Echocardiographic image tracker with a speckle adaptive noise reduction filter for the automatic measurement of the left atrial volume curve

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Aims
Since tracking accuracy in left atrial (LA) images decreases due to low image quality around the LA in the apical view, a practical tracking method for LA images has not yet been proposed. The aim of this study was to assess an accurate and high-speed LA volume tracking (LAVT) method for the automatic measurement of LA volume (LAV) curves.

Methods and results
We used three approved protocols in this study: (i) LAV curves were measured by LAVT on computer-simulated images; (ii) in 20 healthy volunteers, we assessed the feasibility and accuracy of this method compared with expert’s measurements; and (iii) echocardiography and multi-detector row computed tomography (MDCT) imaging were performed on the same day in 20 patients with suspected coronary artery disease. On computer-simulated images, mean absolute percentage LAVT error in one cardiac cycle was 3% in filtered images and 16% in original images. In 20 healthy volunteers, there are strong correlations between LAVT and the expert’s LA measurements (LA maximum volume; $R = 0.93, P \leq 0.001$). In 400 LA images with 20 patients, an excellent correlation was obtained between LAVs using echocardiography and MDCT ($R = 0.98, P \leq 0.001$), with a small bias ($–14\%$ of the mean) and narrow limits of agreement ($+15\%$ of the mean). The mean time required for the LAVT analysis was 1.8 min, for the MDCT analysis was 35.8 min, and for the manual echocardiographic analysis was 14.0 min.

Conclusion
This LAVT method is fast, valid, accurate, and reproducible for determining LAV in both simulated images and the clinical setting.

Keywords
Echocardiography • Image tracking • Left atrium • Speckle • Noise reduction

Introduction
In routine examinations, mandatory global cardiac function indexes such as fractional shortening and ejection fraction have been measured by M-mode, B-mode, and Doppler methods.¹,² Local cardiac function measurements are also necessary to reveal the mechanism of heart diseases. In the evaluation of left ventricle (LV) systolic function, myocardial strain measurement systems using image tracking techniques have been proposed.³–⁵ In contrast, in the evaluation of LV diastolic function, although transmural flow patterns have been generally calculated, the measurement of left atrial (LA) dynamic states is also attempted to reveal the relationship between LA dynamic states, exercise capacity,⁶ and heart failure.⁷ However, imaging assessment of LA function is challenging and even more demanding, compared with LV for several reasons.⁸ The thin walls of the LA make the technical aspects of imaging difficult. In addition, LA depth and surrounding structures may also influence the imaging results due to their higher signal noise. A practical tracking method for LA images has not yet been proposed. Furthermore, many tracking points on the LA wall must be tracked in a short time for clinical use. Hence, an accurate and high-speed image tracker is required for the measurement of LA volume (LAV) curves, which could be useful LA function indexes. We attempted the newly developed LAV tracking (LAVT) method using the combined techniques of the two-dimensional Gaussian filter as a speckle adaptive noise reduction filter and the Kanade-Lucas-Tomasi (KLT) tracker as a

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high-speed image tracker (Supplementary data online, S1). Accordingly, this study was designed to achieve the following aims in three separate protocols. The aim of Protocol 1 was to assess the errors of LAVT in one cardiac cycle on computer-simulated images. In Protocol 2, we assessed the feasibility and accuracy of this method compared with expert experience. In Protocol 3, we validated the automatic measurement of LAV curves using multi-detector row computed tomography (MDCT) measurements as a reference.

Methods

Echocardiographic image tracker for automatic measurements of LAV curves

Since speckle patterns represent tissue characteristics, tissue motion could be estimated by the KLT tracker, which calculates the motion vectors of image patterns between frames. However, the KLT tracker had difficulty providing highly accurate tracking in ultrasound images due to the presence of image noise. Therefore, the echocardiographic image tracker combined with the KLT tracker and a preprocessing filter (Supplementary data online, S2). The echocardiographic image tracker was applied to measure LAV curves. Tracking points on the LA wall were set at 10-pixel intervals automatically and were tracked in one cardiac cycle. The LAV curve was constructed using the time-series volumes bounded by tracked points in each frame. The cylindrical volumes were calculated by the modified Simpson’s method with 30-sliced disks.

