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Development of quantification software using model-based segmentation of left ventricular myocardium in gated myocardial SPECT☆

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ABSTRACT

Gated myocardial single photon emission computed tomography (SPECT) is being used for the diagnosis of coronary artery diseases. In this study, we developed new software for the quantification of volumes and ejection fraction (EF) on the gated myocardial SPECT data using a cylindrical model. Volumes and EF by developed software were validated by comparing with those quantified by quantitative gated SPECT (QGS) software. Cylinder model for left ventricular myocardium was used to eliminate background activity and count profiles across the myocardium were fitted to the Gaussian curve to determine the endocardial and epicardial boundary. End-diastolic volume (EDV), end-systolic volume (ESV) and EF were calculated using this boundary information. Gated myocardial SPECT was performed in 83 patients. EDV, ESV and EF values estimated using present method were compared to those obtained using the commercialized software QGS, and reproducibility in the parameter estimation was assessed. EF, EDV and ESV obtained using two methods were correlated well (correlation coefficients = 0.96, 0.96 and 0.98). The correlation between the parameters repetitively estimated from the same data set by an operator was very high (correlation coefficients = 0.96, 0.99 and 0.99 for EF, EDV and ESV). On the repeated acquisition, reproducibility was also high with correlation coefficients of 0.89, 0.97 and 0.98. The present software will be useful for the development of new parameters for describing the perfusion and function of the LV.

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1. Introduction

Gated myocardial single photon emission computed tomography (SPECT) provides information about the myocardial perfusion as well as the cardiac function. Segmentation of the left ventricular myocardium in gated myocardial SPECT is an essential step in estimating the indices representing this information [1–4]. A variety of segmentation methods of the myocardium have been developed for various cardiac imaging modalities: threshold, edge detection, wavelet, morphological, and model-based methods [5–8]. However, the general segmentation methods have a limitation in their application to the myocardial perfusion SPECT because the boundary of the myocardium is not well detected in patients with ischemic heart disease [9,10]. Segmentation of the myocardium is also affected by the nearby hot signals such as the hepatic or bowel uptake. These limitations make the myocardial boundary thicker and discontinuous [10,11]. Therefore, the development of particular segmentation method that is adequate for myocardial SPECT data is required for the development of new software.

In this paper, a method for the segmentation of the left ventricular myocardium using a cylindrical model is proposed. In order to evaluate the accuracy and reproducibility of this method, the quantification results, such as the end-systolic volume (ESV), the end-diastolic volume (EDV), and the EF of the left ventricle, obtained using the proposed method, were compared with those using commercial software QGS (ADAC Labs, Milpitas, USA).

2. Materials and data acquisition

Patients with suspicious coronary artery disease were enrolled in this study. The patients who showed serious arrhythmia were excluded. Tc-99 m-MIBI gated myocardial SPECT data acquired from 83 patients (58 males, 25 females, mean age = 62 ± 10 years) after dypiridamole (0.56 mg/kg) stress were analyzed using both the proposed method and the quantitative gated SPECT (QGS) software. Ejection fraction (EF), end-diastolic volume (EDV), and end-systolic volume (ESV) values obtained using both the methods were compared. Among the 83 cases, SPECT data from 40 randomly selected patients (35 males, five females, 58 ± 10.9 years) were used to test the intra- and inter-observer reproducibility of the data processing using the proposed method.

The SPECT were acquired twice from the 26 patients (18 males, eight females, mean age = 58 ± 9.0 years) and analyzed using the proposed method to test the short-term reproducibility in not only the data processing and but also the acquisition. The patients continuously were laid on the camera without the break interval between both studies. The heart rate did not differ between the scans.

A dual head gamma camera (Vertex EPIC, Philips-ADAC Labs, Milpitas, USA) mounted with a low energy high-resolution collimator was used for image acquisition. Sixteen gating images were obtained by step and shoot method. The center of energy window was 140 keV, and energy window was 20%. The gating window was opened up to 40% so that the accepted number of cycles was about between 800 and 2100 (For example, if the time of *R–R* interval is 0.7 s, the low tolerance time is about 0.36 s and the high tolerance time is about 1.09 s). Acquired images were reconstructed using filtered back-projection with ramp filter and Butterworth filter (degree = 5, cutoff frequency = 0.33). Voxel size of the reconstructed image was 5.04 mm × 5.04 mm × 5.04 mm. The images were not corrected by attenuation correction technique. The images were reoriented in order to obtain short axis images (matrix size = 64 × 64) used for the segmentation.

