Dynamic Programming-based Automatic Myocardial Quantification from The Gated SPECT Myocardial Perfusion Imaging

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***Abstract*—The gated single photon emission computed tomography (SPECT) myocardial perfusion imaging (MPI) is a widely established method to assess left-ventricular (LV) functions and diagnose coronary artery disease in western countries. Software packages for automatic quantification from SPECT MPI have been developed in order to make the interpretations more standardized. However, it has been frequently reported that there are underestimation of end-systolic volume (ESV) and overestimation of LV ejection fraction (EF), especially for the eastern Asian female patients with a small heart. Having recognized the superiority of an optimization-based approach, in this study we developed a dynamic programming-based automatic quantification method for the gated SPECT MPI. Our method was successfully tested with real patients and some of them have small hearts. The preliminary results demonstrated that it performed well when compared with the QGS program and echocardiography as a reference standard.**

***Index Terms*—SPECT, MPI, Automatic Quantification, Left-ventricular Ejection Fraction, Dynamic Programming**

I. Introduction

The gated single-photon emission computed tomography (SPECT) myocardial perfusion imaging (MPI) is a widely established method to assess left-ventricular (LV) functions and diagnose coronary artery disease in western countries. It has been extensively used in clinical units in connection with Technetium-99m-sestamibi and electrocardiographic (ECG) gating [1, 2]. Various software packages (e.g., the Quantitative Gated SPECT (QGS) program [2]) for automated quantification from SPECT MPI have been developed in order to make the interpretations more standardized. However, it has been frequently reported that there are underestimation of end-systolic volume (ESV) and overestimation of LV ejection fraction (EF), especially for the eastern Asian female patients with a small heart. Having recognized the superiority of dynamic programming-based approach [3], in this study we developed a dynamic programming-based automatic quantification method for the gated SPECT MPI.

In patients with a small heart, defined as an end-systolic volume (ESV) of $\leqslant$20 mL calculated using the QGS program, underestimation of ESV and overestimation of EF using the gated SPECT MPI are considered errors [4]. In small hearts, due to the severe partial volume effects of the gated SPECT MPI and the short distance to the opposite ventricular walls, the endocardial and epicardial surfaces are shifted in the epicardial direction [4].

Using the gated SPECT MPI images of the eastern Asian patients some of whose hearts are small, we carried out a preliminary study to investigate the performance by comparing the LV volumes and EFs estimated by the proposed method with those by the QGS program and the echocardiography as a reference standard.

II. Methodology

In this section, the algorithmic steps of the proposed method are summarized as a flow chart in Fig. 1, which will be explained below in details.

A. Conversion from Short- to Long-axis Slices

We firstly convert the image volume acquired by the gated SPECT MPI from the short-axis slices to the long-axis slices as shown in Fig. 2. Sampling is carried out every 9 º along the direction of latitude (i.e., 20 total). One of the potential benefits for this conversion is that this process can help locate LV apex, which is hard for the short-axis slices.

B. Transformation from Cartesian to Polar Coordinate

Since the LV approximately has the shape of an ellipsoid, it will be convenient for the implementation of the dynamic programming, if we transform the original Cartesian to a polar coordinate (see the 1st row in Fig. 3) whose origin is supposed to be at the center of mass (COM) of the LV. Sampling is carried out every 2 º longitudinally (i.e., 180 total). This transformation strategy has also been practiced in the QGS program [2] and other researches [3] before.

This work is supported by the New Star Team of XUPT, by the Key Lab of Contemporary Design and Integrated Manufacturing Technology, Northwestern Polytechnical University, Ministry of Education, China, under Grant KF201401, by the Department of Education Shaanxi Province, China, under Grant 15JK1673, and by Shaanxi Provincial Natural Science Foundation of China, under Grant 2016JM8034.