Protocol 1

We simulated a sector scan moving image to evaluate the accuracy of LAVT quantitatively. An LA in the apical view was composed of a half ellipse with a major radius of 30 mm and with a minor radius of 10 mm, and a half concentric ellipse with wall thickness of 2 mm at 100 mm depth from a transducer. The scatterer positions were defined by the uniform pseudorandom number in the wall area. The scatterer density was 10 scatterer/mm², which was sufficient to generate speckles. LA motion in one cardiac cycle was simulated by expanding and shrinking with 5 mm in a direction perpendicular to the ellipse curve at constant speed. LA moving images with each wall speed of 5, 10, 20, and 40 mm/s were simulated with a fixed frame rate of 79 frame/s. When the frame rate was fixed, the magnitude of the motion from one frame to the next frame was large in high wall speed and was also small in low wall speed. Therefore, the performance of the tracking was evaluated depending on the wall speed. Noise components were added to the moving images to evaluate tracking errors due to motion, excluding LA wall motion. The effect of the noise reduction filter was evaluated by comparing the contrast, which was a kind of textural feature using the co-occurrence matrix, of the small regions (20 × 20 pixels) in the original and the filtered images. Figure 1 shows the effect of the speckle adaptive noise reduction filter in the simulated image. In Figure 1, the small regions (20 × 20 pixels) bounded by white lines show the region of interests used for the calculation of the tracking. Figure 1B is the filtered image of Figure 1A. Regardless of the depth and the angle from the transducer, the laterally long shape of speckles was preserved and the granular noise was reduced.

Protocol 2

Using the proposed method, we measured the LAV of 20 normal volunteers without heart diseases (mean age, 37 years). Echocardiographic images were acquired in the audio video interleave (AVI) format by an ultrasound equipment (EUB-8500, Hitachi Medical Corporation, Tokyo, Japan). On the apical two- and four-chamber views, the contour of an LA was traced manually on the intensity edge of the LA wall from a hinge point to the opposite hinge point of a mitral valve. Tracking points were set on a contour at 10-pixel intervals automatically and were tracked in one cardiac cycle. These measurement results were compared with an expert’s results on still images. The medical expert’s method was to measure the LAV of the same 20 normal volunteers as above by three steps: (i) extracting the frames of the three phases from moving images, (ii) tracing the contours of the LA, and (iii) measuring the volumes by the modified Simpson’s method. The LAV index was calculated by dividing the volume by a body surface area. Accordingly, the LAV indexes of the three phases extracted from the volume curve constructed by the LAVT were compared with the LA indexes of the three phases measured by the expert’s method. We obtained approval for this study from the ethics committee of the Fujita Health University and received informed consent from each study participant.

Protocol 3

Consecutive patients with suspected coronary artery disease were approached for recruitment. Twenty patients (mean age, 66 years) underwent echocardiography, and MDCT imaging was performed on the same day. The left atrium was encompassed by 3-mm slices. The LA area of each slice was calculated from manually drawn endocardial boundaries of the LA cavity using the commercially available software (Ziosoft, Inc., Tokyo, Japan). LAV was achieved using the slice summation method, which is based on the summation of the volume of each slice taking the slice thickness into account. The atrial appendage and pulmonary vein were excluded from the LAV calculations. LAV–time curves were depicted by plotting each instantaneous LAV against the time after the R-wave of the electrocardiogram. All MDCT images were reconstructed every 5% from 0 to 95% of the R–R interval. We assessed 20 LA images of each patient by MDCT. Therefore, a total of 400 LAVs were evaluated. Echocardiographic images were acquired as the AVI format by an ultrasound equipment (EUB-8500, Hitachi Medical Corporation). We measured echocardiographic LAV using the LAVT method from the apical two- and four-chamber views (Figure 2). All echocardiographic images were also reconstructed every 5% from 0 to 95% of the R–R interval. Finally, we compared 400 LAVs between MDCT and echocardiography. To assess the standard expert’s method (manual calculation by modified Simpson’s method), we randomly selected 10 patients in this group. We obtained approval for this study from the ethics committee of the Tokushima University Hospital and received informed consent from each patient to participate in this study.
Statistical analysis
Data are reported as mean ± SD. Agreement between each technique was expressed by Pearson’s correlation coefficient. Bland–Altman analysis was used to determine the bias and 95% limits of agreement (LOAs) between the echocardiographic measurements and MDCT counterparts. The median value of MDCT LAV was used to divide patients into two equal groups for Bland–Altman analysis. Inter- and intra-observer variability was examined for echocardiographic data. Measurements were performed in a group of 10 randomly selected subjects by one observer then repeated on two separate days by two observers who were unaware of the other’s measurements and of the study time-point. Reproducibility was expressed as the mean percentage error (absolute difference divided by the average of the two observations). Statistical analysis was performed using a standard statistical software package (SPSS software 20.0, SPSS, Inc., Chicago, IL, USA), and statistical significance was defined by \( P < 0.05 \).

