A ROBUST EDGE DETECTION ALGORITHM FOR VOLUMETRIC ANALYSIS OF LEFT VENTRICLE IN CINE MAGNETIC RESONANCE IMAGING

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ABSTRACT

A semi-automatic algorithm using the cine MRI images was developed to calculate the volume history of left ventricle (LV). The program can delineate the blood pool from the myocardial boundary, and calculate the time course of the area of scanned contour and the total volume of left ventricle. The program is user friendly, that a well-trained operator can analyse one subject within 30 minutes. With the accurate volumetric data, the LV end-diastolic volume, LV end-systolic volume, LV ejection fraction, and peak filling rate (PFR) can be obtained. In addition to its quick and easy operation, the advantage of this program is that no geometric assumption is required to derive volumes, and so measurements of different shapes of objects should be equally close to the actual volumes. The program also showed the potential of accessing the volumetric data of the left atrium, right atrium, and right ventricle for the clinical evaluation of heart function.

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1. Introduction

Volumetric data of the left ventricle (LV) provide useful information about functional status of the LV. The information can be crystallized into three basic quantities, LV end-diastolic volume (LVEDV), LV end-systolic volume (LVESV), and LV ejection fraction (LVEF), representing preload, afterload and contractility, respectively. To reliably assess LV function, an accurate measurement technique of the LV volume is desirable.

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Conventionally, LV function is assessed by angiographic ventriculography. This technique requires cardiac catheterization, which is invasive and has associated patient risks. Recent advances in technology permit many imaging modalities to evaluate LV function noninvasively. These methods include radionuclide scintigraphy, echocardiography, computed tomography and magnetic resonance imaging (MRI). The accuracy of each method depends on the limit of spatial and temporal resolution of the technique, as well as the theoretical assumptions used in determining LV volumes [1-5]. Among these, cardiac cine MRI is considered an ideal alternative to conventional techniques because of its noninvasiveness, no potential hazards from ionizing radiation and contrast agent, sufficient spatial and temporal resolution, and no assumption needed for LV volume calculation [6].

Although cardiac cine MRI can provide images with adequate resolution to define volumetric data, the processing time is still an issue. The most straightforward and correct method is to manually define the endocardial contours, however, it is labor-intensive and extremely time-consuming. For example, one center took 18 months to process 18,000 images (50 subjects); approximately 10 days for each case [7]. Such speed is not suitable for clinical applications. Model-based estimation methods were hence developed to speed up the processing time, and claimed to be able to complete the analysis within 5 minutes [8]. However, the accuracy of the methods depends on the prescribed models. Another disadvantage of model-based methods is that it omits details of local wall motions and can only find global cardiac function in relatively normal heart shapes. The boundary tracking algorithm was developed to eliminate the artefact by the model-based algorithm; [9] however, the efficiency of the program and the temporal results of left ventricle were not reported.

In this study, we developed a semi-automated program to determine endocardial boundary of the cardiac cine images. Based on the temporal and spatial locations of these contours, the time course of the LV volume and the basic quantities of the LV function were calculated. The program was user friendly; a trained operator was able to complete the whole analysis within 30 minutes. The accuracy of the program was illustrated by showing quantitative volumetric data that are consistent with previously reported values obtained from conventional techniques.

2. Methods

Cardiac cine MRI was performed on four healthy volunteers (three male and one female, 20 to 30 years of age) with a 1.5 Tesla Magnetom Vision (Siemens, Germany). All images were acquired under electrocardiography (ECG) gating. Ten contiguous short-axis slices encompassing the whole LV from base to apex were prescribed with slice thickness at 8 mm and spatial resolution at 1 mm. For each level, 30 time frames over one cardiac cycle, starting from R-wave trigger and at a 30 ms time interval, were recorded. The pulse sequence used a two-dimensional gradient echo technique with 30 ms repetition time (TR), 7 ms echo time (TE) and 30 degrees flip angle. The scanning time was 20 minutes yielding 300 images in total.

Image data were analysed off-line with a PC using MATLAB 5.2 (Mathworks, Inc., USA). The boundary between the endocardium and the blood was detected using a gray level auto-contouring algorithm provided by MATLAB. After automated contouring was finished, self-developed correction algorithms were applied to adjust incorrect contours resulting from signal inhomogeneity in the blood and the myocardium. The procedure of correction required attendance of an operator to identify incorrect contours and to judge the goodness of fitting after correction. To facilitate the correction, a tomographic movie of the resulting contours was displayed to check the quality of the outcome.