DOI: 10.12059/Fully3D.2017-11-3202023

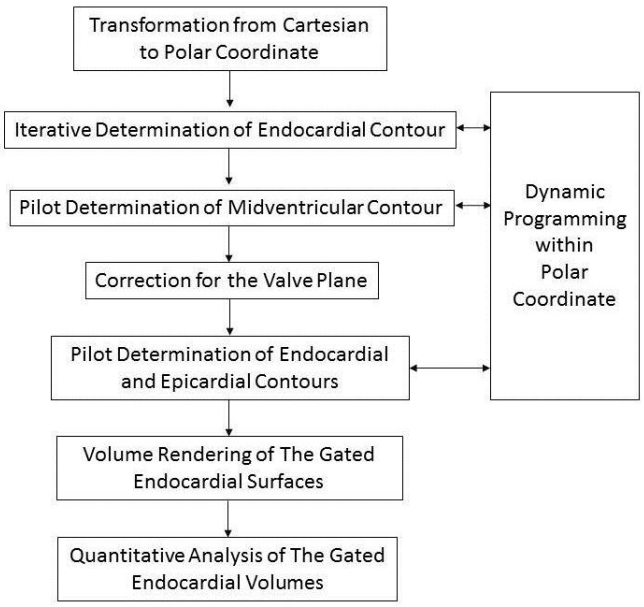
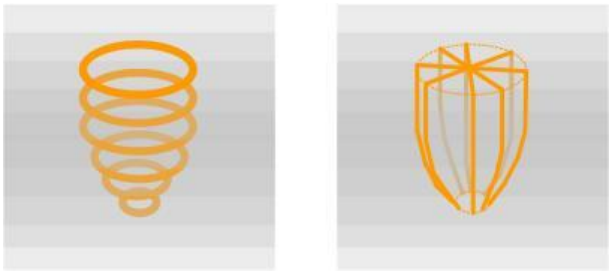
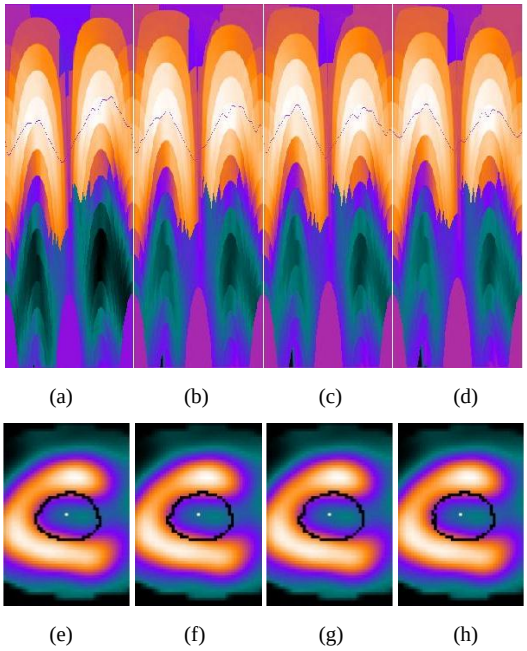


Fig. 1. Flow chart of the algorithmic steps of the proposed method.



(a) (b)

Fig. 2. Schematic showing the image volume acquired by the gated SPECT MPI in the forms of (a) short- and (b) long-axis slices.



(a) (b) (c) (d)

(e) (f) (g) (h)

Fig. 3. The 1st and 2nd rows correspond to the polar and Cartesian coordinates, respectively, while from the 1st to 4th columns are the iterative procedure of the determination of the endocardial contour and its center of mass.

C. Dynamic Programming within Polar Coordinate

In a general method [2], the radial count profiles originating from the COM are generated to achieve spherical sampling of the product of the binary mask of the LV myocardium and the short-axis slice. Then, the locus of the profiles' first maxima represents the maximal count myocardial contour. This approach ignored the neighborhood relationship between nearby sampling points on the locus, whereas dynamic programming-based optimization is pretty flexible in emphasizing this neighborhood relationship. Analyzing in details, we may find that a dynamic programming without any constraint on the neighborhood relationship will degrade into the strategy adopted by the general method, while the one with the strongest constraint on the neighborhood relationship will force the maximal count myocardial contour to be a regular circle shape, which is not consistent to the real situations. We believe that both extreme cases are not good to the totally automatic, accurate and stable implementation of a quantification analysis tool.

Meanwhile, the endocardial and epicardial contours are also desired, so the maximal count needs to be replaced by the maximal gray level value, and then its maximal differential value along radial orientation is calculated.

D. Iterative Determination of the Endocardial Contour

We firstly assume the center of the gated SPECT MPI image volume coincide the COM of the LV. The COM is used as the origin of polar coordinate for the first iteration. Then, the endocardial contour is determined by using the dynamic programming strategy as mentioned above. The COM (x_0, y_0) is updated by calculating the geometrical center of endocardial contour for each long-axis slices,

$$x_0 = \sum_{n=1}^{N} x_n \Big/ N, \tag{1}$$

$$y_0 = \sum_{n=1}^{N} y_i \Big/ N, \tag{2}$$

where N is the total number of the sampling points on the contour. The updated COM is used as the origin of polar coordinate for the next iterations (see Fig. 3 for illustration). The total number of iterations is set as 4 in this study. It is noted that there is a similar updating strategy in the Ref. [2].

