Accurate Estimation of the Myocardium Global Function from Reduced Magnetic Resonance Image Acquisitions

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Abstract— **Evaluating the heart global function from magnetic resonance images is based on estimating a number of functional parameters such as the left ventricular (LV) volume, LV mass, ejection fraction, and stroke volume. Estimating these parameters requires accurate calculation of the volumes enclosed by the inner and outer surfaces of the LV chamber at the max contraction and relaxation states of the heart. Currently, this is achieved through acquisition and segmentation of a large number of short-axis (SAX) views of the LV, which is time-consuming and expensive. Reducing the number of acquisitions results in undersampling the LV surfaces and hence increases the calculation errors. In this work, we describe and evaluate a method for estimating the cardiac parameters from a small number of image acquisitions that includes one long-axis (LAX) view of the LV. In this method, the LAX contour is used to swipe the SAX contours to fill in the missed LV surface between the SAX slices. Results on 25 patients and CT phantoms shows that, given the same number of slices, the proposed method is superior to other methods.**

I. INTRODUCTION

Calculation of the volumes enclosed by the left ventricular (LV) surfaces is essential for the assessment of the global cardiac function [1][2]. Using MRI modalities, such LV surfaces can be easily constructed from multiple 2D slices. Current clinical protocols include the acquisition of a stack of parallel short-axis (SAX) views, or slices, of the heart from apex to base using standard MRI pulse sequences. Typically, nine to twelve (adjacent) slices are acquired on separate breath-holds. In each breath-hold, a sequence of images covering the entire cardiac cycle is acquired with reasonable temporal resolution. That is, each extra slice increases the total scan time, cost, and inconvenience to the patient. Reducing the number of slices causes undersampling of the LV surface and thus decreasing the accuracy of the calculated volumes.

Given a number of slices, the first step to calculate the volume is to delineate the (outer) epi- and (inner) endo-cardium contours. This can be done manually by an expert or automatically through a number of techniques [3]. The process is repeated for the end-diastole and end-systole phases of the cardiac cycle. The points of these contours represent samples from the LV inner and outer surfaces. Since the in-plane spatial resolution is usually much higher than the through-plane resolution (the gaps between the SAX slices along the direction of the heart long axis), the number of contours, and thus the number of slices, should be increased to capture the curvature of the LV surfaces.

To calculate the LV volume from these contours, the modified Simpson's (mSimp) method is used [4]. In the mSimp method, the area of the myocardium in each slice is calculated and multiplied by the slice thickness, *t*, and the inter-slice gap, *l*. That is,

$$V = \sum_{i=1}^{N} A_i.(t + l) \quad (1)$$

Where V is the LV volume and A_i is the area enclosed by the contour in the i^{th} slice. The mSimp method is considered the golden reference in volume calculations due to its robustness to LV shape anomalies [5]. Nevertheless, the performance of mSimp method deteriorates rapidly with decreased number of cross-sectional slices. This is due to the invalid approximation of large segments of the LV as regular discs. In fact, parametric models can be used to estimate the LV volume when the number of the acquired slices is low. Prolate spheroidal models are widely used in echocardiography and thus can be adopted in cardiac MRI studies [6]. It is worth noting that, in such models, long-axis (LAX) views of the heart are sometimes used to improve the accuracy of the volume calculations. In fact, LAX views have advantage over the SAX because the partial volume averaging effects are significantly reduced especially at the apex [7]. This leads to more accurate delineation of the blood-tissue borders in LAX views.

In this work, we describe a method for estimating the LV volume from few numbers of slices that includes one LAX slice. The LAX contours are used to fill in the missed LV surface information at the gaps between the SAX views.

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Experiments using CT phantoms and human subjects are presented in this paper.

II. Methodology

A. Surface Reconstruction and Volume Computation

Given a set of SAX contours and one LAX contour, it is required to reconstruct an accurate and smooth LV surface. Direct application of conventional triangulation techniques can be used to build (or interpolate) the surface between the vertices of the contours [8]. Nevertheless, this leads to course approximation of the true surface. A more accurate method is to build a course grid of points using information from the LAX contour prior to the triangulation step. In order to construct this grid, the LAX contour is rotated around the cardiac long axis with steps of five degrees. At each rotation step, the new position of the long axis contour is used as one string of a grid as shown in Fig 1. A correction operation is usually required to compensate off-axis rotation as discussed in [9]. After obtaining the course grid, Delaunay Triangulation is used to reconstruct the LV surface [10]. The resulting surface is composed of polyhedrons whose faces are planar and have constant normal vectors. To calculate the volume enclosed by the surface, the following equation can be directly applied:

$$Volume = \frac{1}{3}\sum_{face\ i} \vec{x}_i \cdot n_i A_i \quad (2)$$

Where, $\vec{x}_i$ is the centroid of the i_{th} face, $\hat{n}_i$ is a unit vector normal to the face, and A_i is the area of the face.

