TECHNICAL POINT OF VIEW

Development of Digital Myocardial Phantom to Evaluate Software for Gated SPECT

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Abstract

Background: **Real cardiac phantoms are often used to assess the performance of software for gated single-photon emission computed tomography (SPECT). However, these phantoms have disadvantages in that they are not very similar to actual hearts and setting a perfusion defect is not easy. To overcome these problems, we developed a digital myocardial phantom, named "Myo-Simu". The aims of this study were to check its operation when being incorporated into gated SPECT software and to elucidate its usefulness to assess properties of software.**

Methods: **Myo-Simu yields a simulated left ventricle (LV) approximated as a moving spheroid that preserves shape similarity during the cardiac cycle with a fixed total myocardial volume. Wall thickness, background activity, spatial resolution, statistical noise, and perfusion defects are incorporated into the phantom, and these conditions can be modified by changing the input parameters. We generated various types of hearts by changing the length of the short and long axes, patterns of perfusion defects, spatial resolution, and image noise. Generated SPECT images were applied to Quantitative Gated SPECT (QGS), Heart Function View, and EXINI Heart software to check the adaptability to gated SPECT analyses. We also evaluated the influences of wall thickness and spatial resolution on QGS analyses.**

Results: **Myo-Simu successfully generated SPECT images of various geometries. These images can be applied to gated SPECT analyses without any problems in operation. In QGS, measured LV volumes changed greatly depending on wall thickness and spatial resolution.**

Conclusions: **Myo-Simu is a feasible phantom for assessing gated SPECT software.**

Keywords: Digital Phantom, Simulation Study, Myocardial Perfusion SPECT, Cardiac Function, Quantitative Gated SPECT

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Various types of software for analyzing cardiac function in gated myocardial single-photon emission computed tomography (SPECT) have been developed, including Quantitative Gated SPECT (QGS) (1), Emory Cardiac Toolbox (2), 4D-MSPECT (3), Heart Function View (HFV) (4), and EXINI Heart (EXH) (5). Analyses using such software are necessary for ensuring reproducibility and accuracy in calculating parameters of the ejection fraction, volumes, and others. Validation of these analyses is generally performed using real cardiac phantoms. However, these phantoms do not satisfactorily resemble the actual heart shape, wall motion, and wall thickness. Furthermore, they are not convenient for simulating perfusion defects

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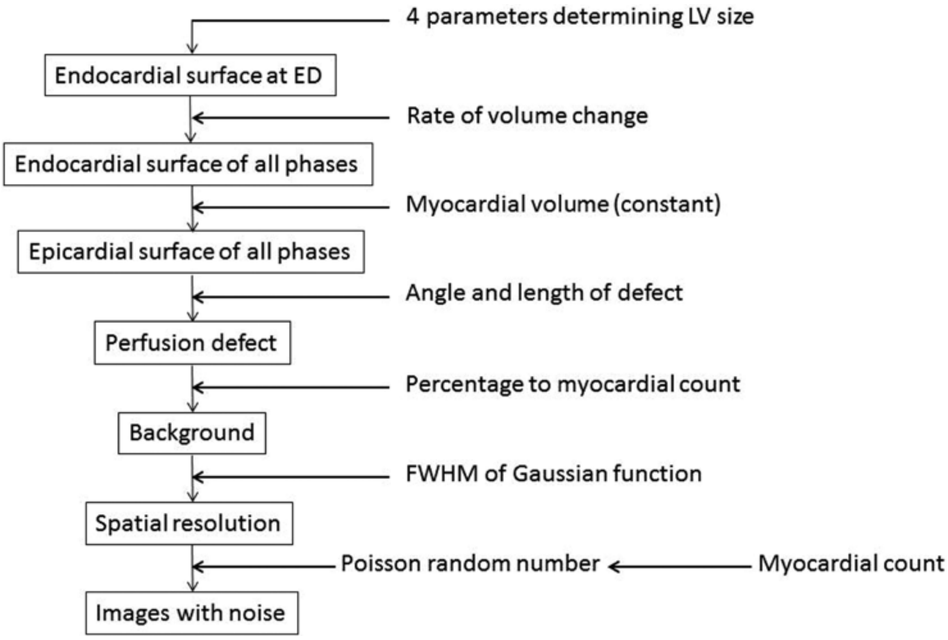


