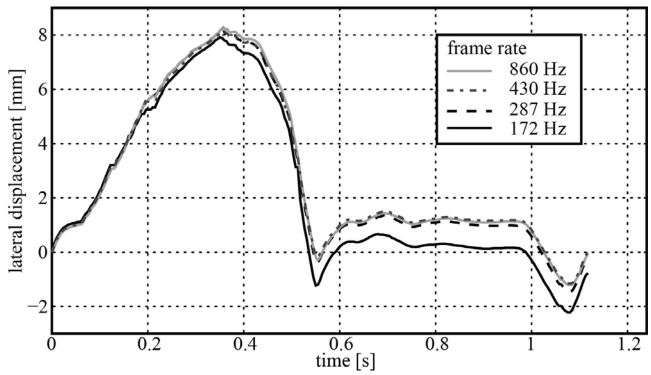


Fig. 6. Lateral displacement of a tracking point in the IVS during a cardiac cycle at the frame rates of 860, 430, 287, and 172 Hz.

Table 1. Comparison of the calculation time per frame. Calculation time ratio denotes the ratio of the calculation time using a GPU system to that using a desktop PC with a single CPU.

The number of tracking points	2	4	8	16	32	64	128	256
Calculation time using a CPU [ms]	141	263	517	1119	2277	4468	8188	16769
Calculation time using a GPU system [ms]	49	49	51	56	67	100	162	326
Calculation time ratio (%)	35	19	10	5	3	2	2	2

4. Discussions

As shown in Fig. 6, the lateral displacement of a tracking point is much larger than the ultrasound beam width of 2.48 mm. Therefore, the 2D speckle tracking should be desirable for the measurement of myocardial contraction and relaxation compared with one-dimensional tracking techniques.

The calculation time of a GPU system was substantially constant up to $N = 16$, and monotonically increased for $N > 16$. When the number of tracking points N was 16, the number of threads in the present study was 2640. Since the number of threads was 2496, the number of the threads exceeded the number of the streaming processors, and 2496 threads were processed at the same time and the remaining 144 threads remained to be processed. Thus, the GPU system became sequential processing for $N > 16$. These results support the investigation described in Section 2.5.

When the frame rate was 287 Hz and the number of tracking points was 64, the proposed method with a GPU system required 28.7 s to estimate 2D myocardial contraction and relaxation during 1 s. In contrast, a desktop PC with a single CPU required more than 20 min. Previous work has realized a six-GPU platform(35). The employment of a six-GPU platform is supposed to decrease the calculation time to about 5 s, indicating the high potential of the proposed method with a GPU system in a near real-time estimation of myocardial contraction and relaxation.

5. Conclusion

In the present study, we proposed a near real-time method for the estimation of myocardial contraction and relaxation based on high-frame-rate ultrasound with a GPU system. From an *in vivo* experimental study of a healthy male, the high frame rate acquisition of 287 Hz and more was required for a 2D tracking technique to suppress the effects of myocardial motion in the elevational direction and deformation on motion estimation. The parallel computing principle using a GPU system with 2,496 streaming processors succeeded to reduce the calculation time to 1/50 of that using a desktop PC with a single CPU. When the frame rate was 287 Hz and the number of tracking points was 64, the proposed method required 28.7 s to estimate 2D myocardial contraction and relaxation during 1 s. These results show a high potential of the proposed method with a GPU system in a near real-time estimation of myocardial contraction and relaxation.

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