After optimum contour data were obtained, the area for each contour was calculated, and the LV volume was obtained by adding up areas of all levels multiplied by the slice thickness:

$$\text{LV volume} = \left(\sum_{i=1}^{n} A_i\right) \cdot d$$

where n is the number of slices covering the left ventricle, Ai is the contour area at i-th level, and d is the slice thickness. In this way, a time course of the LV volume over one cardiac cycle was obtained. From the fitted time curves of the LV volume, we identified end-diastolic and end-systolic volumes by specifying the maximum and minimum volumes, respectively. The LVEF was then computed with an equation as follows:

LVEF = (LVEDV - LVESV) / LVEDV.

The ejection fractions of basal, mid-ventricular, and apical levels were also calculated in similar manner. The ejection fractions of basal, mid-ventricle and apical level were obtained from the time course of the average area of level 1, 2, level 3, 4, and level 5, 6, 7, respectively. The derivative of volume in respect to time was also obtained to show the filling rate during diastolic period.

3. Results

Most images of cardiac cine MRI showed clear delineation of boundary between flowing blood in the LV cavity (shown as bright, see Fig. 1) and the myocardium (shown as dark, see Fig. 1). The edge detection algorithm could automatically define the endocardial contours of 90% of the total images in the first run without further adjustment. About 10% of the images, which were taken mainly in the period of diastasis, showed relatively poor contrast between the blood and the myocardium owing to signal saturation of the slow-flowing blood. Endocardial contours in these images were often incorrect and required manual operation to fine tune them. With the aid of self-developed algorithms, a trained operator could correct the contours of these images within 30 min. Figure 1 shows images of a volunteer at the mid-ventricular level superimposed with the resulting endocardial contours. In these ten images, only the image of time at 510 ms at the anterior endocardial wall region and the image of time at 870 ms at the posterior endocardial wall region were manually refined. All the other contours are the results of automatic contouring. We can see that the edge detection algorithm successfully

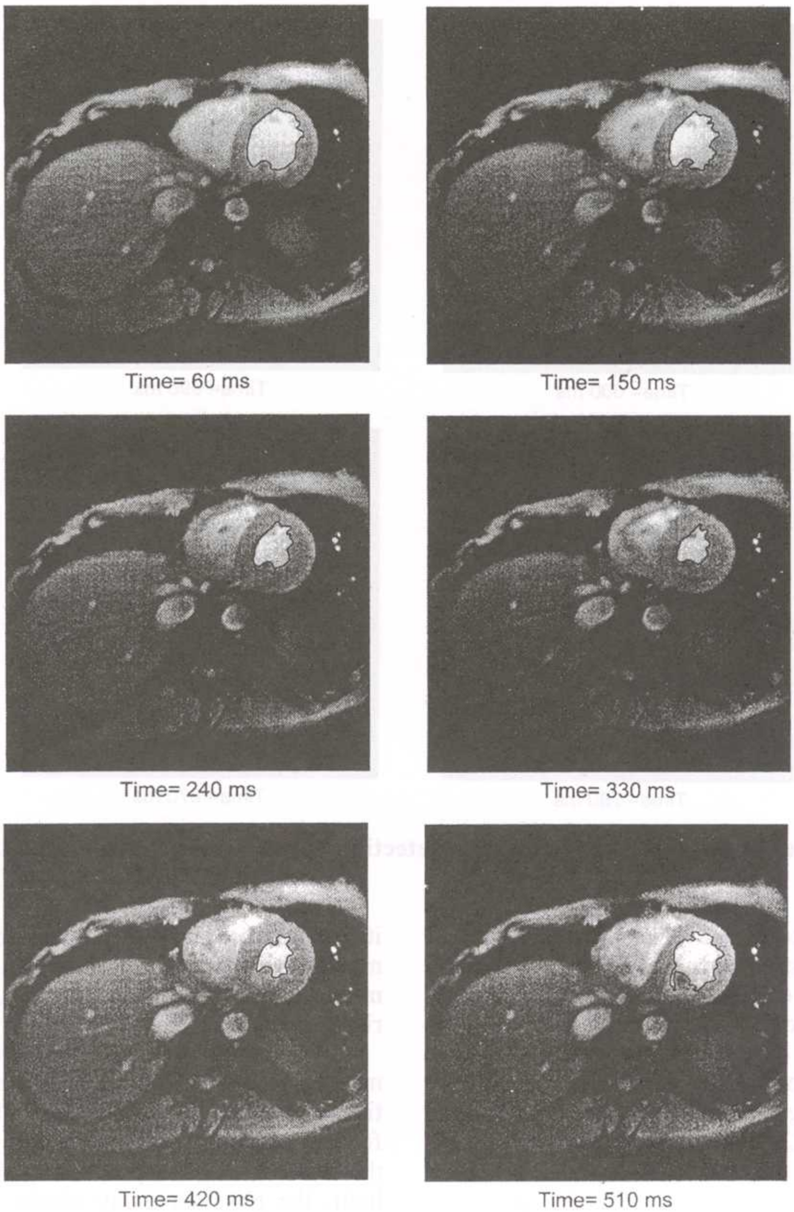

Fig. 1 Examples of the results of boundary detection at mid-ventricular level, from 60 ms to 870 ms at 90 ms interval.