Fig. 1 Phantom generation
The algorithm comprises 7 processes. Phantoms for various geometries are obtained by changing the combinations of input parameters. ED: end-diastolic phase

with various settings of extent, severity, and position. The aims of the present study were therefore to generate numerical cardiac phantoms of various geometries, and to check their adaptability to gated SPECT analyses. In addition, we assessed the usefulness of Myo-Simu in observing the properties of gated SPECT software.

Materials and methods

We generated a numerical cardiac phantom, which we named "Myo-Simu", using Microsoft Visual Basic 2010 Express on a personal computer (Core i7 CPU running Windows 7). The image data of the phantom was converted to DICOM format and transferred to an image processor (Symbia_T16-Syngo MI applications VA60A, Siemens Medical Solutions USA, Inc., Hoffman Estates, IL). Transferred images were applied to gated SPECT analyses using software consisting of QGS (Cedars-Sinai Medical Center, CA), HFV (Nihon Medi-Physics Co., Ltd., Tokyo, Japan) and EXH (Sahlgrenska University Hospital, Gothenburg, Sweden, and FUJIFILM RI Pharma Co., Ltd., Tokyo, Japan).

As indicated in Fig. 1, the algorithm for simulating the heart comprises 7 processes. In the first process, the setting of X/Y radii, Z radius, valve position, and myocardial thickness is necessary to determine the endocardial surface at the end-diastolic (ED) phase (Fig. 2). The shape of the left ventricle (LV) was approximated as a spheroid. After the endocardium at the ED phase was determined, we provided the changes in LV volume from the ED phase to each phase of the cardiac cycle. This procedure establishes the endocardial surfaces of all phases by assuming that the shape of the LV at each phase is similar to each other. The epicardial surface and wall thickness at each phase were automatically determined using the total myocardial volume, which remains constant throughout the cardiac cycle.

A perfusion defect was then placed, as determined using the start and end angles in a short-axis slice, the start and end slices in the long-axis direction, and the lesion-to-normal count ratio (Fig. 3). The background activity was determined by giving the background-to-myocardial count ratio. We set the full width at half maximum (FWHM) of the convoluted Gaussian function to the original image to adjust the spatial resolution. Poisson random numbers were generated based on the count (per pixel) at the myocardium to simulate count distribution with inclusion of statistical noise. By changing the combinations of the above parameters, we could obtain phantoms for various geometries.

In this preliminary study, background activity was not considered, and the percent uptake value of perfusion defects was set to 0. First, we generated hearts of different sizes and shapes by changing the four input parameters indicated in Fig. 2. We obtained long and short hearts of different LV volumes. A perfusion defect was then placed on the inferior wall with the extent ranging from 50 to 170 degrees. In addition, we made a heart with two perfusion defects in the apical

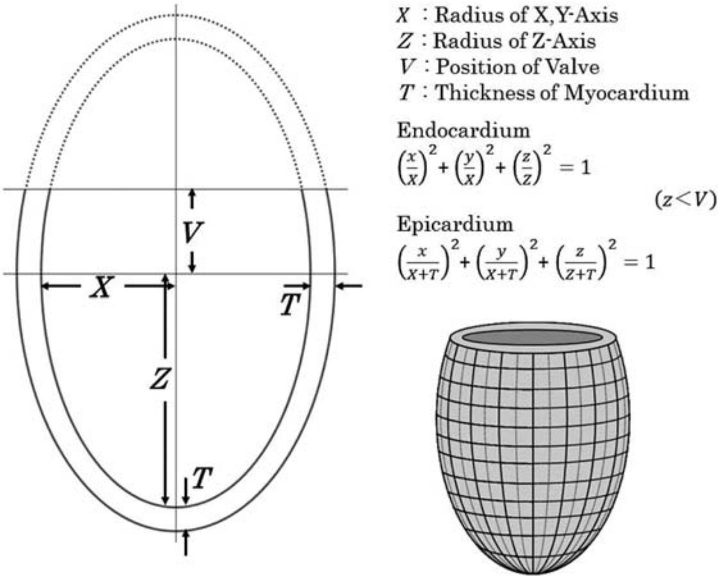


Fig. 2 Parameters determining left ventricle (LV) size
The shape of the left ventricle was approximated as a spheroid. Four parameters are required to determine the endocardial surface at the end-diastolic (ED) phase.