3. Segmentation methods

Myocardium boundary was segmented on short axis image. Volume of left ventricle and EF was then calculated from the boundary of endocardium. In order to estimate the volume changes of left ventricle, short axis images with 16 gating frame were used. The followings are the procedures used for the segmentation of the myocardium (Fig. 1):

1. The central axis and outer surface of the cylinder including the left ventricular myocardium and excluding most of the background activity was determined user-interactively.
2. The remaining background activity within the cylinder was discarded using a threshold method. The threshold was set to 75% of the maximum count within the slice in the upper 20% and lower 20% slices, and at 50% in the remaining slices. Pixels with a count lower than the threshold were regarded as the background region.
3. In order to determine the boundary of the myocardium, the radial count profiles from the central axis were sampled for every 10° after smoothing the image. Therefore, a total of 36 count profiles were sampled from each slice. Each profile was fitted to the Gaussian functions using a gradient decent learning algorithm, and the centre (μ) and standard deviation (σ) of the function were determined:

$$M^{i+1} = M^{i} - r \times \frac{\partial M}{\partial G} \qquad (1)$$

   M is the μ of Gaussian function, r the learning rate and $\partial M/\partial G$ is the differentiation about M at Gaussian function.
4. The endocardial point in each profile was determined so that the distance from the central axis to that point was equal to μ–σ.
5. For each slice, mean distances between the central axis and the endocardial points were calculated. If the distance of an endocardial point deviated from the mean value by more than 3 pixel, it was regarded that this point was not correctly determined and the distance for this point was replaced by the average of the two adjacent points.
6. Finally, the moving average of the distances were performed in order to reduce the random error in the distance determination: the distance of each point was averaged with those of the six neighboring points (adjacent two