delineated the details of the endocardial profile including the anterior and posterior papillary muscles and major trabeculae.

The area-time curves for each level were plotted in Figure 2. In general, the curves showed a consistent pattern of change in area over time indicating synergy of the myocardial motion. Closer inspection, however, still reveals functional variation from base to apex. The ejection fraction was the smallest at the basal levels (57 % on average of level 1 & 2), intermediate at the mid-ventricle (71 % on average of level 3, 4) and the largest at the apical levels (79% on average of level 5, 6 & 7). Moreover, the times from the ECG R-wave to the minimum LV areas, i.e., end-systole at each level, showed a systematic trend of time delay from base to apex. The times to end-systole were about 297 ms, 327 ms, and 332 ms for the basal, mid-ventricular, and apical levels, respectively.

The volume-time curves showed a classic pattern similar to those obtained from angiographic ventriculography or radionuclide scintigraphy [10,11]. As illustrated in Fig. 3 for a volunteer with a heart rate of 70 beats per min (equivalent to 860 ms per cardiac cycle), the times of end-diastole and of end-systole were

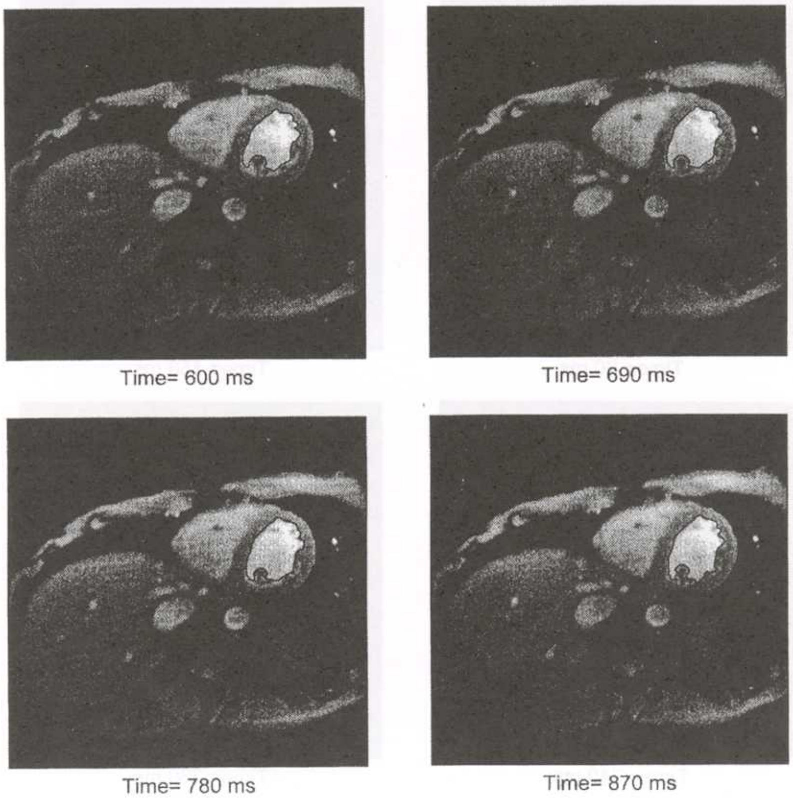

Fig. 1(cont.) Examples of the results of boundary detection at mid-ventricular level, from 60 ms to 870 ms at 90 ms interval.

at 0 ms and 330 ms after R wave, respectively. The ratio of diastole to systole was about 1.6. For this subject, the volume at end-diastole was 66.2 ml, and was 21.2 ml at end-systole. The ejection fraction was 68%. Differentiation of the volume curve with respect to time gave two indices of diastolic function (Fig. 4): the peak filling rate and the time to peak filling rate; they were 282 ml/sec and 414 ms, respectively.