E. Pilot Determination of the Mid-ventricular Contour

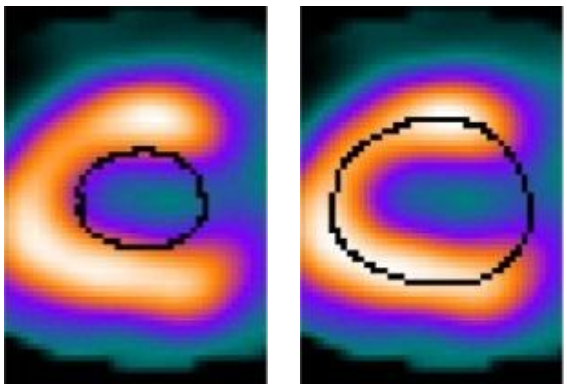
After the endocardial contour is estimated, the determination of the mid-ventricular contour can be subsequently piloted by the endocardial contour. The piloting is achieved by combining the following constraint with the dynamic programming-based optimization process,

$$\left| c'_{\text{pilot}}(\theta) - c'_{\text{optimized}}(\theta) \right| \le \varepsilon, \theta \in [0°, 360°), \tag{3}$$

where ε is a small boundary value, and θ represents the angle variable in the polar coordinate, while c'_{pilot} and $c'_{\text{optimized}}$ are the derivatives of the curves on the pilot contour and the contour being optimized, respectively. Note that all piloting operations in this study are similar to the one described here. In the

practice, we notice that, this piloting strategy is very useful in correctly positioning the contour being optimized, here the mid-ventricular contour (see Fig. 4), since the spurious hot structures such as the liver, spleen or intestine present in the proximity of the heart may impose a negative influence to the dynamic programming.

Meanwhile, it is noted that, in the place of the valve plane, the mid-ventricular contour thus determined is an arc rather than a straight line desired (see Fig. 4), which is due to the characteristic of dynamic programming in purchasing a smooth curve of maximal gray level values. This characteristic may distort the accuracy of quantitative indexes such as LVEF and will be dealt with in the next subsection.



(a) (b)

Fig. 4. (a) The endocardial contour finally determined in the subsection D and (b) the mid-ventricular contour piloted by the endocardial contour in (a).

F. Correction for the Valve Plane

In the long-axis slice, there is a perfusion hole corresponding to the basal portion of the valve plane. After determination of the mid-ventricular contour (see Fig. 4), the curve in the basal portion should be straightened in order to derive a more accurate LV volumes and EF. The way to straighten the curve in the basal portion of the valve plane is demonstrated in Fig. 5.

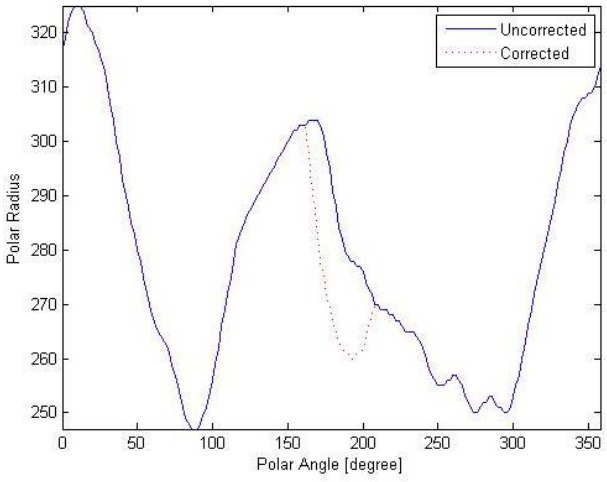
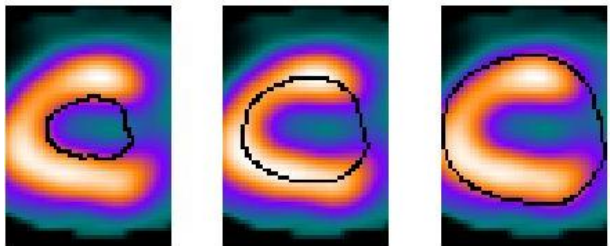


Fig. 5. Uncorrected and corrected curves correspond to the mid-ventricular contour in Fig. 4(b) and the mid-ventricular contour corrected for the valve plane, respectively.