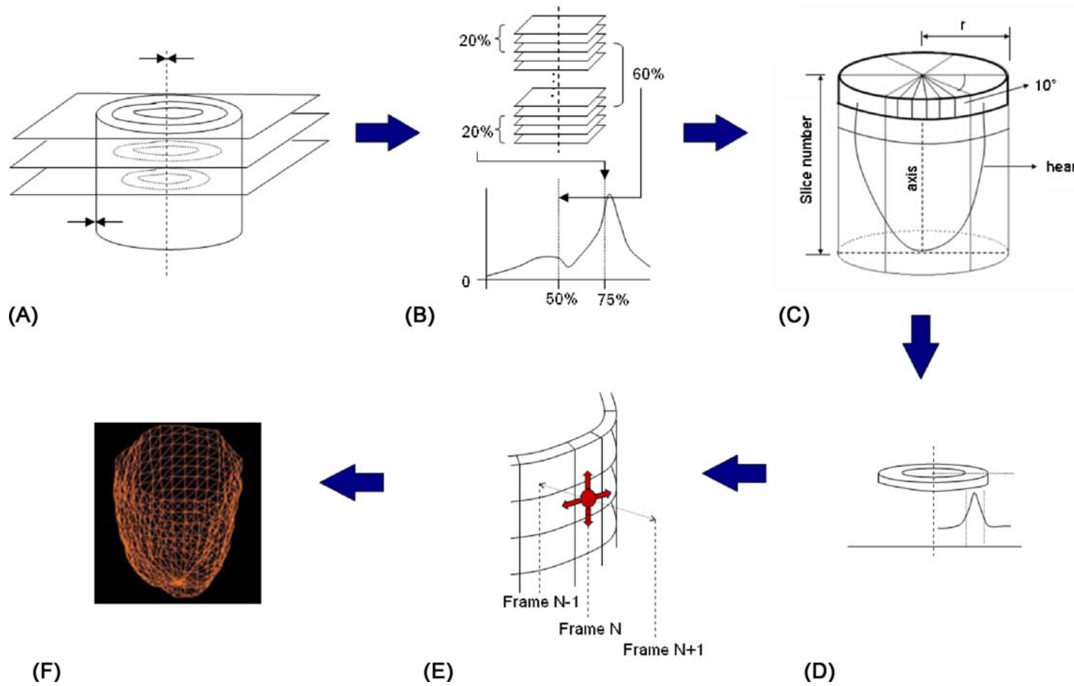

Fig. 1 – Segmentation method. (A) User-interactive determination of the central axis and outer surface of the cylinder including the left ventricular myocardium. (B) Removal of the remaining background activity within the cylinder using a threshold method. (C) Extraction of the radial count profiles from the central axis in order to determine the boundary of the myocardium. (D) Determination of the endocardial point in each profile. (E) Correction of outliers in the endocardial points. (F) Three-dimensional visualization.

points in the same slice, two points with the same angle in the adjacent two slices, two points in the same position in the previous and next frames).

Segmentation using the moment and the three-dimensional Sobel mask was also performed for comparison.

4. Software development

Quantification software was developed using visual C++ and OpenGL library which is a high level language for three-dimensional modeling and graphical visualization.

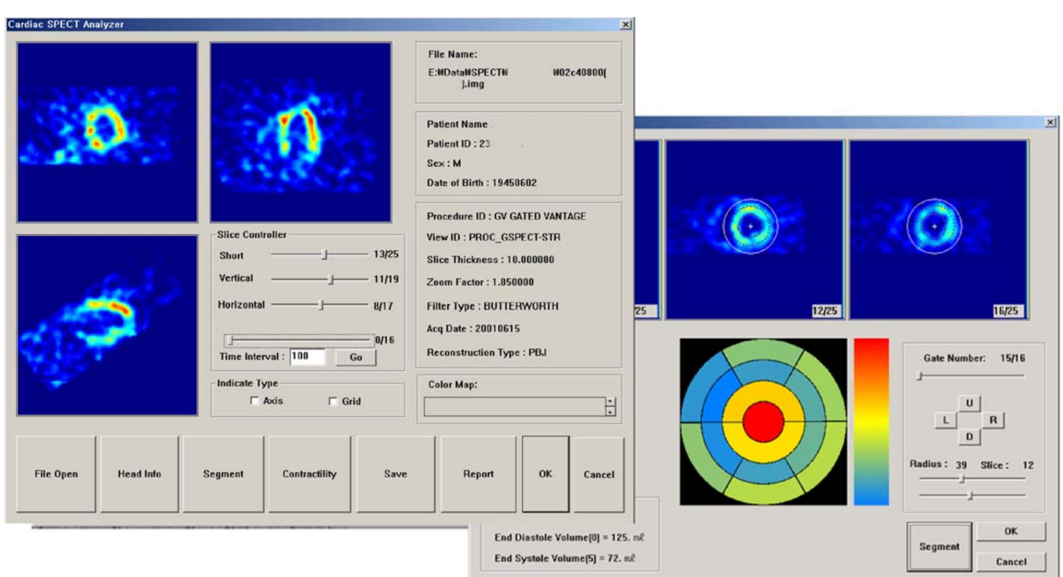

Fig. 2 – Image was visualized with three orthogonal views and information about the patient and data acquisition was provided. Animation of the gated SPECT data could be performed, and location of the boundary points detected semi-automatically were saved in the text file. Mesh structure and surface rendering image could be visualized using the saved data with OpenGL library.