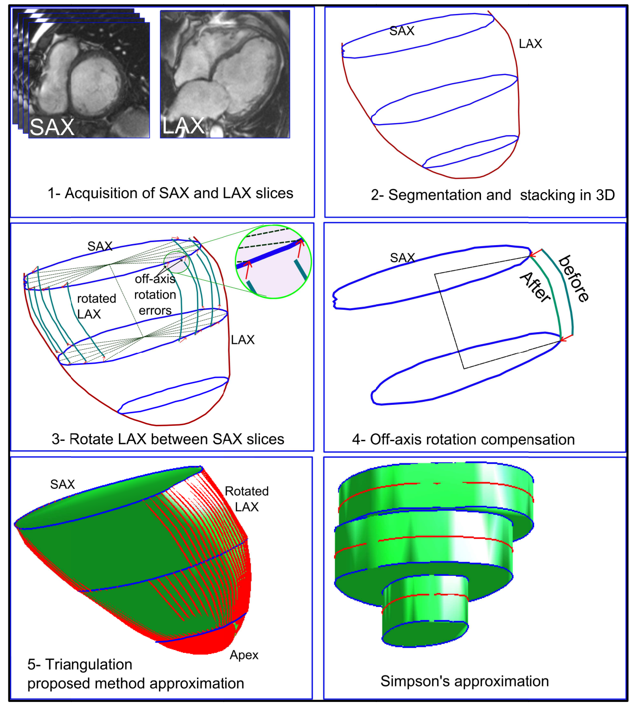

Figure 1. The proposed method, first, the SAX and LAX slices are acquired, segmented and stacked in its 3D positions and orientations. The LAX contour is then rotated between pairwise each two consecutive SAX contours. In the fourth step, the new generated LAX points are returned to the SAX contours. Delaunay Triangulation is performed to the whole geometry and the volume is estimated. Finally the difference between the proposed method approximation and the mSimp approximation are compared.

B. CT-based Phantom Experiment

Ideally, testing and validating any method for cardiac volume estimation requires accurate measurement of the true volume of the heart; i.e. the ground truth. In MRI, the latter is challenging due to several reasons including the limited resolution of the MRI images and the inter-breath-hold motion. To avoid such effects, Computed-Tomography (CT) has been used to generate single breath-hold cardiac images with high-resolution (0.429x0.429 mm). Three subjects have been imaged and the 3D cardiac volume has been reconstructed for each case. The ground truth volume for each heart is calculated from images created with the highest available resolution.

Then, to imitate MRI images, SAX and LAX views of the reconstructed volumes have been created using open source 3D Slicer software [11], where the intensity value of any voxel is obtained by interpolating the CT axial slices (as shown in Fig. 2). The resolution of each image, the inter-slice gaps, and the exact orientation are set arbitrary depending on the experiment. First, a stack of SAX slices is created from the CT-constructed volume with a slice thickness of 8 mm and no interslice gaps. The created slices cover the entire heart from apex to base (16-24 slice depending on the heart). Then, a horizontal LAX slice, i.e. standard 4-chamber view (4CH) as shown in fig. 2.b, is created with the same slice thickness. The images are of resolution 0.429x0.429 mm and matrix size 512x512. In this experiment, the modified Simpson method, the proposed method, and the model-based methods are applied to a subset of n generated images, where n=1:11. The volume estimated by each method is recorded and the mean and standard deviation of the error (relative to the ground truth) is calculated.

C. Real Data Experiment

An image database containing 25 patients have been used to test and evaluate the proposed method. Ten patients were scanned using 1.5T Siemens scanner, and 15 patients were scanned using 3T Philips scanner. The number of slices for each dataset was 9 SAX slices and one LAX slice.

The pixel size was in the range of (1.116 to 1.406 mm) and the slice thickness ranges from 5 to 8mm. Only the end-diastole and end-systole timeframes were considered for processing and analysis. Manual image segmentation was achieved using VIRTUE software package (Diagnosoft, Inc.). For each dataset, we assumed that all slices were acquired while the patient was holding his/her breath at the same level. If this is not the case, simple registration algorithm such as [12] [13] can be used before segmentation.

The ground truth volume for a given dataset was calculated using mSimp method applied to all nine SAX

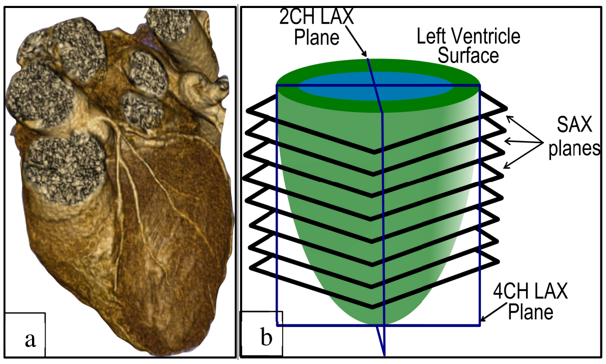

Figure 2. Cardiac CT volume, a) LV CT volume that used in re-slicing operation. b) Showing the directions of LAXs and SAXs planes for the new slices.

slices of this dataset. Then, the proposed method was applied to reconstruct the surface and compute the volume using one LAX slice in addition to different numbers of SAX slices: 0, 1, 3, 5, 7 and 9.

