Evaluation of Cardiac Function Analysis System Using Magnetic Resonance Images

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Cardiac disease is one of the leading causes of death in Korea. In quantitative analysis of cardiac function and morphological information by three-dimensional reconstruction of magnetic resonance images, left ventricle provides an important role functionally and physiologically. However, existing procedures mostly rely on the extensive human interaction and are seldom evaluated on clinical applications.

In this study, we developed a system which could perform automatic extraction of enpicardial and endocardial contour and analysis of cardiac function to evaluate reliability and stability of each system comparing with the result of ARGUS system offered 1.5T Siemens MRI system and manual method performed by clinicians.

For various aspects, we investigated reliability of each system by compared with left ventricular contour, end-diastolic volume (EDV), end-systolic volume (ESV), stock volume (SV), ejection fraction (EF), cardiac output (CO) and wall thickness (WT).

When comparing with manual method, extracted results of developed process using minimum error threshold (MET) method that automatically extracts contour from cardiac MR images and ARGUS system were demonstrated as successful rate 90% of the contour extraction. When calculating cardiac function parameters using MET and comparing with using correlation coefficients analysis method, the process extracts endocardial and epicardial contour using MET, values from automatic and ARGUS method agreed with manual values within ± 3% average error. It was successfully demonstrated that automatic method using threshold technique could provide high potential for assessing of each parameters with relatively high reliability compared with manual method.

In this study, the method developed in this study could reduce processing time compared with ARGUS and manual method due to a simple threshold technique. This method is useful for diagnosis of cardiac disease, simulating physiological function and amount of blood flow of left ventricle. In addition, this method could be valuable in developing automatic systems in order to apply to other deformable image models.

Key Words: automatic extraction, ARGUS system, MET, SSM, cardiac function

INTRODUCTION

Cardiac magnetic resonance imaging (MRI) provides a wealth of morphological and physiological information. One type of information concerns left ventricular (LV) global function. Its assessment by modalities such as two-dimensional echocardiography or nuclear medicine requires geometric assumptions. On the other hand, MR can dynamically acquire the LV function by using multiple contiguous slices at any orientation, giving rise to true temporal volumetric description. Physiological parameters derived from cardiac images require the extraction of the endocardial and epicardial contours in a large number of diastolic and systolic images. When this is performed manually, the process suffers from the disadvantage of being time-consuming, tedious and prone to bias.

In gerneral, a clear need arises for automatic contour extraction. A wealth of automatic and semi-automatic procedures based on various image processing approaches have been proposed in the last few years[1]. However in many of the proposed procedures the degree of automacity was low, because initial or supervised manual contour extraction was required[(2)~(4)]. Moreover, their clinical value was usually not evaluated because physiological parameters assessed by these procedures were rarely compared to parameters derived by manual extraction from the same population of subjects[(5)~(6)]. In this study, a process for near automatic extraction of endocardial and epicardial contours was both developed and clinically evaluated. Images were obtained in the short axis planes by using a gradient-echo protocol. Only manual step required to initiate the procedure in an image chosen for analysis was indication of the point in the center of LV by expert clinicians. The algorithm on which the procedure was based utilized image processing techniques such as thresholding and sharp extraction. Thresholding was performed by implementing minimum error thresholding (MET) on an expanding region, whereas sharp extraction took place by examining the distances of potential epicardial pixels from the LV's center.

The procedures was systematically evaluated using correlation coefficients analysis, in order to determine its clinical utility. LV volume, ejection fraction (EF), stock volume (SV), wall thickness were included to compare both our developed program and ARGUS programming compared with manual method in a population of six healthy subjects and one patient.

Materials and Methods

The extraction of endocardial and epicardial wall boundary detection system was programmed with Visual C++ environment of IBM Pentium PC.

In the first step, we acquired short-axis (SA) cardiac MR images to automatically extract the epicardial, endocardial contours of left ventricle (LV). Then, we extracted contours using gradient operator, MET, and applied to healthy adult subjects (n = 6) and adult cardiac patient (n = 1) suffered from at least one past myocardial infarction (PMI). We compared the developed method with ARGUS system (Siemens Ltd., Germany) and manual method by expert clinicians.

