Improved Quantification of Right Ventricular Volumes from Cardiac Magnetic Resonance Data

C Corsi[1], EG Caiani[2], O Catalano[3], S Antonaci[3],
F Veronesi[1,2], A Sarti[1], C Lamberti[1]

[1]Department of Electronics, Computer Science and Systems, University of Bologna, Italy
[2]Biomedical Engineering Department, Polytechnic of Milan, Italy
[3]Rehabilitative Cardiology Department, Salvatore Maugeri Foundation, Pavia, Italy

Abstract

Right ventricular (RV) volume quantification from cardiac magnetic resonance imaging is based on manual tracing of endocardial boundaries and application of geometric modeling. This procedure is subjective, time-consuming and may bias volume measurements since the right ventricle is a complex structure that is not well suited to a geometric model. We developed a technique for RV endocardial surface detection and direct volumes and ejection fraction (EF) quantification. Our technique was validated against conventional manual tracing and intra- and inter-observer variability were computed to test its reproducibility. Volumes and EF measurements showed high correlations with no significant biases and narrow limits of agreement compared to values derived from manual tracing. Intra- and inter-observer variability were smaller for the proposed method with respect to the reference technique. Our method resulted in fast, reliable and more reproducible measurements of RV volumes and EF when compared to conventional manual tracing.

1. Introduction

The prognostic impact of right ventricular (RV) function has become of interest in many cardiac pathologies underlining the need for accurate imaging modalities of the right ventricle [1]. However, the assessment of RV mass, volumes and function by standard invasive or non-invasive imaging techniques is limited by the complex 3D shape of the RV, especially in patients with deformed or dilated RV. Cardiac magnetic resonance imaging (CMRI) is commonly used for the anatomic and functional assessment of the heart. Nevertheless, while its accuracy and reproducibility have been widely demonstrated for the LV measurements [2,3], few studies have assessed the in vivo validity and reproducibility of the RV dimensions and function using routine CMRI methods [4-6]. In clinical practice, quantification of RV volumes and EF is obtained by manually tracing RV endocardial boundaries on multiple short-axis planes and volume computations are based on disk area summation approximation. This procedure is subjective and experience-dependent and has limited reproducibility with suboptimal quality images. In addition, 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 may bias volume measurements.

We developed a technique for RV endocardial surface detection from CMRI, from which RV volumes can be measured directly with minimal user interaction and no need for geometric modeling. This study was designed to test the hypothesis that this volumetric technique could provide accurate and more reproducible RV volume estimates than the conventional methodology.

2. Methods

Twenty consecutive patients (20♂, age: 47±12 years) referred for CMRI studies were recruited into the study. Exclusion criteria were dyspnea precluding a 12 seconds breath-hold, atrial fibrillation, pacemaker or defibrillator implantation, claustrophobia, cardiac arrhythmia, and prior sternotomy.

CMRI data were obtained using a 1.0 Tesla scanner (Magnetom, Siemens) 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 (TrueFISP) dynamic gradient-echo mode was then 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 (10 mm slice thickness, no gaps) with a temporal resolution of 37 msec per frame.

Images were analyzed on a Sun workstation using commercial software (Argus, Siemens). Initially, RV slices were selected for analysis beginning with the highest basal slice, in which the outflow chamber of right ventricle was still visible, and ending with the lowest

0276−6547/05 $20.00 © 2005 IEEE

Computers in Cardiology 2005;32:37−40.

apical slice, in which the right ventricular cavity was visualized. The frames visually showing maximal and minimal right ventricular cross-sectional areas at the mid-ventricular level were considered as end-diastole and end-systole. For these two frames, in every slice, RV contours were traced semi-automatically, with the outflow tract and the trabeculae included in the right ventricular cavity, and manually corrected to optimize boundary position. Then, end-diastolic and end-systolic RV volumes (EDV and ESV, respectively) were computed using a disk-area summation method (modified Simpson's rule). These RV volumes were used to compute the EF as 100*(EDV-ESV)/EDV.