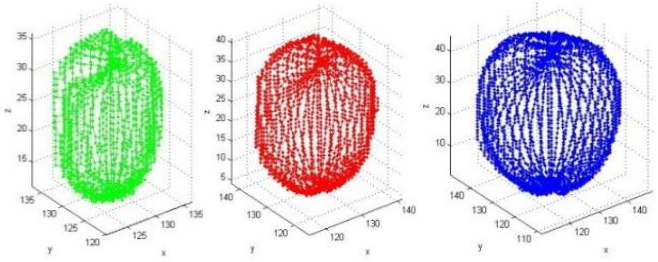
G. Pilot Determination of the Endocardial and Epicardial Contours

After the mid-ventricular contour is effectively corrected as described in the subsection F, both endocardial and epicardial contours can be subsequently piloted by the mid-ventricular contour. Also, we notice that, this piloting strategy is very useful in correctly forming these contours. Here, it is noted that, in the place of the valve plane, these contours thus determined are nearly straight lines as shown in Fig. 6. This piloting strategy can effectively improve the accuracy of quantitative indexes such as LVEF as expected. Shown in Fig. 7 are all the contours in all the long-axis slices.



(a) (b) (c)

Fig. 6. (a) The endocardial contour. (b) The mid-ventricular contour. (c) The epicardial contour. (a) and (c) were piloted by (b),which has been corrected for the valve plane.



(a) (b) (c)

Fig. 7. (a) The endocardial, (b) mid-ventricular and (c) epicardial contours of the image volume acquired from the gated SPECT MPI.

H. Volume Rendering of the Gated Endocardial Surfaces

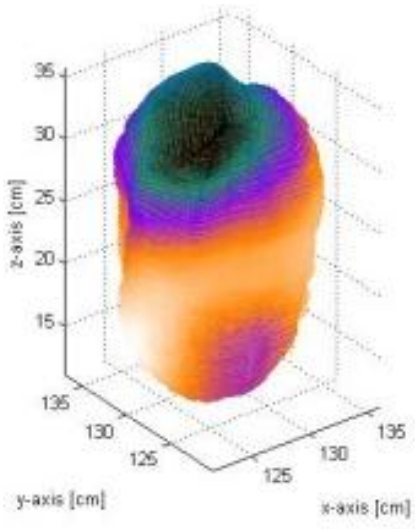
After all the endocardial contours are accurately determined, the endocardial surface can be formed and volume rendering can be exploited to visualize the myocardial perfusion and cardiac functions. The gray level values, i.e., the perfusion counts, of the image volume are incorporated into the endocardial surface as its pseudo-color (see Fig. 8 for all the eight gated endocardial surfaces in a cardiac cycle).

I. Quantitative Analysis of the Gated Endocardial Volumes

LV volumes can be easily calculated by using the knowledge of solid geometry and therefore the detail is omitted here. In the gated SPECT MPI, LVEF is derived by using the LV endocardial volumes EDV (at end-diastole) and ESV [2],

$$\mathrm{EF} = (\mathrm{EDV} - \mathrm{ESV})/\mathrm{EDV} \times 100 \ \ [\%]. \qquad (4)$$