In the next step, we calculated five parameters using slice summation method (SSM) quantitatively in each method. Then, for the comparative evaluation of the performance of the developed method five parameters were compared with ARGUS system and manual method using correlation coefficients analysis.

1. Image acquisition

Study population consisted of healthy adult subjects (n = 6) and adult cardiac patient (n = 1). All subjects gave informed consent and study was approved by St. Mary Hospital. All studies were performed by the Magnetom scanner (Siemens Ltd., Erlangen, Germany, 1.5-Tesla MRI).

The acquisition protocol was a multi-slice, multi-frame (MSMF) electrocardiogram (ECG) gated spin-echo sequence with time of echo (TE) = 6.1 ms, repetition time (TR) = 80 ms and a flip angle of 25. Short-axis (SA) images (Fig. 3) were obtained simultaneously at 11 different positions (slices) and at 8 time intervals (phases) during cardiac cycle. FOV was 25 × 25 cm and slice thickness was 10 mm. On the image the physician extended a line from the mitral valve to apex.

Figure 1 shows experimental instrumentation for acquisition of ECG-gated MR images.

2. Image Preprocessing

The purpose of automatic procedure is to delineate the inner (endocardium) and outer (epicardium) borders of the myocardium in the image selected for analysis. Initial segmentation into LV blood, myocardium and lung pixels were performed by thresholding, followed by extraction of the endocardial and the epicadrial contours.

2.1. Thresholding Selection

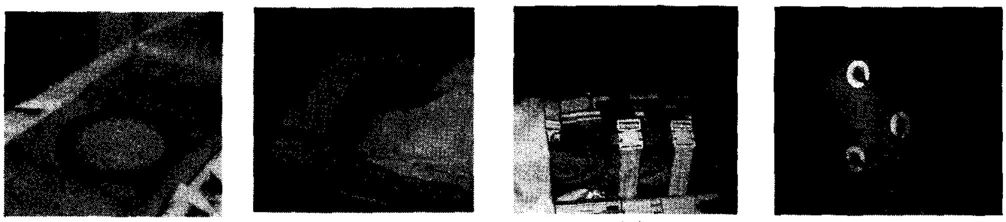
Figure 2 shows an example of a gray level histogram derived from typical short axis image. The purpose of this processing stage is to partition the histogram into three ranges by determining thresholding. The highest range (brightest pixels) will be associated with LV blood, the intermediate range with the myocardium and some surrounding tissues and the lowest range (darkest pixels) with the lung. The differentiation of LV blood from myocardium is more complex and requires the use of a more sensitive thesholding method. Many thersholding techniques appear in the literature[(7)~(8)], of which *minimum* error threshold (MET) was shown to be relatively sensitive to the attributes of a relatively small pixel population when differentiating between small pixel and a much larger pixel population found next to small pixel on the histogram.

This makes MET attractive to our needs, because we are confronted with a tail-like blood related range found to the right of a myocardium-related peak. In the present study, bi-modal MET to tri-modal histogram introduced the concept of thresholding expending regions. Around a point selected by a physician as the center of the LV, we gradually expended a circular region in small increments. A circular expending shape was chosen, because it is the typical shape expected from the LV. When the expending region is small, it consists of only LV blood pixels. We utilized this expected behavior by thresholding the histogram using MET, when each time the circular region was expected. We obtained, therefore, a series of threshold, each one linked to a histogram which was derived from a slightly large population. When the histogram comprises LV blood pixels only, the resulting threshold values are high because MET splits a blood range.

Further expansion of the region should not significantly change this low value. This was clearly shown in Fig. 3, which displays threshold values obtained from thresholding an expanding circular region. The threshold obtained after the sharp drop is easily identified to separate the LV blood-related range from the myocardium-related range.

2.2. Extract the epicardium

The highest range (brightest pixels) will be associated with LV blood, the intermediate range with the myocardium and some surrounding tissues and the lowest range (darkest pixels) with the lung. The determination of the lowest threshold poses no particular difficulties. This is because the lung-related peak in the histogram is



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

Fig. 1. Experimental instrumentation for acquisition of ECG-gated MR images: (a),(b) ECG connector, (c) CP Body Array, (d) ECG electrodes.