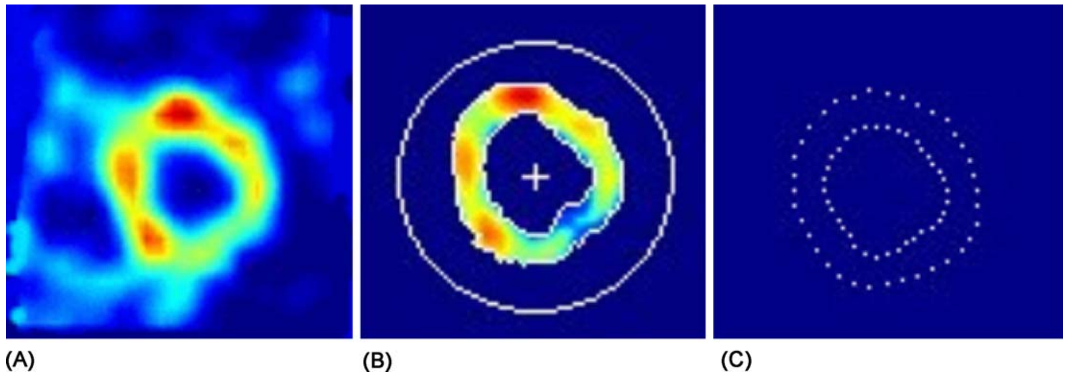

Fig. 3 – (A) Original SPECT image. (B) Boundary points originally determined by fitting the count profile. (C) Adjusted boundary with the constraints of the spatial and temporal continuity in their distribution.

Preprocessing for semi-automatic background elimination could be performed by moving the cylindrical model using mouse. Command buttons to control the working procedures were arranged in the low column (Fig. 2).

Left ventricle volume was calculated from the segmented endocardium boundary in each slice. Regional volumes calculated at every 60° of each slice were accumulated to estimate the total ventricle volume. Maximum and minimum volume during the cardiac cycle (16 frames) was considered as EDV and ESV of the left ventricle, respectively. EF, the percent change between EDV and ESV was calculated by the following equation:

$$EF = \frac{(EDV - ESV)}{EDV} \times 100 \qquad (2)$$

EF is the ejection fraction, EDV the end-diastolic volume and ESV is the end-systolic volume.

The volume change with 16 frames was calculated using the segmented endocardial line of the left ventricle. The volume change and coordinates of the epicardial and endocardium points were saved for the further use. Volume

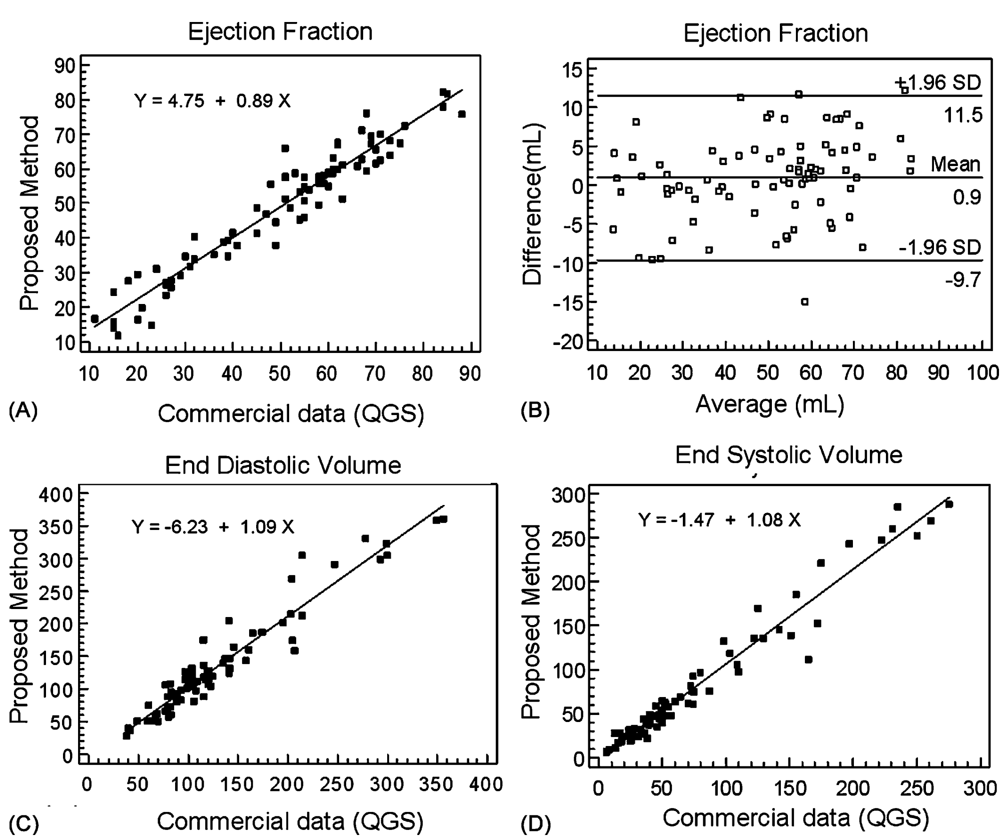

Fig. 4 – Correlation between the proposed method and the QGS software in the ejection fraction (A), end-diastolic volume (C) and end-systolic volume (D). (B) Difference in the ejection fraction between the proposed method and the QGS software plotted against the averages of the two measurements (Bland Altman plot).

