Automated Algorithm for Computing Left Ventricle Volume Changes from Cine-MR Images

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Abstract

To determine the left ventricle (LV) chamber volume from cine-MR images, it is necessary to locate the aortic / mitral valve plane with guidance from the long-axis images to isolate (or trim) the LV. However, manual identification of the trimming planes for all frames in the cine-MR scan is tedious and does not guarantee that the LV myocardium volume is kept constant. This work aims to develop an automatic algorithm to compute the LV volumetric changes during the cardiac cycle while ensuring constant myocardium volume. We reconstruct 4D (i.e., spatial + time) LV mesh models from border-delineated cine-MR images. The trimming value at end-diastole (ED) is determined manually and the corresponding ED myocardium volume is computed and used as a reference. For the remaining frames, an iterative Newton-Raphson-like procedure is used to find the trimming plane such that the resulting myocardium volume is conserved. The end-systole (ES) frame is determined as the frame with the smallest LV chamber volume. ECG-gated cine-MR scans of 8 normal subjects were acquired and the LV chamber volumes over the cardiac cycle were computed based on our proposed algorithm. The results showed a mean ejection fraction (EF) of 62.4 ± 4.4%, which agrees with the clinical EF of 67.1 ± 6.2%.

1. Introduction

Left ventricle (LV) remodelling is the progressive degeneration of the LV function after an acute myocardial infarction (MI) [1]. This remodeling is often accompanied by an enlargement in LV size in response to altered mechanical compliance of the injured myocardium tissues and can potentially lead to heart failure. To assess the LV function after MI, the ejection fraction (*EF*) is computed and is one of the most important index for diagnosis and prognosis. However, recent studies have shown that a preserved *EF* does not necessary imply freedom from heart failure risks [2, 3]. Here, we note that the computation of the *EF* uses only the LV chamber volumes at the end-diastolic (ED) and end-systolic (ES) phase of the cardiac cycle. The chamber volumes for the other phases are usually not computed. Computing the volume-time curve for the whole cardiac cycle can potentially provide more quantitative information on the LV filling / pumping efficiency as compared to solely using the *EF*. This can possibly provide more information for clinicians in making diagnosis and prognosis. Typically, the estimation of the LV chamber volumes is performed using echocardiography due to its availability and low costs. But, this method has inherent limitations because of low signal to noise ratio and intra- / inter-operator dependency [4]. To overcome these limitations, cine-MR (Magnetic Resonance) scans has been increasingly used for LV chamber volume computation.

One challenge in computing the LV chamber volumes using cine-MR images at all phases of the cardiac cycle is the estimation of the location of the aortic / mitral valve plane to isolate (or trim) the LV. This step is necessary as the cine-MR images include both the LV and the atrium / aorta regions. Currently, this identification is performed manually with guidance from the long-axis images. However, manual identification of the trimming planes for all frames in the scan is tedious and does not guarantee that the LV myocardium volume is kept constant. Furthermore, manual identification can often result in intra- / inter- observer discrepancies. Also, the task of identifying the valve plane is compounded in difficulty by the following issues: (i) shortening and twisting of the LV from ED to ES and (ii) large inter-slice distance of the short-axis images (typically about 8mm), possibly resulting in the valve plane not being captured on the cine-MR image. These difficulties can potentially lead to variations in the valve plane location, thereby leading to variations in the computed LV chamber volumes. In this study, we aim to develop an automatic algorithm to compute the LV volumetric changes during the cardiac cycle while ensuring constant myocardium volume based on the user-defined trimming value at ED.

The use of such an automatic and quantitative method of deriving LV chamber volumes can also potentially reduce intra- and inter-observer variation in *EF* computation.

2. Methods

The cine-MR scans of 8 healthy subjects are taken using a 1.5T Siemens scanner (Avanto, Siemens Medical Solutions, Erlangen). Three sets of images are taken, with the first set of images (short-axis) taken along the plane which pass through the mitral and aortic valves of the heart. The second set of images (angled-axis) are taken on planes orthogonal to the short-axis images, and oblique to each other, giving an angular cross sectional view of the LV. The last set of images is the vertical cross section (long-axis) orthogonal to and connecting with the short-axis plane images. The short- and long-axis views are taken at an interval of 8mm thickness. Each image has a spatial resolution of 1.5mm, acquired in a single breath hold, with 22 temporal frames per cardiac cycle. The borders representing the endocardial and epicardial surfaces of the LV are manually delineated from the cine-MR images for all 22 temporal frames.