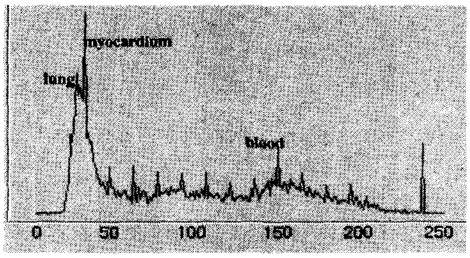


Fig. 2. The typical histogram splits into three major part; a 'tail' like bright blood distribution, one or more peaks possibly associated with myocardium and a distinct dark peak associated with the lung.

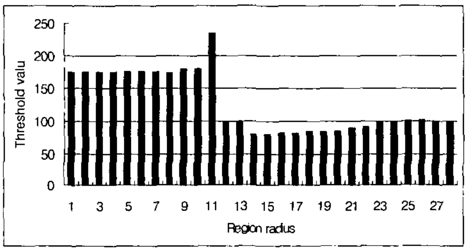
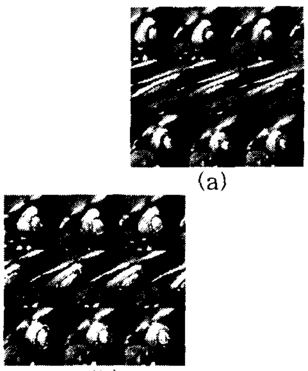
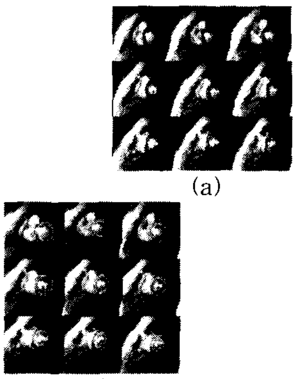


Fig. 3. Thresholds derived expending circle; Threshold values obtained from gradually expending a circle region. The black threshold bar (radius = 11) indicates the value of the threshold at which the sharp drop in threshold values has occurred.



(a) (b) (c)

Fig. 4.1. Extraction of endocadial and epicardial contour for Subject 2 (normal): (a) manual, (b) automatic, (c) ARGUS.



(a) (b) (c)

Fig. 4.2. Extraction of endocadial and epicardial contour for Patient 1 (abnormal): (a) manual, (b) automatic, (c) ARGUS.

usually very steep and distinct. It can be located by the use of a simple gradient operator applied on the histogram.

The algorithm for extraction of the epicardium was initiated by dividing the LV into 128 angular sectors and performing in each sector a search from the LV center in a radial direction[(9)~(10)]. The purpose of this search was to direct in each sector the locations of the first encountered lung or RV blood-related pixels. In some sector, whereas in others the located pixels might be false and belong to other tissues or blood vessels. The large number of possibly false epicardial pixels drove us to derive the epicardial contour only from pixels which have a large possibility of belong to the epicardium.

This was achieved by introducing the concept of the distance histogram. We formed an histogram which held the frequency of the distances of detected epicardial pixels relative to the LV center. Two histograms were formed, one for lung and the other for blood-related pixels. We then search for the peaks in each of these histograms and sectors to which those pixels belong to serve as a base for the construction of the epicardial contour. The empty sectors were filled by circular interpolation using surviving epicardial pixels.

2.3. Extract the endocardium

The extraction of endocardial contour requires the determination of the threshold which differentiates LV blood from myocardium. This threshold was not uniquely set in the previous stage, but instead had to be selected from some candidates. In general, basic approach for selecting the optimal threshold is based on a comparison between the properties of the endocardial contours derived from these thresholds. We did not alter the shape or enhance the qualities of the contour.

Endocardial contours were formed by thresholding the raw image using MET, and then by applying morphological operators on the threshold image[11)]. We then tested that the contours assured to be continuous and did not process significant irregularities.

We chose the area of the contour to be the parameter by which contours were evaluated using correlation coefficients, and then volumes and physiological parameters were eventually determined.