At very small number of slices, other model-based methods described in literature have been investigated and compared to the proposed method [14]. These methods simplify the shape of the LV and model it as: hemisphere cylinder, Teichholz, and single-plane ellipsoid.

III. Results and Discussion

In the phantom experiment, the error of the estimated volume produced by the proposed method at the different number of SAX slices is shown in Fig. 3. As can be shown, the error decreases as the number of slices increases. The maximum error is -4.2±2.8% and converges close to 0.54±0.74%. The over estimation of the volume at large number of slices is due to the fact that the 4CH view of the heart shows the largest profile of the LV (because it includes the elevated LV side of the mitral plane).

For the real data experiment, figure 4 showing the error of the LV volume calculated using the proposed method at different number of slices. At low number of SAX slices (3 SAX + 1 LAX slices), the error was about (-4.7% ±3.3) which decreased to be (-1.15% ±3) at five SAX slices; the error at number of SAX slices more than five is almost close to zero error.

Table 1 shows the error of model-based methods at very small number of slices. As can be seen in the table the error of these model-based methods is much higher than that of the proposed method. Table 2 shows the error of the proposed method when used to calculate the LV volume, ejection fraction and stroke volume. As can be seen although the error is very low while the standard deviation is a little bit high (5%). This can be attributed to the differences between the mSimp and the proposed method. That is, while the first model the slice as a disc; the latter tries to approximate it using the real LAX contours. Errors in delineating the LAX contour would also increase the volume calculation errors.

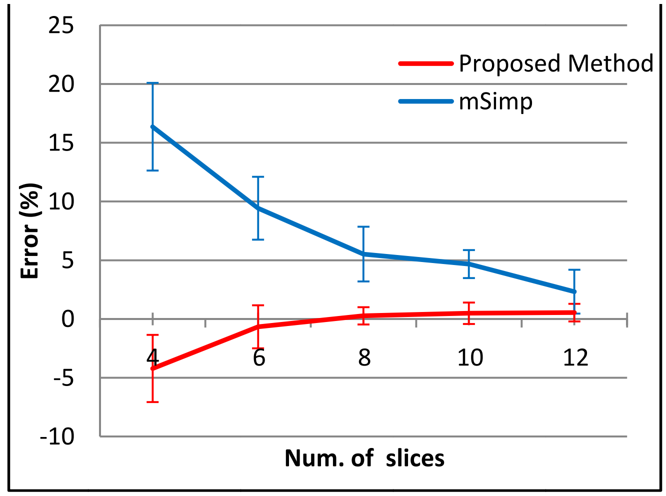

Figure 3. The error (mean±SD) of the estimated volume at different number of SAX slices using the proposed method (phantom experiment).

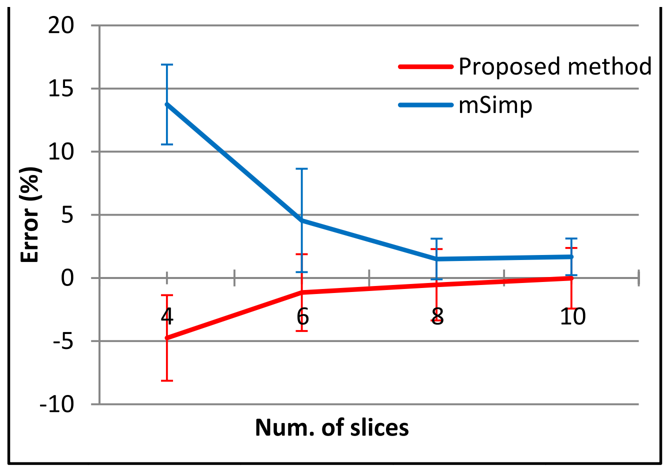

Figure 4. The error (mean±SD) of the estimated volume at different number of SAX slices using the proposed method (real MRI data).

Table 1. Percentage cardiac volume error (mean±SD) computed from different number of slices using different techniques.

	Model Based	**Proposed Method**
1 LAX Slice	Ellipsoid: 30.5 ±32.1	6.5±13.7
1 LAX+1 SAX	HemiSphr: 18.9± 12.5 Teichholz: 21.9 ± 29.14	2.26± 12.5

Table 2. Percentage error (mean±SD) of LV volume, EF and Stoke volume computed by proposed method.

# slices	**3**	**5**	**7**	**9**
LVV error	-4.7±3.4	-1.2±3.1	-0.54±2.8	-0.02±2.4
EF error	-1.5±3.7	-1.4±4.6	-2.2±3.1	-0.97±2.6
SV error	-7.4±8.6	-6.2±7.5	-4.3±5.3	-4.7±2.9

IV. Conclusion

In this work, a method for estimating the left ventricular volume from segmented MRI images has been presented. The method combines information from the long axis view to compensate missing information in the short axis views. This allows accurate estimation of the volume from few number of images and thus from reduced number of acquisitions. The method includes registration of the long and short axis contours to compensate the respiratory motion. It also includes a novel method for estimating surface information between the different short axis slices.

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