Semi-Automated Quantification of Left Ventricular Volumes and Mass from Cardiac Magnetic Resonance Images by Level Set Models

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Abstract

Cardiac magnetic resonance imaging (CMRI) is the standard for estimates of LV volumes, ejection fraction and mass. These computations are based on extensive manual tracing of endocardial and epicardial borders and are subjective and time-consuming. We developed a new technique for semi-automated surface detection for the measurement of LV end-systolic and end-diastolic volumes, ejection fraction and mass from CMRI data. This procedure is performed in the 3D domain, and does not rely on geometrical approximations. Twenty-two consecutive patients referred for CMRI were studied. Measurements were compared with the values derived by manual tracing using linear regression and Bland-Altman analyses. For both volumes, ejection fraction and mass, the analysis resulted in high correlation coefficients and depicted no significant biases and narrow limits of agreement. The proposed technique is fast and objective and provides accurate measurements of LV volumes, ejection fraction and mass.

1. Introduction

Cardiac magnetic resonance imaging (CMRI) is the standard for left ventricular (LV) volume, ejection fraction (EF) and mass measurements [1-3]. However, LV volumes are obtained using semi-automated tracing of LV borders on multiple 2D slices and computations based on disk area summation approximation. This methodology is subjective and experience dependent. Moreover, the use of fixed slice thickness for disk summation in segments where the endocardium is not perpendicular to imaging planes and the use of fixed number of slices throughout the cardiac cycle without taking into account systolic longitudinal shortening, may bias volume measurements.

To overcome these limitations, we have developed a semi-automated volumetric surface detection (VoSD) algorithm, based on the level-set method [4-6], for rapid and objective quantification of LV volumes, EF and mass, without any geometric modeling and performed directly in the 3D domain. This study was designed to test the feasibility of applying this procedure to CMRI data and comparing the results with those obtained by conventional manual tracing of LV endocardial and epicardial boundaries.

2. Methods

2.1. Image acquisition

Twenty-two consecutive patients referred for CMRI studies to assess LV volumes, EF and mass were recruited into the study. MRI data were obtained with a 1.5 Tesla scanner (General Electric) with a phased-array cardiac coil. Electrocardiogram-gated localizing spin-echo sequences were used to identify the long-axis of the heart. Steady-state free precession (FIESTA) dynamic gradient-echo mode was used to acquire images during 12-second breath-holds. Cine-loops were obtained in 6 to 10 short-axis slices, from the atrioventricular ring to the apex (9 mm slice thickness, no gaps) with a temporal resolution of 20 frames per cardiac cycle.

2.2. Image analysis: Reference technique

Images were analyzed using the commercial software (General Electric, MASS Analysis). In every slice, LV endocardial contours were traced semi-automatically frame-by-frame, with the papillary muscles included in the LV cavity, and manually corrected when necessary to optimize boundary position. Then, ventricular volume was computed throughout the cardiac cycle using a disk-area summation method (modified Simpson's rule). End-diastolic (EDV) and end-systolic (ESV) volumes were determined as the maximum and minimum ventricular

cavity volume reached during the cardiac cycle, and used to compute the EF, as 100*(EDV-ESV)/EDV.

LV epicardial boundaries were then semi-automatically traced at end-diastole in each slice. LV mass was computed as the difference between end-diastolic epicardial and endocardial volumes times the mass density constant (1.05 g/cc). All tracings were performed by an experienced investigator.

2.3. Image analysis: VoSD technique

The MRI datasets were then analyzed using custom software, which allows semi-automated ventricular surface detection by the level set approach [4-6]. This method uses an implicit representation of curves in the form of a partial differential equation to track boundaries, without geometrical assumptions or a-priori shape knowledge.

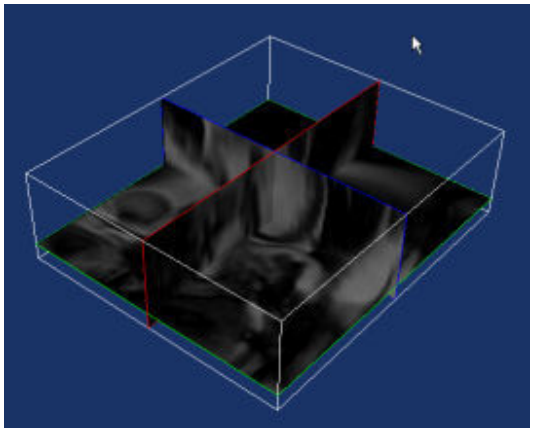

Figure 1. 3D reconstruction and visualization of a CMRI dataset in a compact orthogonal view.