2.1. Reconstruction of LV geometry from MRI

The manually delineated contours for the endocardial and epicardial LV surfaces are first used to generate a dense set of points to represent the LV geometry with guidance from the long-axis contours. The sets of contour points are then triangulated to form the LV geometry using an in-house meshing toolkit [5].

As the cine-MR scans capture the geometry of both the LV and the atrium / aorta regions (see Figure 1a), there is a need to trim these images based on the location of the aortic / mitral valve plane to compute the actual LV chamber volume. The location of this valve valve plane at ED is specified by the user and the LV geometry is trimmed based on this input (see Figure 1b).

2.2. Calculation of left ventricular chamber volume

The representation of the LV geometry as 3D meshes presents us with the convenience of calculating its volume by making use of only its vertex information. The general approach is to apply a series of mathematical operations to reduce the volume integral into integrals of lower-dimensions so that the volume can be calculated from the vertex coordinates of the mesh alone. In this regard, the divergence theorem [6] is use to reduce the volume integral to a sum of surface integrals over the individual faces of the LV mesh. These surface integrals are then further reduced to a sum of line integrals using Green's theorem [6]. Similar approach has been successfully employed to calculate mass parameters such as center of mass and inertia tensor [7].

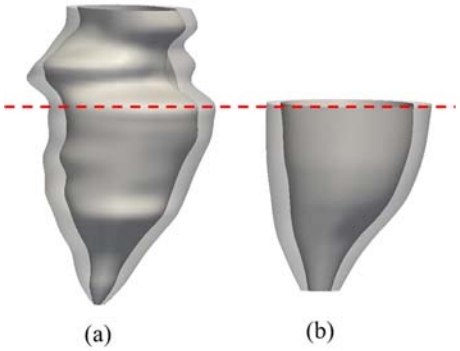

Figure 1. LV geometry reconstructed from cine-MR images at ED. (a) Untrimmed geometry of LV and atrium / aorta regions. (b) Trimmed geometry of LV only. The dotted red-line represents the aortic / mitral valve plane used for trimming.

Based on the method described above, the endocardial chamber volume V (the volume bounded by the endocardial surface of the LV) is given by:

$$V = \sum_{F \in \Omega} (y_1 - y_0)(z_2 - z_0) - (y_2 - y_0)(z_1 - z_0)(x_0 + x_1 + x_2), \quad (1)$$

where (x_0, y_0, z_0), (x_1, y_1, z_1) and (x_2, y_2, z_2) are the coordinates of the vertices of a face ϕ of the LV mesh Ω. Note that the convention of the face vertex ordering is taken in the counter-clockwise direction with the face normal pointing away from the LV chamber.

The LV myocardium volume is obtained by subtracting the volume enclosed by the endocardial surface from the volume bounded by the epicardial surface.

The *EF* of the LV is then defined as:

$$EF = \frac{V_{ED} - V_{ES}}{V_{ED}}, \quad (2)$$

where V_{ED} and V_{ES} is the endocardial chamber volume at ED and ES, respectively.

2.3. Calculation of trimming values at subsequent temporal frames

The myocardium volume at ED is computed based on the user-specified trimming value and used as a reference. For the remaining frames, an iterative Newton-Raphson-like trimming procedure is used to find the trimming plane such that the resulting myocardium volume is the same as the reference. The ES frame is determined as the frame with the smallest LV chamber volume.

Schematically, the workflow of our algorithm is as

follows:

(i) For the *i*th temporal frame, the trimming value at the *(i-1)*th frame is used as initial guess. A mesh splitting is performed using a plane-triangle splitting operation with local re-triangulation if the trimming plane does not coincide with the planes of the original surface contours

(ii) LV endocardial / epicardial chamber volumes and myocardium volume are computed using Equation (1) above.

(iii) Trimming plane is adjusted iteratively such that the myocardium volume at the *i*th frame is within a specified tolerance of the reference volume.

3. Results and discussion

ECG-gated cine-MR scans of 8 normal subjects were acquired and the LV chamber volume-time curves were computed based on our proposed algorithm. Table 1 summarized the results of our algorithm and compared the computed LV *EF* with the corresponding clinical *EF*. The mean *EF* computed using our algorithm is 62.4 ± 4.4% as compared to the mean clinical *EF* of 67.1 ± 6.2%. Individually, the computed *EF* from our algorithm is within a ±10% range of the clinical *EF* with the exception of C4. These results demonstrate that our algorithm can be used to determine the LV chamber volume at ES and the corresponding *EF* with reasonable accuracy.

and all subsequent frames are less than 0.5% (second last column in Table 1). This result shows that our automated trimming algorithm is successful in conserving the myocardium volume throughout the whole cardiac cycle.