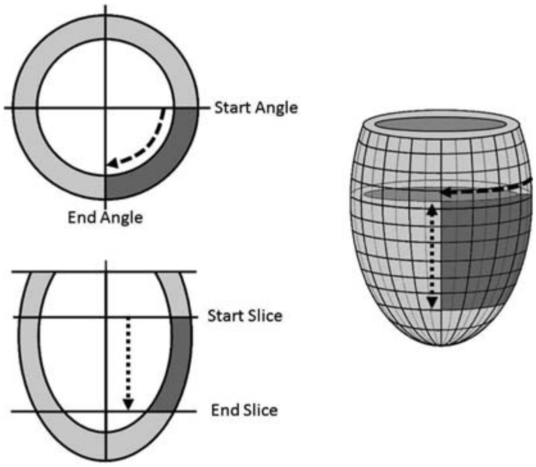


Fig. 3 Setting of perfusion defect
A perfusion defect was simulated by using the start and end angles in a short-axis slice, the start and end slices in the long-axis direction, and the lesion-to-normal count ratio.

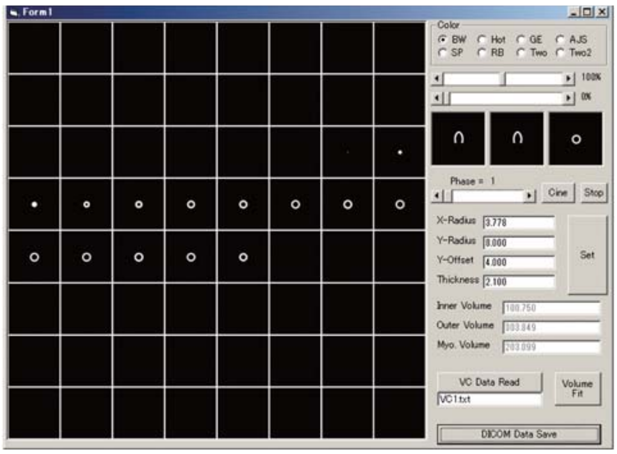


Fig. 4 Operation panel of Myo-Simu
After setting the input parameters, measured volumes of the LV and myocardium, the cine-mode display of myocardial SPECT is shown in this panel.