2.4. Evaluation

Once endocardial and epicardial contours are extracted in continuous slices, physiological parameters can be assessed. In each analyzed slice, LV area is defined as the difference between the areas enclosed by epicardial and endocardial contours. It should be pointed out that if the automatic process had failed to procedure an endocardial or myocardial contour, then its respective myocardial area is assumed to neighboring slices. Diastolic and systolic areas were summed separately by using SSM (Slice Summation Method - SSM), which was obtained by adding together the volumes of the individual slice. That the slice gap must be considered, giving rise to end diastolic volume (EDV) and end systolic volume (ESV). Using these values, the EF= (EDV-ESV)/EDV, SV=EDV-ESV and CO=SV×heart rate, were calculated. Wall thickness was obtained using the average distances between endocarial and epicardial contours in each eight sectors[5)] in developed, ARGUS system and manual method, respectively.

3. Statistical Analysis

For evaluation of developed system and ARGUS system reliability, we utilized manual method by performed clinician as standard[6)].

The individual differences between the physiological parameters among three methods, manual, developed auto system, ARGUS system were averaged. A correlation coefficient was obtained from the each studied values (manual, Auto., ARGUS).

For the evaluation of developed system and ARGUS system, we used differences of averaged value between manual method, developed system, and ARGUS system.

RESULT

Figures 4.1-4.2 displayed examples of endocardial and epicardial contour extraction from images belonging to healthy and patient using manual, automatic and ARGUS method, respectively. As shown in Figs. 7.1-7.2, the automatically extracted endocardial contours were well adjusted to different LV morphologies and were smooth and continuous. However, it was noted that automatic endocardial contours had in many cases underestimated the extracted contours in comparison with manual, ARGUS. This was mainly attribute to the fact that gray values of blood were not homogeneous and tended to have a few papillary muscle. This condition could have possibly risen from causes such as volume measurement, non-uniformity in blood flow velocity and motion artifact.

Figure 5 showed the horizontal and vertical axes that are the radial distances from center to the two contours in manual, automatic and ARGUS method, respectively. The correlation coefficients between automatic and manual were 0.94 and 0.84, between ARGUS and manual were 0.97 and 0.82, and between automatic and ARGUS were 0.95 and 0.85, respectively. The success ratio of the contour extraction was approximately 90%. This results showed automatic method had superior to ARGUS system in extraction of endocardial contours compared with manual method as a standard.

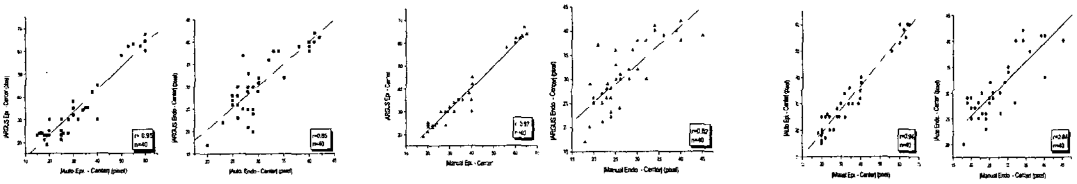
The automatic procedure was systematically evaluated by comparing the physiological parameters derived from automatically, manually and ARGUS. Tables 1 and 2 showed EDV, ESV, SV, EF, CO, and WT derived from the MR images in the healthy and patient groups using the manual, automatic and ARGUS. It is interesting to note that patient's pathology (PMI) is clearly reflected in Table 1. EDV and ESV were lower, while EF was higher than healthy values.

Figures 6 displayed the results of LV volume curve in manual, automatic and ARGUS, respectively. It showed volume curve in automatic method was similar to manual volume.

Figure 7 showed correlation coefficients in EF that was 0.90, 0.91 in automatic and ARGUS compared with manual method, respectively. Both automatic and ARGUS method had high correlation compared with manual method as standard.