change curve and calculated indices were shown on the result window with 15-segment polar map. Information on patients, acquisition, and image data were provided as the user asked. The saved endocardial points were visualized in three-dimensional mesh structure. User can rotate the visualized endocardial wall and observe the motion of the left ventricle. Surface rendering was coded using OpenGL library.

5. Statistical analysis

EF, EDV, and ESV on 83 patient's data were compared with those obtained using a commercial software QGS (Pearson's correlation). Reproducibility study of the parameter estimation using the parameters obtained twice was assessed ($n=40$, correlation analysis and Bland Altman plot). Correlation between two sequential SPECT measurements on 26 patients was also assessed. Paired t-test for each parameter between the methods or the operators was performed to test whether any observed differences were significant.

6. Experimental results

It took about 15 s for loading raw file and segmentation to calculate the EF. The boundary extracted using moment-based method and the three-dimensional Sobel mask, which was performed for the comparison, was greatly affected by the regional distribution of the tracer, background noise level and spillover of the activity particularly from the liver beneath the heart. Discontinuity was also observed in the boundary of the myocardium determined. Most of the disconnected boundaries were detected in the ischemic or infarct regions with a low uptake of the radiotracer, where the available anatomical information for the myocardium was rare. Several blobs of segmented regions in a slice were also observed.

Such errors in the boundary extraction were not detected when the proposed method using the cylindrical model was applied, where the background noise was filtered out, the neighboring structures with a high uptake were masked out, and the endocardial boundaries were extracted by fitting the count profile and adjusting them with the constraints of the spatial and temporal continuity in their distribution (Fig. 3).

The ESV and EDV were determined using the endocardial points extracted using the proposed method, and the EF was calculated. Mean EF, EDV, and ESV estimated using developed software for 83 patients were 48 ± 18%, 132 ± 71 mL, 79 ± 68 mL, respectively. Those measured using QGS were 49 ± 18%, 137 ± 76 mL, 79 ± 72 mL, respectively.

The correlation coefficient between the proposed method and the QGS software was 0.96 for the EF, 0.96 for the EDV, and 0.98 for the ESV ($n=83$, Fig. 4). The slope of the regression equation was 0.89 for EF, 1.09 for EDV, and 1.08 for ESV. There was no significant difference in each parameter between the two methods (paired t-test, $P>0.05$).

The correlation between the parameters repetitively estimated from the same data set ($n=40$) by an operator was very high (correlation coefficient = 0.96, 0.99 and 0.99 for EF, EDV and