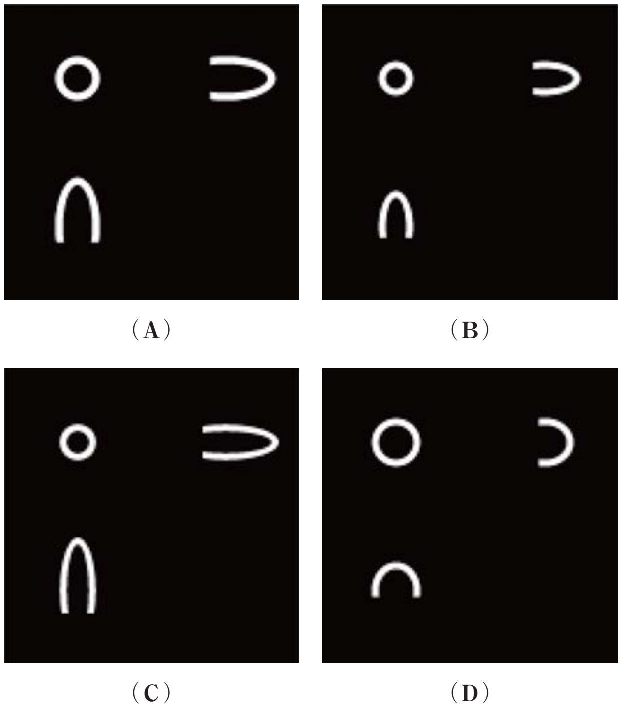


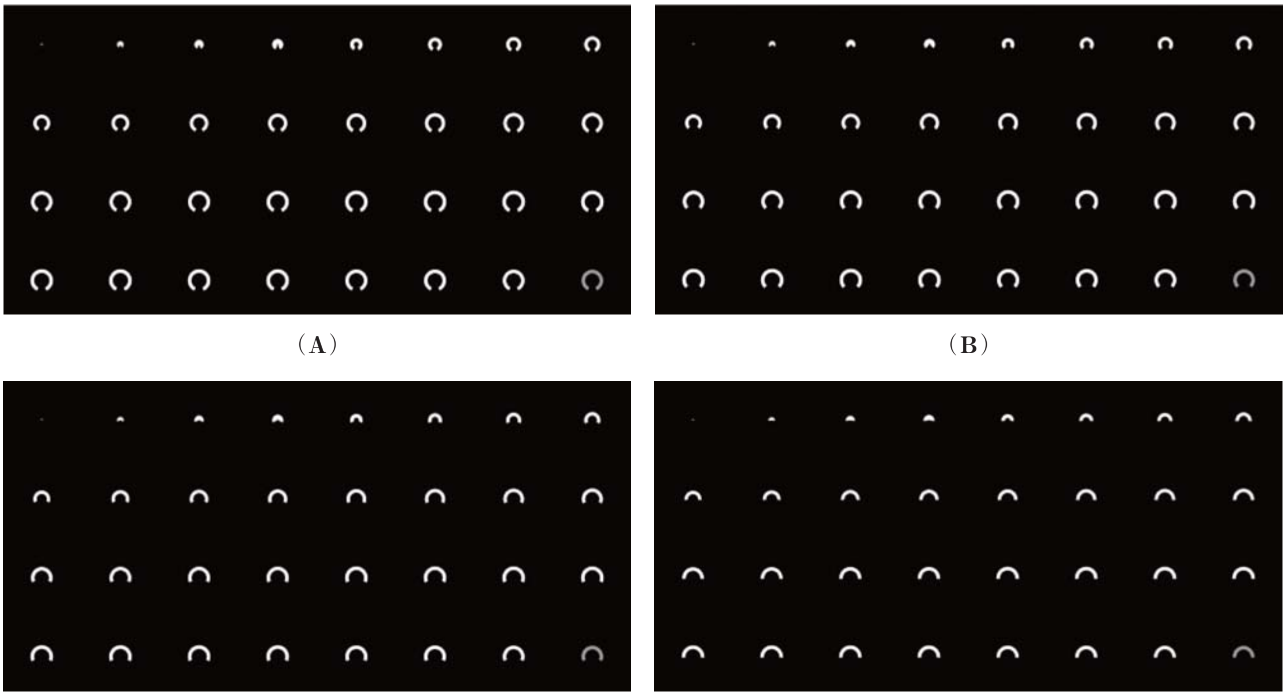
Fig. 5 Myo-Simu images
SPECT images were generated by Myo-Simu adjusting the LV volume to 200 ml (**A**) and 50 ml (**B**). Long and short hearts with the ED volume of 100 ml are included in panels (**C**) and (**D**).

half of the septal side and the basal half of the lateral side. Then, we changed the FWHM and image noise of SPECT. The phantom image possessed a 64×64 matrix with a voxel size of 4 mm on each side. The cardiac cycle was divided into 16 phases for gating. Myo-Simu images were analyzed by using QGS, HFV, and EXH. We also evaluated the influences of wall thickness and FWHM on QGS analyses by changing these input parameters of Myo-Simu.