First, an automated 3D reconstruction of the multiple short-axis slices was performed. For each frame, a 3D dataset was generated by trilinear interpolation (Figure 1), considering the slice thickness, the spacing between slices and the number of the acquired slices. This resulted in a dynamic representation of the LV cavity, from which end-diastolic and end-systolic frames visually determined as the largest and smallest LV cavities in 3D space, were selected for the analysis.

Then, endocardial surface detection was performed starting with surface initialization. A small number of short-axis planes (4 to 6) from apex to base were selected in the 3D dataset. , In each of these planes, a number of points was manually set to initialize the endocardial surface. To be consistent with manual tracings, papillary muscles were included in the ventricular cavity. The selected points were connected to define a surface, representing the initial condition for the partial differential equation (Figure 2, top). This partial differential equation was used to guide the evolution of this initial surface towards the endocardial boundaries (Figure 2, bottom). From the final surface the ventricular volume was measured as voxel count.

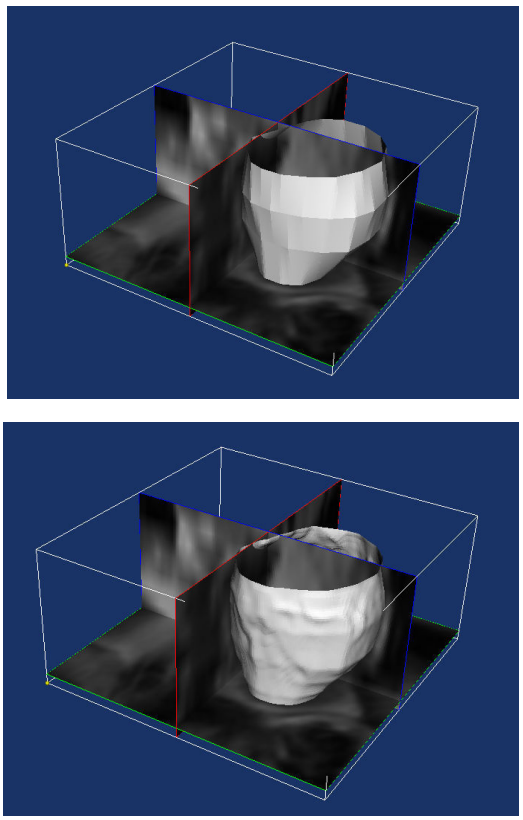

Figure 2. Initial endocardial surface for the evolution process (top) and final detected surface (bottom).

Following the same detection procedure, including the initialization of points of a small number of points, the epicardial surface was detected at end-diastole. LV mass was computed as the difference between epicardial and endocardial volumes times the mass density constant (1.05 g/cc).

A visualization procedure, based on superimposition of the extracted surfaces on the original data, allowed the operator to verify the reliability of the detection (Figure 3) and correct the position of initialized points if necessary. Volume was automatically recalculated when surface correction was performed, until optimal surface position was confirmed.

For each patient, measurements were compared with the values derived from the manual tracing using linear regression and Bland-Altman [7] analyses. Paired t-test versus null values was applied to verify the significance of the bias.