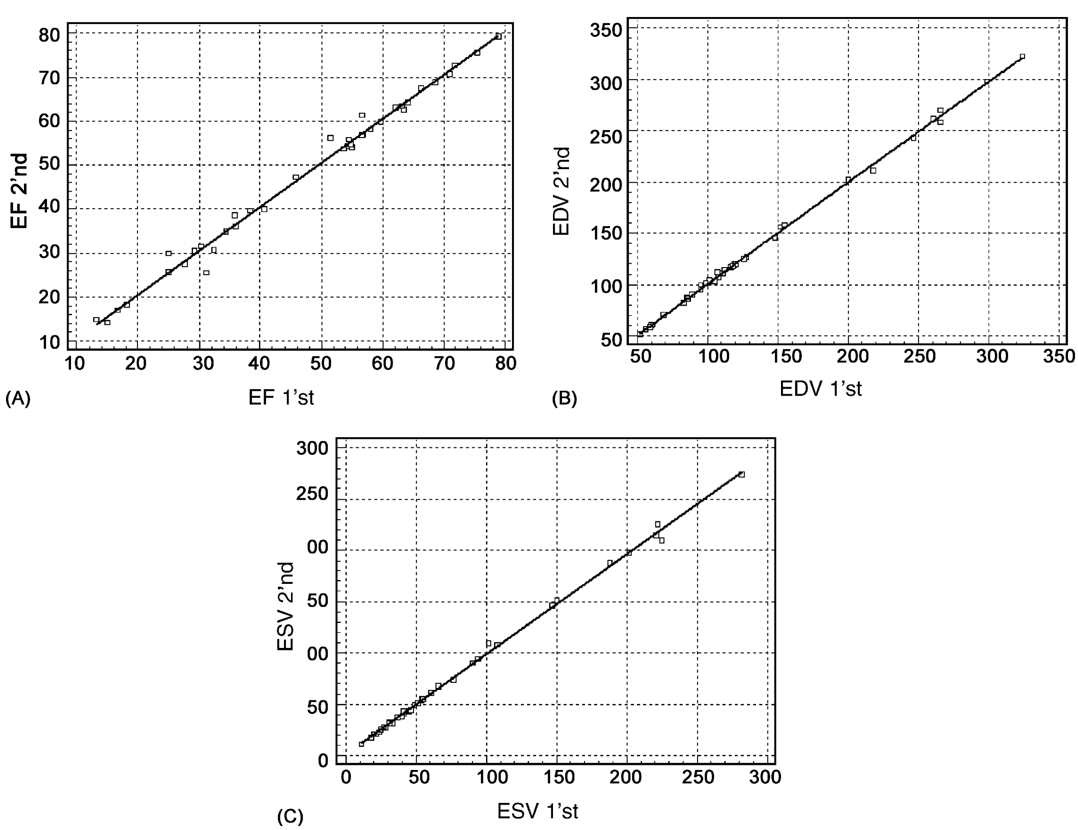

Fig. 5 – Reproducibility in the volume measurement using the proposed method: (A) ejection fraction; (B) end-diastolic volume; (C) end-systolic volume.

ESV) (Fig. 5). There was also no significant difference in each parameter between the two methods by the paired *t*-test. Two standard deviation of the EF on the Bland Altman plot was 3.4%. Intra-observer reproducibility was also high (correlation coefficient = 0.99, 0.99 and 0.99 for EF, EDV and ESV; no significant statistical difference).

On the repeated acquisition of 26 patient's data, reproducibility was also good with correlation coefficients of 0.89, 0.97 and 0.98. Two standard deviation of the EF on the Bland Altman plot was 10.6%.

7. Discussions

Quantification software for the measurement of volume and EF from gated myocardial SPECT was developed, and the results were compared with those using the clinically used QGS software for validation. The development of QGS made clinical utilization extended in the aspect of quantitative analysis [12–14]. Accuracy of estimated volume and EF by the QGS software was validated when the software was introduced and reproducibility was also validated after the clinical usage [15,16]. In addition, the accuracy of estimated volume and EF were certified through the clinical studies performed on multiple centres [17–20]. The results of this study showed that the performance of the developed software was comparable to that of this clinically accepted software.

Segmentation of LV is prerequisite for any myocardial SPECT analysis method to assess the regional myocardial perfusion and function. Although the automatic quantification method for gated myocardial SPECT is well established, it is still difficult to create new parameters describing the LV perfusion or function because the commercially available software does not provide detailed about the determined boundary or volume. In this point of view, the present software will be useful to calculate user-specifically defined parameters from gated myocardial SPECT. For example, the change of regional volume and central artery pressure during the cardiac cycle can be used for the estimation of regional contractility [21]. In the previous study reported in reference [21], we developed a method for the estimation of myocardial contractility using gated SPECT and arterial tonometry in which the measurement of LV volume change was essential. However, the clinically used QGS or Emory toolbox did not provide the exact values of the LV volume to the users and we captured the volume curve on the monitor screen to roughly estimate the LV volume. Therefore, we developed our own method for the segmentation of gated SPECT and would like to suggest that the readers use our relatively simple method if they also need to develop the user-specifically defined parameters like the myocardial contractility.

8. Conclusions

In this study, a fast and reproducible method for the segmentation of left ventricle from the gated myocardial SPECT was proposed and software based on this method was developed. The cylindrical model was used to improve the robustness in the segmentation. The volume and EF of LV estimated using this method were reproducible and agreed well with those obtained using the established software. The present software will be useful for the development of new parameters for describing the perfusion and function of the LV.

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