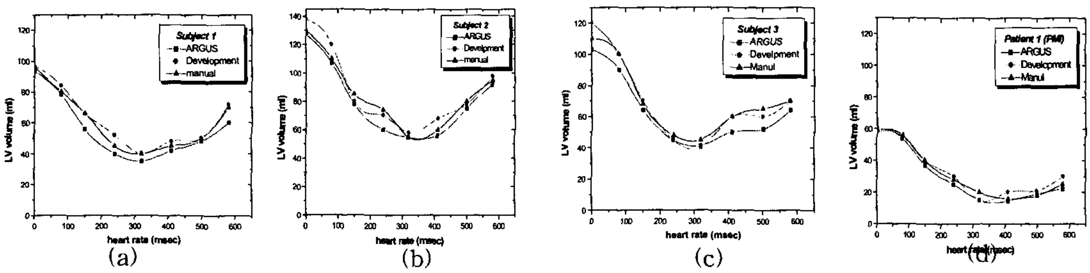
Figure 8 showed correlation coefficients in wall thickness that was 0.86, 0.92 in automatic and ARGUS compared with manual method, respectively. In correlation coefficients in wall thickness, ARGUS method had high correlation compared with automatic method, because it had higher reliability of extraction of epicardial contour than automatic method.

Finally, for the evaluation of reliability between developed system and ARGUS system, we used differences of averaged value between manual method and developed system or ARGUS system. Table 3 displayed a comparison between our results and ARGUS which have assessed theses parameters from short-axis MR images. As can be seen in Table 3, our study showed volumes were within or slightly underestimated ($|p| < 0.05$), whereas our automatic EF's values showed definite underestimation compared with the manual method as standard ($|p| < 0.03$).



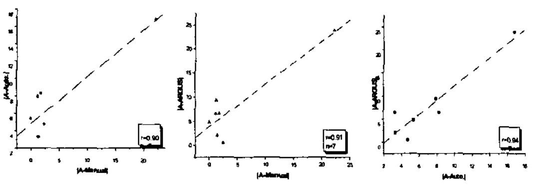
(A) (B) (C)

Fig. 5. Radial distances fitting curve of epicardial and endocardial contour extraction for finding correlation coefficients : (A) manual vs automatic, (B) manual vs. ARGUS, (C) automatic vs. ARGUS.



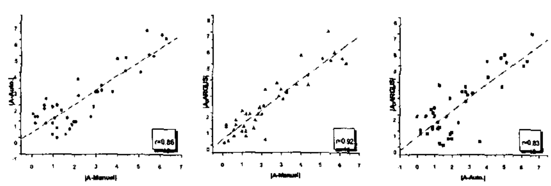
(a) (b) (c) (d)

Fig. 6. LV volume during heart rate in each detection method; (a) Subject 1, (b) Subject 2, (c) Subject 3, (d) Patient 1.



(a) (b) (c)

Fig. 7. Fitting curve for finding correlation coefficients in ejection fraction (EF) : (a) manual vs. automatic, (b) manual vs. ARGUS, (c) automatic vs. ARGUS.



(a) (b) (c)

Fig. 8. Fitting curve for finding correlation coefficients in wall thickness : (a) manual vs. automatic, (b) manual vs. ARGUS, (c) automatic vs. ARGUS.

Table 1. Physiological parameter in each subject

Parameter	EDV [ml]			ESV [ml]			SV [ml]			EF [%]			CO [l/min]		
Extraction	Man.	Auto.	ARGUS	Man.	Auto.	ARGUS	Man.	Auto.	ARGUS	Man.	Auto.	ARGUS	Man.	Auto.	ARGUS
Subject 1	96	100	93.5	40	32	35.2	56	68	58.3	60	68	62.4	3.6	4.1	3.5
Subject 2	130	138	127.5	55	58	54.7	75	80	72.8	57.6	57.9	57.1	4.5	4.8	4.4
Subject 3	110	120	103.1	45	40	41.3	65	80	61.7	59	66.6	59.9	3.5	4.8	3.7
Subject 4	114	110	114	56	60	50.8	58	55	63.1	55.8	55	55.4	3.4	3.3	3.8
Subject 5	125	125	120	54	60	57	61	63	63	58.8	55.4	52.5	3.5	3.8	3.8
Subject 6	125	120	110	54	53	50	61	56	60	58.8	60	55.4	3.5	3.7	3.6
Patient 1	59	58	59.8	16	15	14.5	43	43	45.3	79.8	80.1	85.8	3.8	2.6	3.6
Mean	108	110	103.9	45.8	43	44.4	62.3	60.6	63.8	57.6	63.3	61.9	3.4	4.1	3.8