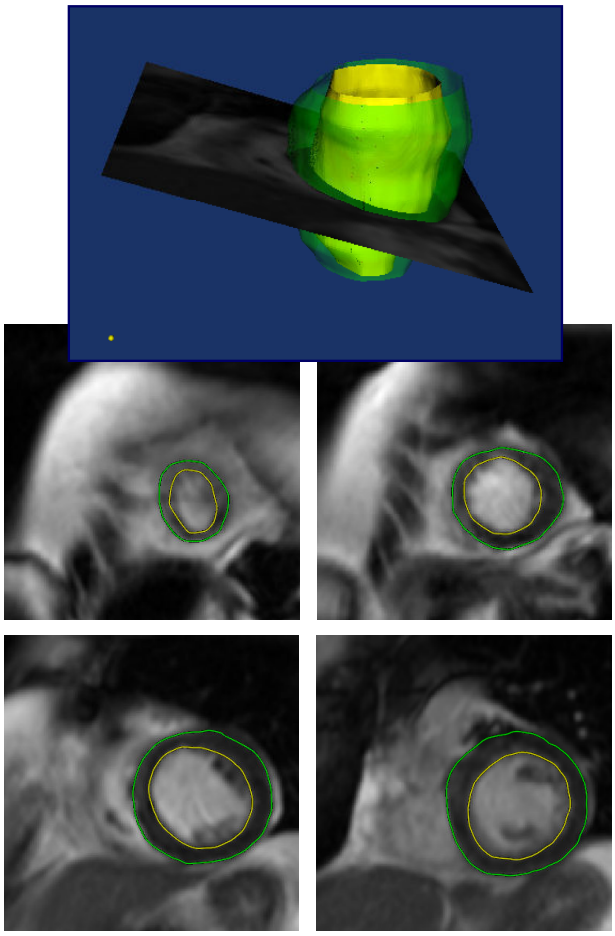

Figure 3. Endocardial and epicardial contours superimposed on the corresponding slice of the 3D dataset.

3. Results

End-diastolic and end-systolic volumes measured from conventional manual tracing ranged from 78 to 345 ml and from 24 to 280 ml, respectively. EF ranged from 19 to 71 % and mass from 57 to 245 g.

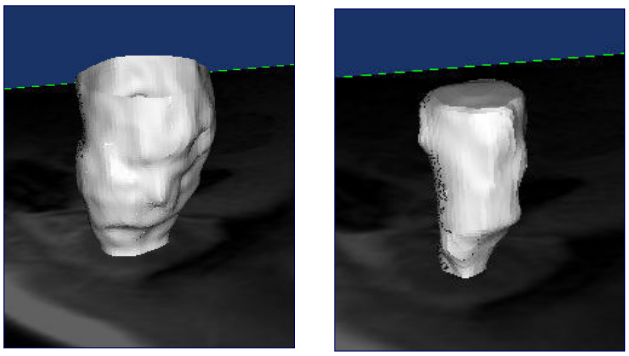

Figure 4. Endocardial surface detected in one patient at end-diastole (left) and at end-systole (right).

The analysis of a single dataset, including data retrieval, frame selection, surfaces initialization, computation of volumes and mass was completed in every one of the patients in less than 5 minutes on a personal computer (Pentium II, 755MHz, 512Mb RAM).

An example of the detected endocardial surfaces obtained in one patient at end-diastole and end-systole is shown in Figure 4.

Linear regression analysis (Figure 5) between the semi-automatically derived and the manually obtained volumes resulted in high correlation coefficients for both volumes (EDV: r=0.95, SEE=18ml, y=0.92x+13.3; ESV: r=0.98, SEE=10ml, y=1.06x-1.7). Excellent correlations were observed also for ejection fraction (EF: r=0.96, SEE=5%, y=1.12x-6.6) and mass (r=0.98, SEE=14g, y=0.98x+4.5).