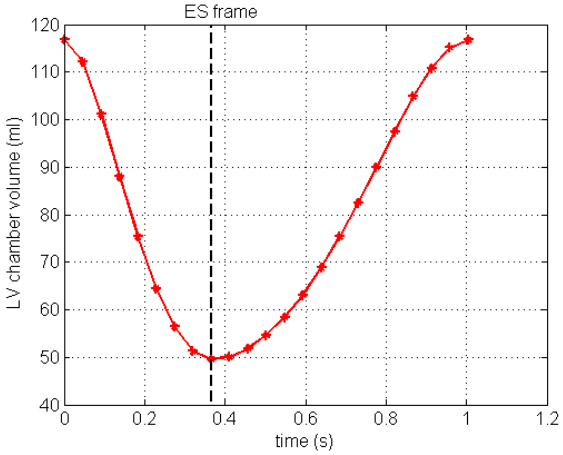

Figure 2. LV chamber volume-time curve for C1. The ED phase is at time t=0s.

A typical LV chamber volume-time curve for one of the healthy subject (C1) is plotted in Figure 2. From the figure, we can potentially compute quantitative information on the filling / pumping dynamics of the LV and provide clinicians with additional indices for both diagnosis and prognosis. Also, the volume-time curve can potentially be used to identify any possible dyssynchrony

Table 1. Comparison of LV *EF* computed using our automated trimming algorithm with the clinical *EF*. The mean myocardium volume difference between the ED frame and all subsequent frames are presented in the form of mean ± standard deviation. No clinical *EF* data was available for C3.

Healthy Group	Algo-derived		Clinical		Difference in *EF* (%)	Δ Myocardium volume (%)	
	EF (%)	ES Frame	*EF* (%)	ES Frame		Mean	Std
C1	57.6	9	61	9	-5.54	-0.10	0.07
C2	60.3	7	58	9	4.01	0.01	0.05
C3	56.3	9	NA	NA	NA	-0.09	0.07
C4	63.6	9	76	9	-16.36	0.28	0.17
C5	69.5	8	72	8	-3.47	0.33	0.25
C6	66.5	8	68	8	-2.17	0.29	0.21
C7	63.8	8	66	8	-3.38	0.24	0.20
C8	61.5	9	69	9	-10.93	0.15	0.12
Mean *EF* computed by averaging over the healthy group							
	62.4		67.1		-4.70		

In additional, we also noted that the ES frame as identified from our algorithm matches the clinical ES frame with the exception of C2. Also, the mean myocardium volume difference between the ED frame

of the global LV function by flagging out discrepancy between the clinically-identified ES frame (measured using ECG-gating) and the frame with smallest LV volume. This discrepancy may imply that there is a time-

lag between the mechanical pumping of the heart (as measured by the LV chamber volume) and the electrical signal. We can also incorporate this automated trimming algorithm into our approach for computing the regional *EF* of the LV [8]. Intraventricular dyssynchrony can then be evaluated by measuring the time-lag between the clinically-identified ES frame and the frames with the smallest chamber volume in all 16 LV regional segments.

3.1. Limitations

In our geometrical reconstruction process for the LV, we did not include the LV apex as it is difficult to determine the true apex position from the short-axis cine-MR scans. As such, the LV is truncated off at the most apical slice of the short-axis image. This can potentially result in some underestimation of the LV chamber volume and myocardium volume in our proposed algorithm. However, as the size of the truncated apical patch is relatively small as compared to the LV, we believe that any such underestimation in volume is negligible.

Another limitation of our approach is that the LV chamber and myocardium volumes are highly dependent on the input trimming value at the ED frame. Thus, the accuracy of our algorithm hinges on the ability of the user to accurately estimate the location of the aortic / mitral valve plane. It should be noted that our proposed algorithm is deterministic and the only variable to affect the volume results is the trimming value specified by the user at the ED frame.

4. Conclusion

We have developed an automatic and quantitative algorithm for deriving LV chamber volumes that can potentially reduce intra- and inter-observer variation in *EF* computation. Our proposed algorithm uses 4D LV geometries (i.e., spatial + time) reconstructed from border-delineated cine-MR images with automated trimming to compute the LV chamber volumes. The automated trimming is based on conserving the myocardium volume at all subsequent temporal frames given the reference volume at the ED frame. The only input to our algorithm is the trimming value at the ED frame and this can be estimated with reasonable accuracy. The *EF* computed using our approach agrees with the clinical *EF*. Furthermore, we also observed LV shortening which is consistent with expectation, and the ES frame identified by our algorithm also matched that identified clinically from ECG-gating.

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