Results

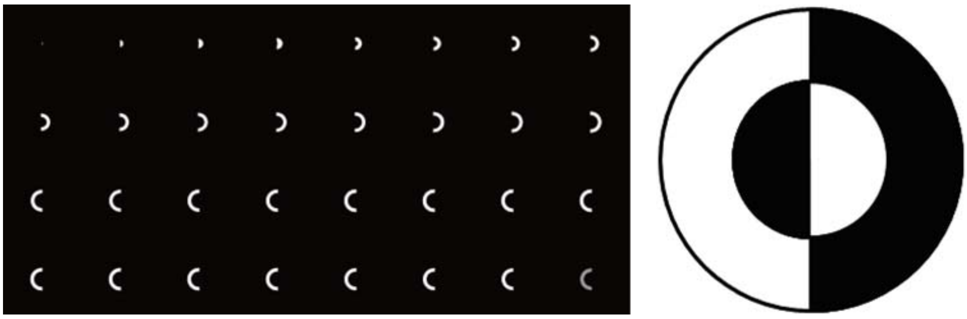
Fig. 4 shows the operation panel of Myo-Simu. In this window, we can set input parameters or retrieve the parameters that were previously saved. After calculation, the measured volumes of the LV and myocardium, and cine-mode display of myocardial SPECT are displayed in this panel. The settings of the background activity, spatial resolution, and image noise are in another window, and the obtained images are also displayed in the same window (not shown).

Fig. 5 includes short, horizontal-long, and vertical-



（**A**）（**B**）（**C**）（**D**）

Fig. 6 Short-axial SPECT images with a perfusion defect
A perfusion defect was placed on the posterolateral wall. The defect angles were 50, 90, 130, and 170 degrees corresponding to（**A**),（**B**),（**C**), and（**D**).



（**A**）（**B**）

Fig. 7 SPECT image with two perfusion defects
（**A**）Short-axial SPECT image.（**B**）Polar map.
Defects were set in the apical half of the septal side and in the basal half of the lateral side.

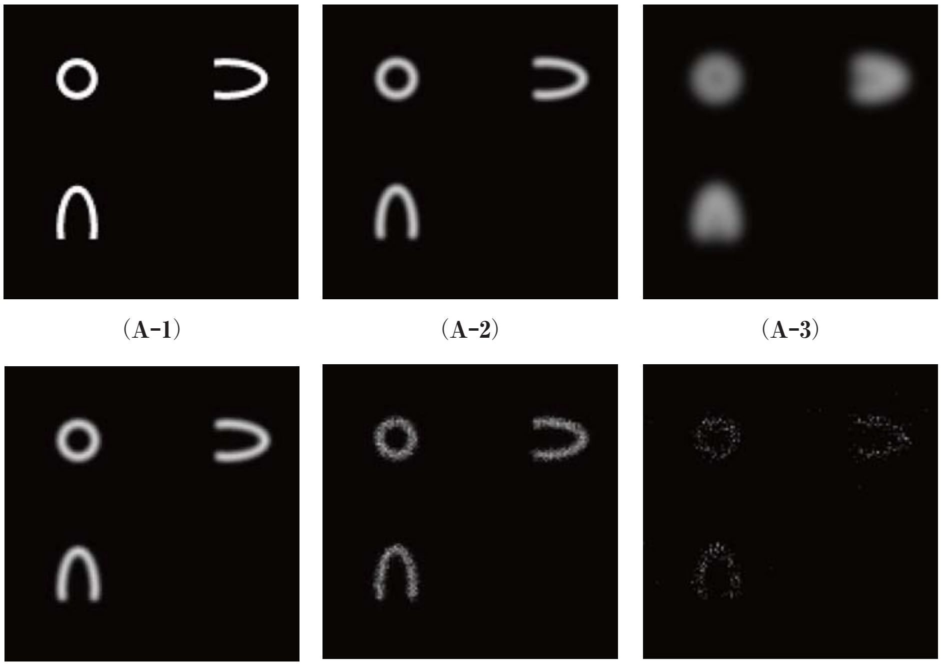
long axial SPECT images generated by using Myo-Simu. LV volumes at the ED phase were 200 and 50 ml in panels（A）and（B), respectively. Long and short hearts with the ED volume of 100 ml are included in panels（C）and（D).

Fig. 6 demonstrates myocardial SPECT images with a perfusion defect in the inferior wall. The extent of the defect was set to 50, 90, 130, and 170 degrees corresponding to the panels（A),（B),（C), and（D).