Results
Protocol 1
Figure 3 shows the volume curve in one cardiac cycle measured in the original and the filtered images with \( v = 10 \) mm/s. Theoretical values were calculated as a half volume of an ellipsoid. Theoretical minimal and maximal values were 6.3 and 16.5 mL, respectively. Mean absolute percentage errors (MAPEs) in one cardiac cycle were 16% in the original images and 3% in the filtered images.

Figure 4 shows that the MAPE curve in one cardiac cycle was mostly constant on any speed of the LA walls.

Protocol 2
Figure 5 shows the LAV curves of the R–R interval (between one R wave and the next R wave of ECG) in the clinical setting. The curve of the original image on standard speckle tracking echocardiography was always below that of the filtered image on LAVT over the one cardiac cycle. This figure showed 15% underestimation of LAV in original images. The volumes at five phases are summarized in
Table 1. The maximal volume and the volume at onset of atrial systole in the original images were smaller than that in the filtered images. The volumes of the other three phases were nearly equal between the original and the filtered images. Table 2 summarizes the volume indexes measured by the expert’s and the LAVT methods. The expert’s method underestimated the maximum volume index compared with the LAVT method. The other volume indexes were nearly equal in the two methods. There were strong correlations between the LAVT method and the expert’s method in LAVs (LA maximum volume, $R = 0.93$; LA pre-contraction volume, $R = 0.91$; and LA minimum volume, $R = 0.90$; all $P < 0.001$).

### Protocol 3

Figure 6 shows the results of the comparison between LAVT and MDCT measurements in 400 LAV images. Bland–Altman analysis showed a mean difference of $-8.9$ mL ($-14\%$ of the mean) with an LOA of $\pm 9.1$ mL ($\pm 15\%$ of the mean). An excellent correlation was obtained between LAVT and MDCT ($R = 0.98$, $P < 0.001$). In patients with enlarged LAV (MDCT LAV of $>64$ mL: median value), Bland–Altman analysis showed a mean difference of $-9.7$ mL ($-12\%$ of the mean) with the LOA of $\pm 11.3$ mL ($\pm 14\%$ of the mean). In the other group, Bland–Altman analysis showed a mean difference of $-8.2$ mL ($-18\%$ of the mean) with the LOA of $\pm 6.0$ mL ($\pm 15\%$ of the mean). In the standard expert’s echocardiographic method, Bland–Altman analysis showed a mean difference of $-12.3$ mL ($-19\%$ of the mean) with the LOA of $\pm 11.1$ mL ($\pm 17\%$ of the mean). Therefore, this LAVT method is fast, valid, accurate, and reproducible for determining LAV even in patients with enlarged LAVs.

The mean time required for LAVT analysis was 1.8 min, for MDCT analysis was 35.8 min, and for standard expert’s echocardiographic-analysis was 17.4 min. The inter- and intra-observer variability, expressed as a mean percent error, of the LA maximum volume were $5.4 \pm 2.8$ and $3.8 \pm 2.1\%$, respectively.

### Discussion

In simulated images, LAVT accuracy is excellent. In addition, LAV by the LAVT method correlates closely with the expert’s method in five phases of the cardiac cycle and in the MDCT method in all phases of the cardiac cycle. The results of these protocols demonstrated that this LAVT method is a valid, accurate, and reproducible method for determining LAV in both simulated and clinical images.
Tracking in simulated images
In Protocol 1, although the LAV curve of the filtered images was a good fit for the theoretical volume curve, the LAV curve of the original images was underestimated more than the theoretical volume curve (Figure 3). Figure 4 shows that the MAPE was not varied on changing speed of the LA wall. Since the tracking accuracy was stable in a wide speed band, the precise measurement was performed in the LA wall with accelerated motion. Although the MAPE is 16% for tracking in the original images, the MAPE decreases to 3% for tracking in the filtered images. Therefore, the improvement of tracking accuracy is confirmed.