where EDV and ESV correspond to the smallest and largest, respectively, of the gated endocardial volumes (see Fig. 9).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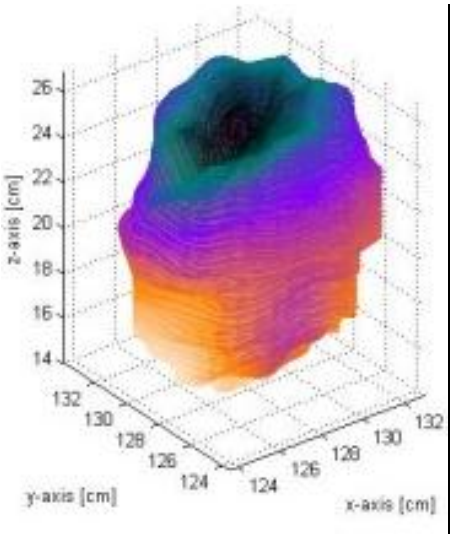
(a)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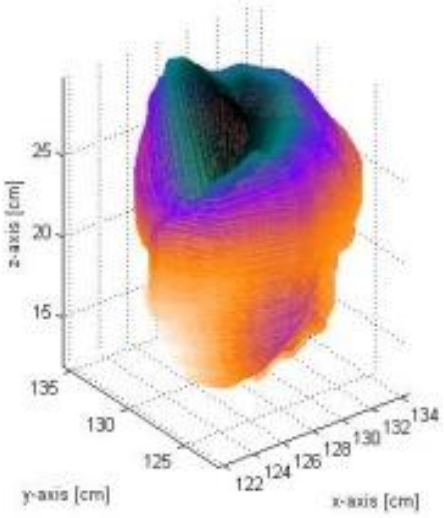
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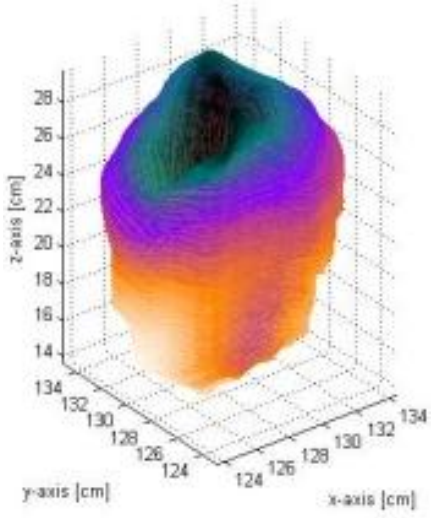
(b)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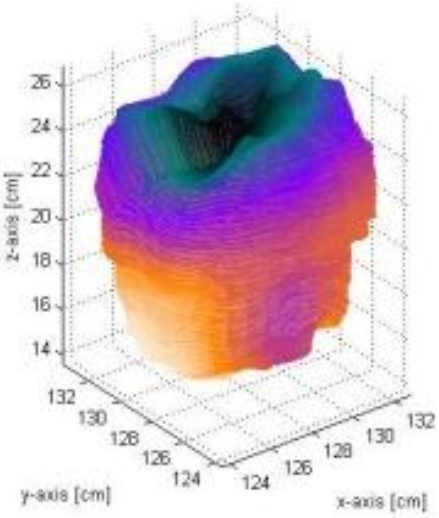
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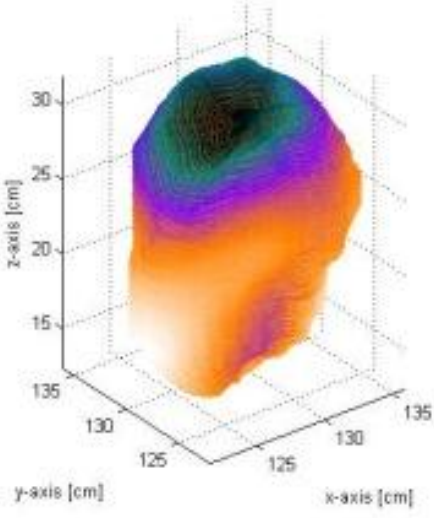
(c)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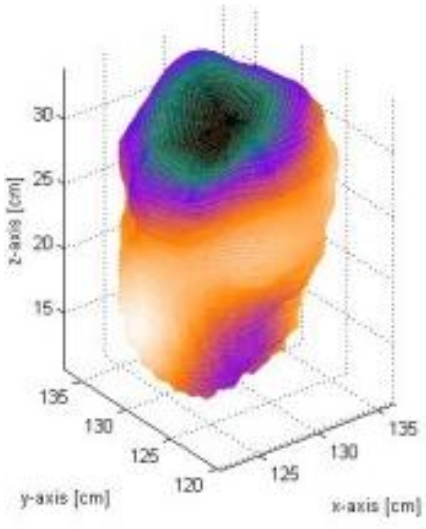
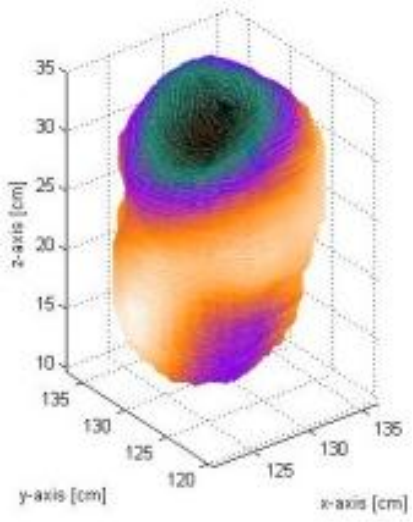
(f)



(g)



(h)

Fig. 8. From (a) to (h) are the pseudo-colorful endocardial surfaces determined for all the eight gated image volumes acquired by the SPECT MPI.