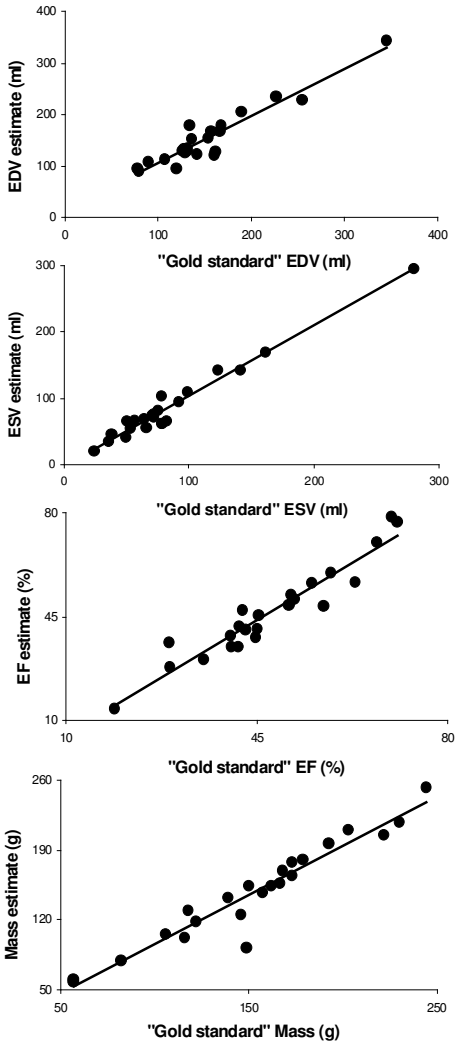

Figure 5. Linear regression analysis for EDV, ESV, EF and mass obtained by the VoSD compared to manual tracing.

Bland-Altman analysis (Figure 6) showed no significant biases and narrow limits of agreement for EDV, ESV and EF (bias: 1.84 ml; 3.4 ml and -1.1%, respectively; SD: 19 ml, 11 ml and 4.7%, respectively), as well as LV mass (bias: -4.8 g; SD: 14.6 g).

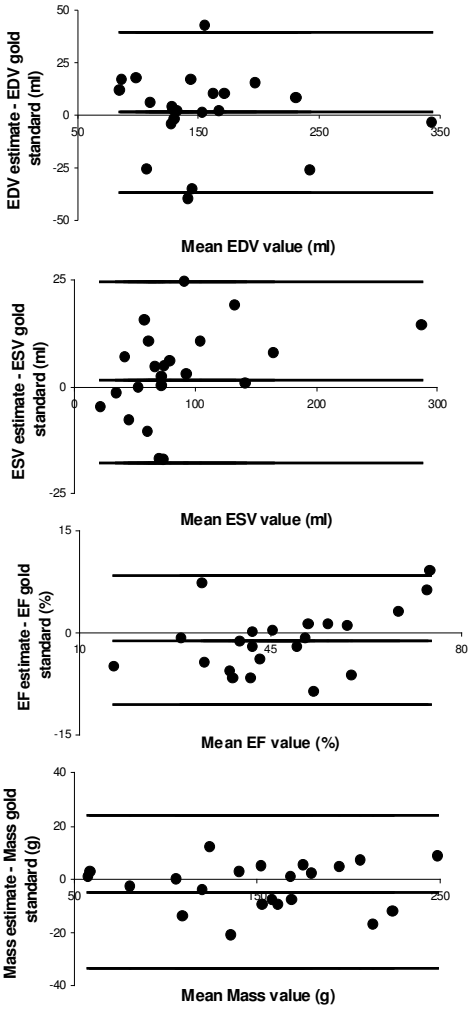

Figure 6. Bland-Altman analysis for EDV, ESV, EF and mass obtained by the VoSD compared to manual tracing.

4. Discussion and conclusions

CMRI provides accurate measurements of LV volumes and mass in different patient populations [1-3]. Nevertheless, the quantification of volumes is based on time-consuming manual or semi-automated tracing of endo- and epicardial boundaries in multiple slices. The subjective nature of this procedure limits the reproducibility of volume measurements [3]. Additionally, the use of disk approximation in slices where the endocardium is not perpendicular to imaging planes may introduce errors that are more significant when slices are thick relative to the LV cavity cross-sectional area. Moreover, volume measurements may also be biased by the use of a fixed number of slices of fixed thickness throughout the cardiac cycle, in slices where endocardial motion is not limited to the imaging plane. This is because during different phases of the cardiac cycle, a fixed plane contains different slices of the ventricle, rather than reflects the true endocardial motion in a single anatomic slice.

The technique we developed overcomes these limitations by directly calculating LV volumes from endo- and epicardial surfaces detected in the 3D space without any a priori shape knowledge and without the use of geometric modeling. Therefore, this procedure is likely to be even more accurate, and as a result more reproducible, than the conventional technique.

In summary, this study indicates that the proposed method allows rapid and accurate measurements of left ventricular volumes, EF and mass from CMRI data, in agreement with conventional manual tracing, with the advantage of being independent of geometrical assumptions or modeling.

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