Myocardial SPECT with two perfusion defects（A）and its polar map（B）are presented in Fig. 7. This perfusion pattern is not encountered in daily clinical practice.

Fig. 8 shows SPECT images obtained by changing the spatial resolution and image noise. In the upper panels, the FWHM was set to 0 mm（A-1), 12 mm（A-2), and 40 mm（A-3). In the lower panels, the noise level（the noise-to-signal ratio）was adjusted to 0%（B-1), 20%（B-2), and 100%（B-3）under a constant FWHM of 12 mm. In this figure, the LV volume was set to 100 ml.

Fig. 9 contains the results obtained by analyzing Myo-Simu images with QGS（A), HFV（B), and EXH（C). A perfusion defect was placed on the posterolateral wall. Image data generated by Myo-Simu was applicable to the above gated SPECT software without any problems in operation.



(A-1) (A-2) (A-3)

(B-1) (B-2) (B-3)

Fig. 8 SPECT images obtained by changing spatial resolution and image noise
The FWHM was set to 0 mm (A-1), 12 mm (A-2), and 40 mm (A-3). The noise level was adjusted to 0% (B-1), 20% (B-2), and 100% (B-3) under a constant FWHM of 12 mm.

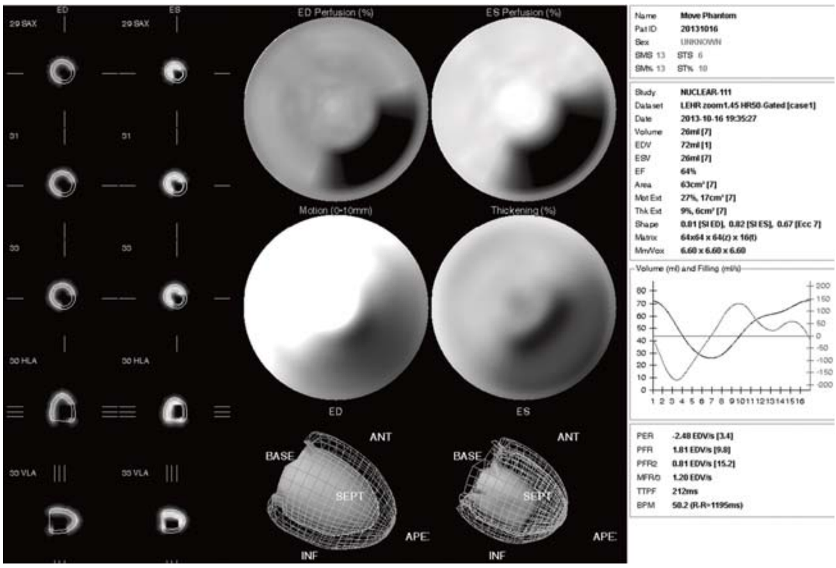
Fig. 10 shows the effects of FWHM and wall thickness on indices calculated using QGS. The end-diastolic volume (EDV), end-systolic volume (ESV), and ejection fraction (EF) values were set to 100 ml, 20 ml, and 80% in the phantom, respectively. FWHM ranged from 0 mm to 30 mm with wall thickness of 12 mm (left) and 8 mm (right). The condition of concentric left ventricular hypertrophy was simulated in the left panel. In both panels, the position of the endocardial surface at each phase was same, and that of the epicardial surface is different reflecting the difference of wall thickness. Measured EDV and ESV decreased with decreasing spatial resolution and wall thickness.