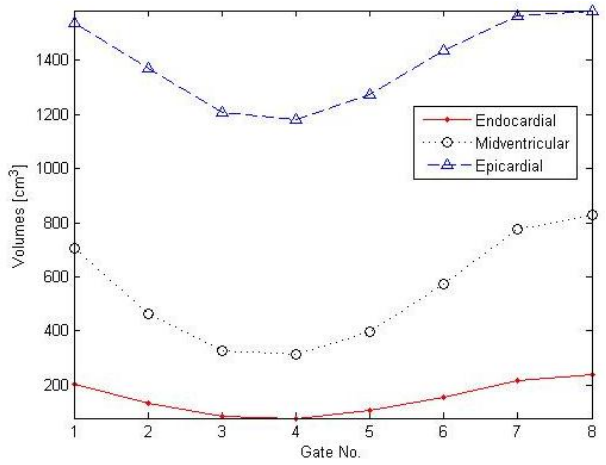


Fig. 9. LV volumes vs. the gates of the SPECT MPI. EF = 65% while EDV and ESV are 235 ml@gate 8 and 82 ml@gate 4, respectively.

III. Experimental Evaluation

The image volume data of the eastern Asian patients acquired by the gated SPECT MPI are used to assess the capability and performance of the proposed method. These image volume data are from the eastern Asian patients, some of whose hearts are small. We carried out a preliminary study on the LV volumes and EFs by comparing the proposed method with the QGS program and echocardiography as a reference standard.

Table 1. The LV volumes and LVEFs evaluated by the proposed method, the QGS program and echocardiography as a reference standard. Note that the proposed method can be further improved in 3 instances (i.e., the instances 1, 4 and 9).

Instance	Method	EDV [mL]	ESV [mL]	EF [%]
1	Proposed	37	15	60
	QGS	47	13	72
	Echo	/	/	69
2	Proposed	39	10	74
	QGS	57	14	76
	Echo	/	/	66
3	Proposed	52	17	68
	QGS	86	33	62
	Echo	/	/	68
4	Proposed	64	15	76
	QGS	94	34	64
	Echo	/	/	63
5	Proposed	34	14	59
	QGS	62	14	78
	Echo	/	/	68
6	Proposed	58	14	76
	QGS	72	17	77
	Echo	/	/	69
7	Proposed	62	18	72
	QGS	62	14	78
	Echo	/	/	61
8	Proposed	72	21	72
	QGS	102	44	56
	Echo	/	/	69
9	Proposed	16	0	99
	QGS	14	1	89
	Echo	/	/	58
10	Proposed	29	10	65
	QGS	39	10	74
	Echo	/	/	60

IV. Experimental Results

Listed in Table 1 are the EDVs, ESVs and EFs evaluated by the proposed method. From Table 1, we can notice that there is a difference between the results derived by the proposed method, the QGS program and the echocardiography. In some instances, the proposed method can be further improved.

Here, it is emphasized that the validation of the LV volumes estimated by the proposed method was not within the scope of this work. Assuming the systematic errors made in estimating the EDV and ESV are positively correlated, we hypothesize that the EF is at least partially independent of the absolute values of the EDV and ESV, because the EF is essentially a ratio of the difference between the EDV and ESV to the EDV. In this work, we consider less on the efficiency of the proposed method, since that of the QGS program is not available. Meanwhile, a high-performance graphic processing unit (GPU) can be used to accelerate the processing, since the processing of the gated SPECT MPI image volume data can be easily parallelized.

V. Discussions and Conclusions

In this study, we proposed a dynamic programming-based automatic quantification method for the gated SPECT MPI and carried out a performance evaluation with the image volume data of the eastern Asian patients some of whose hearts are small. The proposed method is applicable because it is totally automatic, accurate and stable in its implementation as a quantification analysis tool.

Meanwhile, according to the preliminary results reported in this study, we noticed the complication of a small-heart problem which is not uncommon in eastern Asian countries. Even though a small heart has been defined as an ESV of $\leqslant$20 mL calculated using the QGS program [4], we observed that there is a difficulty in the accurately quantitative analysis of a small heart. So, one possible approach to improve quantitative analysis is to divide patients with a small heart into different subgroups, which are then processed by different strategies. Another possible approach is to improve the contrast of the gated SPECT MPI images of patients with a small heart, which will benefit the automatic quantification of myocardial functions. These will be our future's work.

The proposed method is promising in the automatic quantification of LV functional parameters from the gated SPECT MPI. A comprehensive validation with a larger population of patients is being under way, and related results will be reported in the future.

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