Table 2. Wall thickness in each subject

Parameter	wall thickness [mm]														
Extraction	Subject 1			Subject 2			Subject 3			Subject 4			Patient 1		
Sector	Man.	Auto.	ARGUS	Man.	Auto.	ARGUS	Man.	Auto.	ARGUS	Man.	Auto.	ARGUS	Man.	Auto.	ARGUS
0	16.2	17.2	15.9	16.2	16.3	15.6	16.4	18.4	15.1	17.2	16.4	17.5	9.2	10.8	8.9
1	14.6	15.2	14.1	14.2	14.7	13.9	14.2	15.4	12.4	19.0	18.6	19.2	8.8	8.9	7.8
2	15.0	16.5	14.4	14.0	14.6	13.5	15.0	15.4	12.7	16.5	18.6	15.2	12.4	14.2	10.0
3	23.0	22.4	22.7	17.4	16.0	16.8	15.8	15.6	12.7	16.4	18.6	14.2	9.0	10.0	8.9
4	24.2	24.5	22.4	23.0	22.5	22.4	23.4	24.8	23.1	15.5	16.4	14.2	10.8	12.6	10.6
5	23.4	23.5	22.6	23.4	23.8	22.0	22.0	23.0	21.6	16.4	16.4	16.5	9.0	8.6	9.2
6	13.5	14.3	13.1	15.3	16.5	14.8	18.7	20.6	15.6	14.3	16.5	13.1	11.2	8.7	10.4
7	13.5	13.5	13.7	15.2	16.5	14.3	18.6	20.0	15.6	14.4	16.8	13.5	11.4	10.6	11.6
Mean	17.9	18.4	17.4	17.3	17.5	16.7	18.0	18.2	16.1	1.62	17.3	15.4	10.2	10.6	9.7

Table 3. Physiological parameters derived from short-axis MR image

STUDY	EDV [ml]	ESV [ml]	SV [ml]	EF [%]	CO [l/min]
Manual (n=6)	-	-	-	-	-
Automatic	4.17±3.37	3.5±2.43	5.33±3.5	3.42±3.01	0.45±0.34
ARGUS	4.32±4.3	2.9±1.33	4.38±3.61	2.32±2.28	0.2±0.13

CONCLUSIONS

In the last few years, several methods had been proposed for the automatic segmentation of cardiac MR images. They are based on the variety of image processing principles and approaches such as threshold, deformable model, active contours, neural networks and fuzzy clustering[4),12)]. However, a large number of reported procedures possess a low degree of automaticity or supervised contour extraction. In addition, only little attention has been devoted to evaluating their clinical utility.

In this study, we have developed a highly automatic process using gray-level method for the extraction of the endocardial and epicardial contours from MR images acquired in the short-axis plane. The process was designed to combine high automaticity with high reliability and efficiency in the extraction of physiological parameters compared with manual and ARGUS program.

In order to quantitatively evaluate the clinical potential of our procedure, we have compared LV volumes, SV, EF, CO, and wall thickness derived from manually, automatically, and ARGUS in a set of six healthy subjects and one patient. Evaluation of our procedure showed automatic method had high reliability in threshold algorithm compared with ARGUS, manual method. Also, it could decrease processing time compared with ARGUS, manual method, because it used simple threshold technique. On the other hand, both automatic and ARGUS method showed lower reliability in extraction of endocardium contours, because of noise intensity as papillary muscles.

Cardiac MRI has been applied successfully in a variety of clinical applications: diagnosis of congential anomalies such as septal defects, abnormal great vessel orientation and position, chamber enlargement, diagnosis of ischemic heart disease, identifications of mass lessions. Also, it is very useful for diagnosis and therapy of cardiac disease, to simulation cardiac function, motion, amount of blood flow of left ventricle. In addition, it could be valuable to develop automatic detection systems in order to apply to other deformable image models.

Finally, future research should include the utilization of more clinical cases for further feasibility test using the improved method, specially designed technique to exclude the papillary[13)], and septum muscles from the border, addition of algorithm to solve problems of ARGUS system and an image scanning protocol that can improve SNR of 2D cardiac MR images[14)].

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