The CMRI datasets were then analyzed using custom software [7], which allows ventricular surface detection using the level set approach [8-9]. First, a fully automated frame-by-frame 3D reconstruction of the volumetric data was performed from the short-axis slices (figure 1). For each frame, a 3D dataset was generated using trilinear interpolation, while taking into account slice thickness, the number of slices and the spacing between them. This resulted in a dynamic representation of the entire heart. This dynamic display was used to select end-diastolic and end-systolic frames, which were visually determined as the largest and smallest RV cavities in the 3D space. Subsequently, semi-automated endocardial surface detection was performed separately for the end-diastolic and end-systolic frames. For surface initialization, a small number of short-axis planes (4 to 6) from apex to base was arbitrarily selected from the 3D dataset, and few points (6 to 12) were manually selected in each of these planes (figure 2A). To be consistent with the reference technique, the trabeculae carneae were included within the RV. The selected points were connected by straight lines from which a rough surface corresponding to the endocardium was computed using linear interpolation

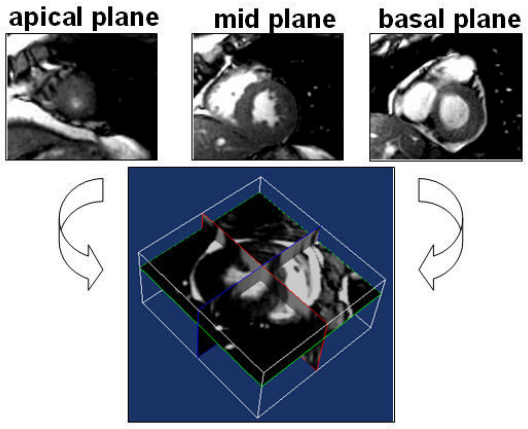

Figure 1. 3D reconstruction and display of a CMRI dataset.

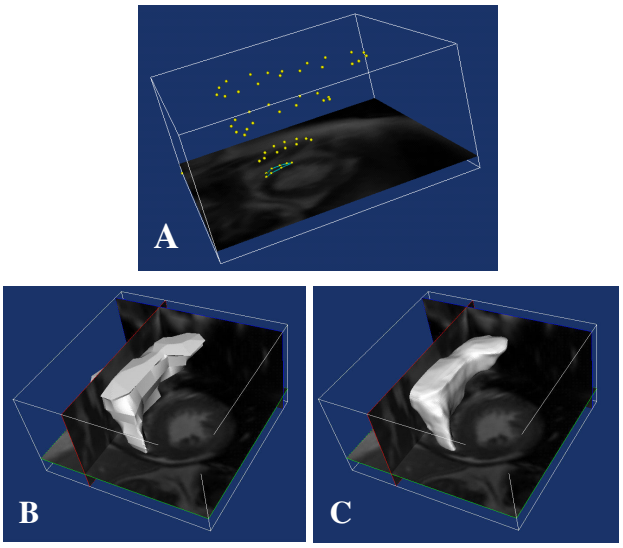

Figure 2. Procedure for volumetric detection of the RV endocardium surface.

(figure 2B). This surface was then used as the initial condition for the level-set partial differential equation, which guided the evolution of this surface within the volumetric dataset towards the endocardium. When the solution of the differential equation converged, the resultant final surface was used to represent the endocardium (figure 2C), and RV volume was calculated as the number of voxels within the detected surface. In addition, EF was calculated from EDV and ESV according to the same formula used for the reference technique.

All tracings were performed by experienced investigators blinded to all prior measurements.

To establish the accuracy of the volumetric technique, the results obtained applying our procedure and the conventional technique were compared using linear regression and Bland-Altman analyses. Paired t-test versus null values was applied to verify the significance of the bias. In a subgroup of ten patients, all measurements were repeated twice to assess the reproducibility of both techniques by calculating their intra- and inter-observer variability. For each technique and for each measured parameter, the intra-observer variability was studied by blindly reanalyzing the datasets by the same investigator at least one week later, and the inter-observer variability was studied by blindly reanalyzing the datasets by a second investigator. In both cases, variability index was calculated as the difference between repeated measurements in percent of their mean. For both inter- and intra-observer variability of each parameter, paired t-test was used to test the significance of the differences between the two techniques.

3. Results

Time required to analyze a single time frame, including data retrieval, surfaces detection and computation of volumes and ejection fraction was approximately 5 minutes on a personal computer (Pentium II, 755MHz, 512Mb RAM).

Superimposing of the detected RV endocardial surfaces on the volumetric data allowed verification of the correctness of the detection in any arbitrary cross-sectional plane (figure 3).