4. Discussion

Cine MRI is an accurate and reproducible tool for the LV function assessment. Studies on accuracy and reproducibility of cine MRI have been carried out in phantoms [12], normal volunteers [13] and patients [5]. In this study, we developed a semi-automated edge-detection algorithm to obtain the time-volume-history of the LV from cine MRI images. The developed program was tested to be user friendly, a trained operator can complete the whole analysis in 30 minutes. Further, our results showed that this program can provide reliable quantitative volumetric information about the LV function, substantiating the feasibility of this program in clinical settings. With minor modification, this program can also be used to determine the volumes of the left atrium, right atrium, and right ventricle.

The current software provides an easy and quick method to evaluate the global heart function in addition to morphological studies. Data analysis is performed off-line, so the scan time is not affected. On the other hand, the processing time is less than one hour, the physician may obtain the quantitative data without significant delay. Improvements on the correction algorithms have been undertaken, in the future the processing time, we expect, can be reduced to 15 minutes.

During the testing, we found that the images tends to be inhomogeneous, i.e., the signal intensity decrease from chest surface to inner organ, when the surface coil is used. This may induce the error of the auto-contouring program, and need manual fine tuning, hence reduce the processing time. The homogeneity of images using body coil is better, however, the image noise is also higher. A filtering program is needed to smooth the images if the body coil is used.

There is no assumption needed in evaluating the volume, hence this method can be used to accurately

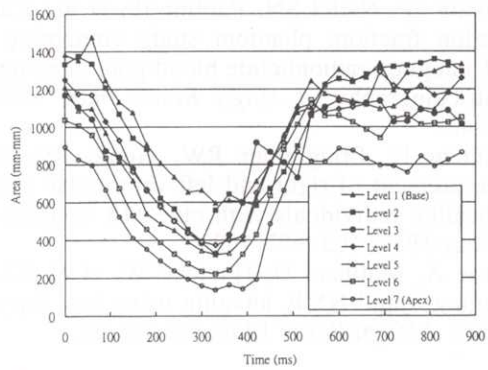

Fig. 2 The area-time curve of seven left ventricular contours from base to apex.

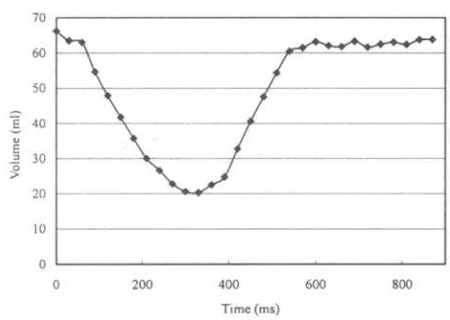

Fig. 3 The volume-time curve of left ventricle, the volume is the summation of the area of seven levels multiplied by the slice thickness.

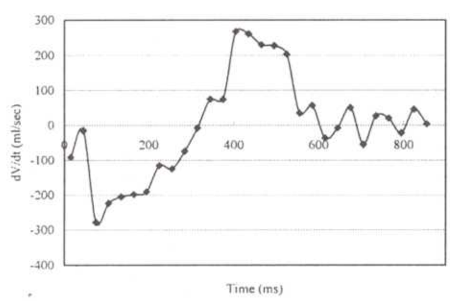

Fig. 4 The derivative of volume of left ventricle with respect to time

find the distorted LV cavities owing to, say, aneurysmal formation, focal hypertrophy, congenital malformation or dyssynergy of LV walls. Radionuclide scintigraphy measures LV volumes by counting radioactivity within LV regions, and does not require any geometric assumption. However, this method is limited by incomplete separation of overlapping activities from the left atrium, and inability to quantify absolute LV volumes.

One limitation of cine MRI is that the whole data set is obtained over many cardiac cycles. Current MRI techniques cannot acquire data in a real-time fashion as angiographic ventriculography or echocardiography does. This limits MRI assessment of LV function in arrhythmic patients whose irregular cardiac rhythm severely degrades the image quality.

Another limitation of MRI is its high cost. The price for a single MRI examination (6500 NT$) is almost 4 times the price for an echocardiographic study (1200 NT$). Current development of MRI will increase its benefit-cost ratio by its multi-purpose capability. As more and more cardiac packages will be available in clinical settings, one could obtain information about coronary artery morphology and flow, myocardial perfusion, and global/local LV function in a single MRI examination.

The recent developed fast MRI technique [14] made the cine MRI to be clinical feasible. A study of ten cardiac levels of one beat cycle at 30 ms temporal resolution can be completed in about 20 min. However, scanning time of 20 minutes is still too long to ignore the respiratory motion. To compensate the motion artifacts, respiratory gating and more than one data averaging are usually adopted. Nevertheless, the respiratory motion will not affect our results since we are finding the global volumetric data but not the wall motion in this study.

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