Discussion

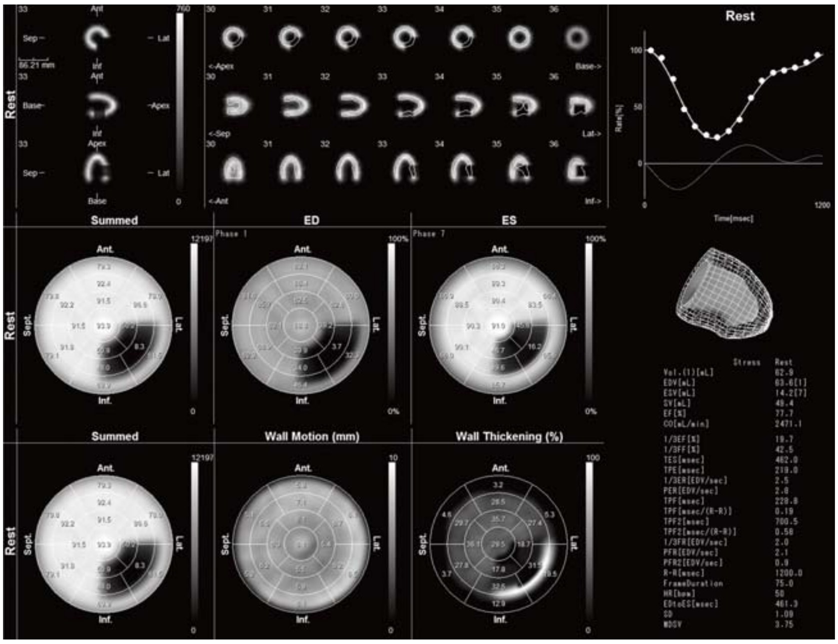
We contrived a digital myocardial phantom named "Myo-Simu" and generated various types of hearts by changing the input parameters of the phantom. Image data was transferred to the image processor to check the adaptability to gated SPECT analyses. We confirmed that the data was analyzed by using QGS, HFV, and EXH without problems in operation.

A number of studies have assessed software for gated SPECT analyses by using phantoms. Kubo et al. used a real phantom with the LV chamber moving along the long axis of the LV (6). This phantom is commercially available in Japan (Type HD Cardiac Phantom; Kyoto Kagaku, Kyoto, Japan) and quite is popular for this purpose. In this phantom, the epicardial surface is fixed, and only the endocardial surface moves. Visser et al. designed another real phantom that is more similar to the actual moving heart (7). The endocardial and epicardial surfaces are made of silicone and are inflated and deflated by a piston that moves through the fluid packed in the LV. These real phantoms have the advantage that the assessment of imaging data, including the characteristics of the acquisition system, is possible. However, the disadvantages are that they cannot contain perfusion defects and that investigators must prepare the phantom by handling actual radionuclides, which carries the risk of contamination.

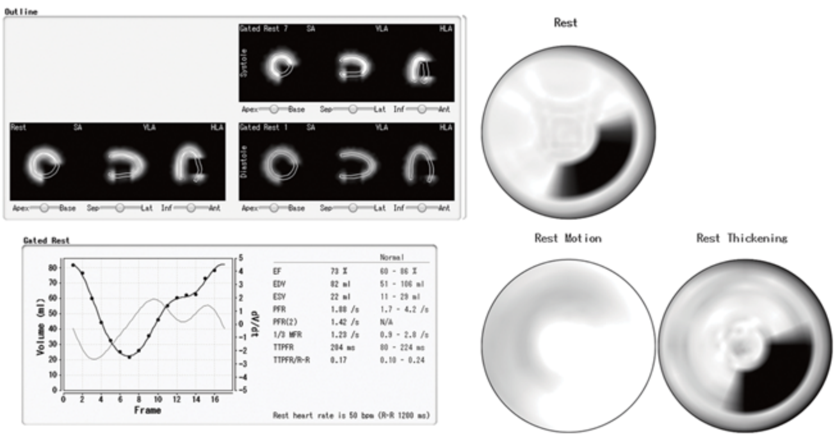
Some researchers have designed digital phantoms for simulation of the actual heart and surrounding structures (8, 9). These phantoms are used for various purposes, including basic and clinical researches. On the contrary, Myo-Simu is relatively simple and is dedicated to radionuclide cardiac imaging. In Myo-Simu, we directly provide parameters related to the myocardial count distribution including the mean count, image noise, and FWHM, meanwhile, other digital phantoms employ Monte Carlo simulation to generate myocardial counts. There have been some reports in which real cardiac phantoms are used in multi-center clinical trials (10, 11), and those in which digital phantoms are used for evaluating the accuracy of analyzing the small heart (12, 13). Authors of these studies employed relatively



（A）



（B）



（C）

Fig. 9　Results of analyzing Myo-Simu images by using gated SPECT software （**A**） QGS, （**B**） HFV, and （**C**） EXH.