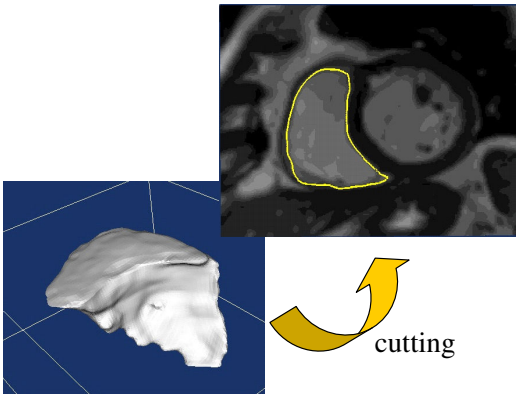

Figure 3. Verification of the correctness of the extracted surface in any arbitrary cross-sectional plane, superimposed to the anatomical data.

Semi-automated measurements showed high correlations with manual values both in EDV, ESV and EF, as shown in figure 4, top panels. All parameters resulted in non significant biases and narrow limits of agreement compared to the gold standard (figure 4, bottom panels).

Intra- and inter-observer variability ranged from 6% to 14% and from 7% to 14%, respectively, for the manual tracings and only from 2% to 4% and from 6% to 11%, respectively, for the proposed method (figure 5).

4. Discussion and conclusions

CMRI provides accurate measurements of RV volumes and EF, nevertheless the quantification of volumes is based on time-consuming manual tracing of endocardial boundaries in multiple slices. The subjective nature of this procedure limits the reproducibility of volume measurements and the use of disk approximation in slices where the endocardium is not perpendicular to the imaging plane may introduce errors that are more significant when slices are thick relative to the RV 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.

The proposed volumetric technique overcomes these limitations by directly calculating RV volumes from surfaces detected in 3D space without any a priori knowledge of the RV shape and without the use of geometric modeling.

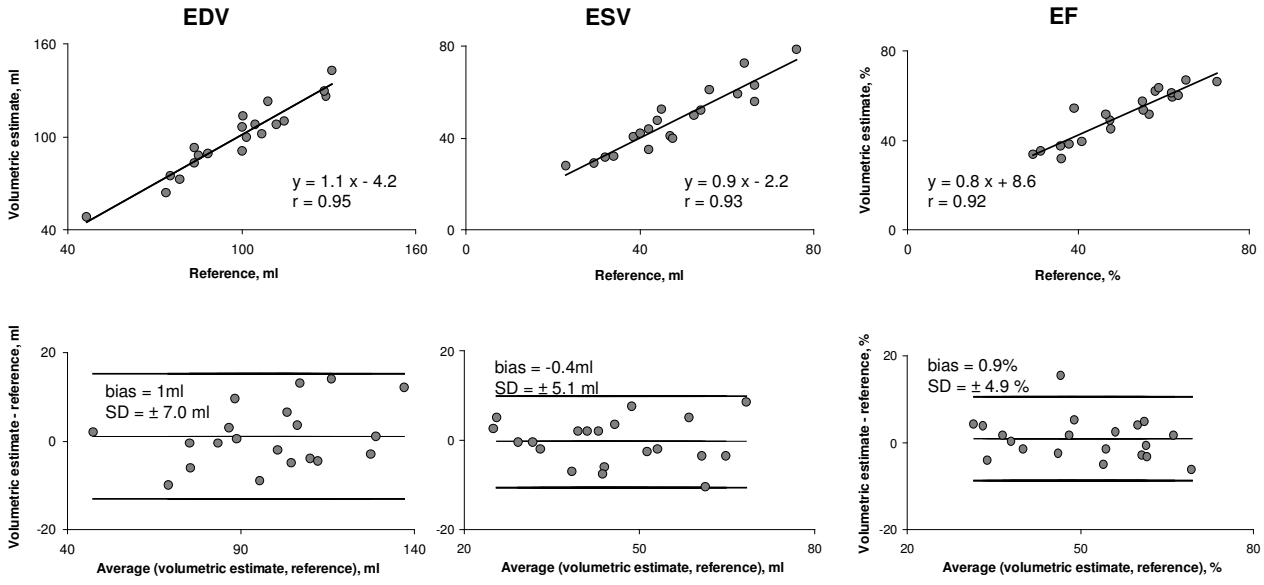

Figure 4. Linear regression and Bland-Altmann analyses between measurements of EDV, ESV and EF obtained with the volumetric analysis and the reference technique .