Tracking in clinical images
In Protocol 2, the maximal volume in the original images was underestimated more than that in the filtered images. This underestimation is considered to be due to the tracking delay as in the above subsection. Compared with the expert’s results reported in Table 2, the maximal volume index was slightly underestimated. However, the LAVT method is considered to be sufficiently useful for constructing the LAV curve automatically. Although the multiple causes of the underestimation of the maximal volume are difficult to identify, some of them are considered to be the loss of image quality and the motion perpendicular to the direction of a two-dimensional (2D) imaging plane. In addition, in Protocol 3, all LAVs were underestimated compared with MDCT volumes. These results suggest that the echo LAVs may be underestimated in the clinical setting. However, this measurement error was not larger in patients with enlarged LAVs. In the clinical setting, we believe that we are able to use the LAVT method in a wide range of LAVs. In addition, tracking in 3D moving images and improving image quality are some tracking accuracy improvement solutions.

Underestimation of volumes by 2D echocardiography has been reported in some studies on the LA. Not surprisingly, we also found a bias between the LA measurements obtained by the LAVT method and MDCT. Our results showed a mean difference of −14% of the mean. This is in moderate agreement with the results of recent studies on the left atrium. Avelar et al. showed a bias of −25% comparing 2DE with CT. Mor-Avi et al. reported a bias of about −20% comparing 2DE with magnetic resonance imaging (MRI). A plausible explanation for the observed improvements lies in the LAVT techniques for detecting and tracking correctly the endocardial surface.

Recently, some studies showed that LAVs and ejection fractions as assessed by three-dimensional (3D) echocardiography were highly correlated with CT and MRI measurements. However, there were several limitations to 3D echocardiography. Feasibility is an important limitation of the 3D approach. The exclusion rate was relatively high in previous papers because of poor image quality, including an unclear endocardial border, small intercostal space, and abundant body fat. In addition, the low frame rate in 3D echocardiography may lead to inaccurate timing of measurement, especially in patients with a high heart rate. Because of these limitations, many laboratories continue to use 2D measurements of the LA in a clinical setting, and refinement in the 2D approach to assess the LA function is needed.

Inter- and intra-observer variability
In addition to the excellent intertechnique agreement, we found that both inter- and intra-observer variability of the echocardiographic LAV was low. An important implication of this improved reproducibility is that this technique is likely to demonstrate meaningful

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**Table 2** LAV indexes measured by the proposed (LAVT) versus the expert’s methods

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<tr>
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<th>Expert’s</th>
<th>Proposed</th>
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<tbody>
<tr>
<td>Maximal volume</td>
<td>22.8 ± 9.6</td>
<td>26.3 ± 8.9</td>
</tr>
<tr>
<td>Volume at onset of atrial systole</td>
<td>15.0 ± 6.5</td>
<td>16.6 ± 5.8</td>
</tr>
<tr>
<td>Minimal volume</td>
<td>10.3 ± 5.0</td>
<td>10.5 ± 4.6</td>
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</tbody>
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**Figure 6** The correlation between LAVT and MDCT.
statistical differences for the serial assessment of LAV changes as a result of surgical or medical interventions even in smaller groups of patients. Therefore, this technique is likely to become the method of choice in pharmaceutical trials focused on changes in LAV.

Limitations
This is a single-centre study that included a relatively selected population of patients with suspected cardiovascular disease—these findings cannot be extrapolated to all patients.

Conclusions
In this paper, we proposed an accurate and high-speed echocardiographic image tracking method with a speckle adaptive noise reduction filter for the automatic measurement of LAV curves. Our method was evaluated in both simulated and clinical images based on off-line analysis and might be useful for measuring LAV curves with sufficient precision. This LAVT method is a fast, valid, accurate, and reproducible method for determining LAV in the clinical setting.

Supplementary data
Supplementary data are available at European Heart Journal – Cardiovascular Imaging online.

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