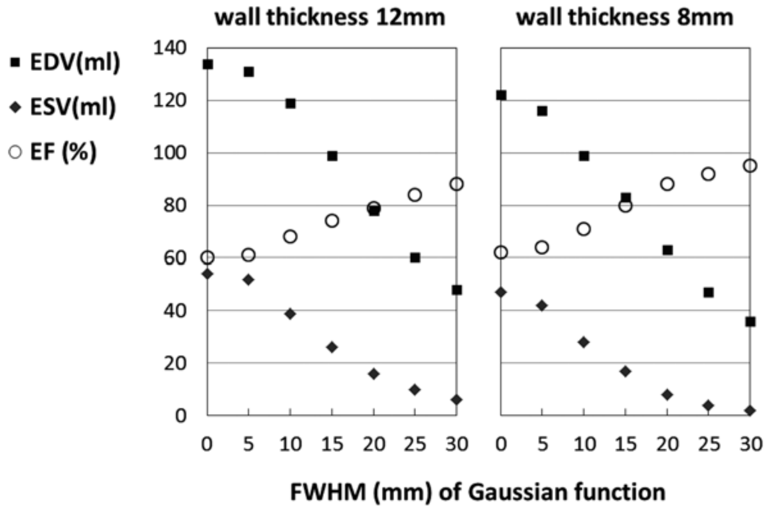


Fig. 10 Effects of FWHM and wall thickness on QGS analysis
Wall thickness was set to 12 mm and 8 mm in the left and right, respectively. The FWHM ranged from 0 mm to 30 mm in each condition.

limited conditions in terms of the geometry of the heart. In contrast, Myo-Simu offers a vast array of simulated conditions as indicated in the results section.

Myo-Simu yields gated SPECT images of all phases of the cardiac cycle based on the input parameters provided, and these parameters can be adjusted to change the LV size, wall motion, wall thickness, and perfusion defects (location, extent, and severity) in the simulated heart as indicated in Figs. 5, 6, and 7. These characteristics enable us to simulate not just a realistic heart but also conditions that are rare in daily clinical practice, as shown in Fig. 7. Moreover, since the background activity, spatial resolution, and image noise are variable, we can indirectly modify the conditions related to data acquisition and image reconstruction (Fig. 8), even though SPECT images are obtained without using the gamma camera or image processor. Furthermore, it takes less than one minute to generate a myocardial SPECT image by using Myo-Simu. Therefore, it is easy to obtain a series of images in which the simulated conditions are similar but are slightly different to each other. By applying these images to gated SPECT analysis as indicated in Fig. 10, we can estimate physical properties of gated SPECT software regarding the response to the change of a specific condition (s). The results shown in Fig. 10 are compatible with the algorithm of QGS, that recognizes myocardial surfaces by using the standard deviation of the Gaussian fitting.

Limitations

There are some limitations to the current study. Because Myo-Simu generalizes the shape of the LV as a spheroid, it is not anatomically equivalent to the human heart. Furthermore, although we can freely select the values of EDV, ESV, EF, peak ejection rate (PER), peak filling rate (PFR), and so on, the spheroid shape of the simulated LV cannot be changed. Consequently, the phantom cannot be used to assess LV dyssynchrony because each part of the endocardial surface moves synchronously, preserving the spheroid shape. These limitations could be overcome by increasing the number of input parameters, but a large number of parameters would increase the complexity of analysis while decreasing the convenience. In addition, the shape of the cardiac base including the membranous portion needs to be improved. Preparation of patterns of perfusion defects with consideration of coronary anatomy and clinical conditions may also increase the usefulness of the Myo-Simu phantom.

Conclusions

We designed a digital myocardial phantom and confirmed its adaptability to gated SPECT analyses. Because the geometry and motion of the phantom can easily be modified by changing the input parameters, it may be helpful to understand the characteristics of gated SPECT software by showing its responses to the change of a specific parameter (s) defining myocardial count distribution.

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Conflicts of Interest

None

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