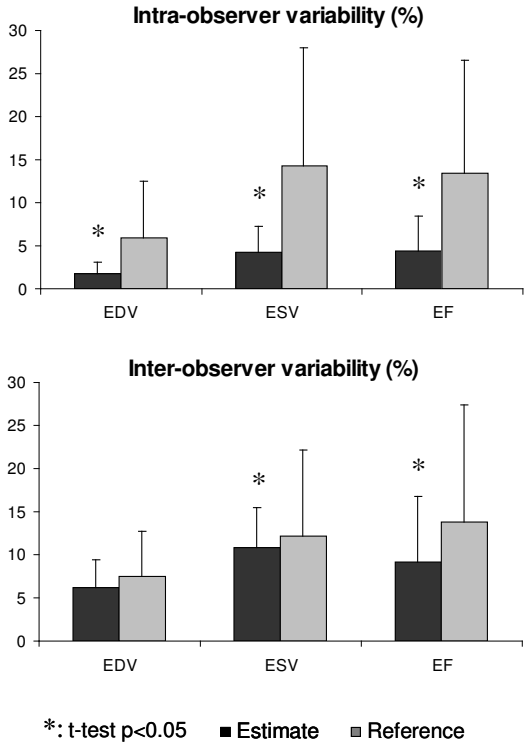

Figure 5. Intra-observer (top) and inter-observer (down) variability of the volumetric technique and the standard reference technique for RV EDV, ESV and EF.

Despite these advantages the volumetric technique still requires manual initialization of endocardial surfaces and the subjective nature of this initialization accounts for the non-zero inter-measurement variability. In addition, our technique was not tested in different specific patient populations. However our goal of testing the feasibility and validating it in a wide range of conditions was achieved by enrolling unselected patients representing a variety of cardiac disease states.

Our results showed that volumetric analysis of CMRI data based on direct detection of endocardial RV surfaces allows fast and reliable quantification of RV volumes and EF without geometric approximations and modeling. The accuracy of this technique was demonstrated by the excellent agreement with the conventional methodology and the smaller intra- and inter-observer variability compared to manual tracings. This demonstrated that the proposed procedure is more reproducible than the standard reference technique.

In conclusion, the proposed volumetric semi-automatic method resulted in accurate detection of RV endocardial surfaces, which lead to fast, reliable and more reproducible measurements of RV volumes and EF when compared to conventional manual tracing.

References

[1] Bleasdale RA, Frenneaux MP. Prognostic importance of right ventricular dysfunction. Heart 2002; 88: 323–324.

[2] Myerson SG, Bellenger NG, Pennell DJ. Assessment of left ventricular mass by cardiovascular magnetic resonance. Hypertension 2002; 39: 750–795.

[3] Moon JC, Lorenz CH, Francis JM, Smith GC, Pennell DJ. Breath-hold FLASH and FISP cardiovascular MR imaging: left ventricular volume differences and reproducibility. Radiology 2002; 223: 789–797.

[4] Grothues F, Moon JC, Bellenger NG, Smith GS, Klein HU, Pennell DJ. Interstudy reproducibility of right ventricular volumes, function, and mass with cardiovascular magnetic resonance. Am Heart J 2004; 147:218–223.

[5] Pattynama PM, Lamb HJ, Van der Velde EA, van der Geest RJ, van der Wall EE, De Roos A. Reproducibility of MRI-derived measurements of RV volumes and myocardial mass. Magn Reson Imaging 1995; 13:53–63.

[6] Beygui F, Furber A, Delepine S, Helft G, Metzger JP, Geslin P, Le Jeune JJ.Routine breath-hold gradient echo MRI-derived right ventricular mass, volumes and function: accuracy, reproducibility and coherence study. Int J Cardiovasc Imaging. 2004 Dec;20(6):509-16.

[7] Corsi C, Lamberti C, Catalano O, MacEneaney P, Bardo D, Lang RM, Caiani EG, Mor-Avi V. Improved quantification of left ventricular volumes and mass based on endocardial and epicardial surface detection from cardiac MR images using level set models, Journal of Cardiovascular Magnetic Resonance, 2005; 7(3):595-602.

[8] Malladi R, Sethian JA, Vemuri BC. Shape modeling with front propagation - A level set approach. Ieee Transactions on Pattern Analysis and Machine Intelligence 1995; 17:158-75.

[9] Sarti A, Mikula K, Sgallari F, Lamberti C. Evolutionary partial differential equations for biomedical image processing. J Biomed Inform 2002; 35(2):77-91.

Address for correspondence

Claudio Lamberti
DEIS – University of Bologna
Viale Risorgimento 2, 40136 Bologna, Italy
clamberti@deis.unibo.it