

A Nearly-Automated Approach for Left Ventricular Segmentation using Feature Asymmetry from Real-time 3D Echocardiography

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Abstract

Quantification of left ventricular (LV) function from real-time 3D echocardiography has already been proved to be more accurate compared to LV function derived from 2D echocardiographic imaging. However, tools available in clinical practice depend on cardiologist's experience in selecting the correct views for volume computation, tracing endocardial contours or selecting some feature points. The aim of this study was to develop a new LV segmentation algorithm driven by feature asymmetry (FA) information. The proposed approach was based on a 3D modified Malladi-Sethian level-set model, driven by FA as an edge indicator, followed by a curvature flow and isosurface extraction. It was tested and validated on 3D echo data made available for the challenge on endocardial 3D ultrasound segmentation, organized during MICCAI 2014, in 9 patients, by correlation and Bland-Altman analysis for end-diastolic and end-systolic volumes and ejection fraction. LV surfaces were compared by means of absolute and Hausdorff distance and Dice coefficient. Clinical indexes derived from the detected surfaces were in good agreement with the reference ones. These promising results were supported by the results obtained by comparing LV surfaces. This study provides the basis for a fast and accurate quantification of cardiac function from real-time 3D echocardiography.

1. Introduction

Ultrasound imaging is the technique of choice for diagnosis and monitoring of cardiac diseases [1,2].

Real-time three-dimensional echocardiography (RT3DE) has already been proved to be an accurate tool for cardiac function quantification, representing a significant step forward for left ventricular morphology and function quantification. It allows truly volumetric acquisition of the cardiac chambers avoiding limitations intrinsically associated to 2D imaging such as out of plane motion, foreshortening and geometric assumptions for volume estimation.

Unfortunately RT3DE suffers from low spatial and temporal resolution, as well as the potential presence of motions artefacts. Consequently commercial tools towards LV segmentation require some degrees of manual interaction. The user usually needs to interact, in the initialization phase or after segmentation is performed, to manually correct detected LV surfaces. Depending on the tool utilized, the cardiologist needs to select the correct views for volume computation, some feature points, or to manually trace endocardial contours on 2-chamber and 4-chamber views. These tasks rely on the cardiologist's experience, are cumbersome and time-consuming and may affect the values of cardiac indexes resulting from the analysis.

Thus, several methods have been proposed to perform fully automatic segmentation of the LV chamber in RT3DE. Automated segmentation techniques based on image intensity usually fail due to the presence of speckle noise and low contrast in echocardiographic data [3].

In order to overcome these limitations, in this study we present a new highly-automated algorithm driven by feature asymmetry (FA) information aimed at LV segmentation from RT3DE.

2. Methods

2.1. RT3DE imaging and population

Three-dimensional echocardiographic data were obtained from a repository available online for the challenge on endocardial 3D ultrasound segmentation (CETUS), organized during MICCAI 2014. This database includes data acquired using different ultrasound systems together with the reference measurements (end-diastolic and end-systolic surfaces and the corresponding volumes - EDV, ESV, respectively). Reference measurements were obtained by manual tracing performed by three expert cardiologists, using an in-house developed software package (Speqle_3D, University of Leuven, Belgium). LV trabeculations and papillary muscles were included within the left ventricle cavity, according to the American Society of Echocardiography guidelines [4].

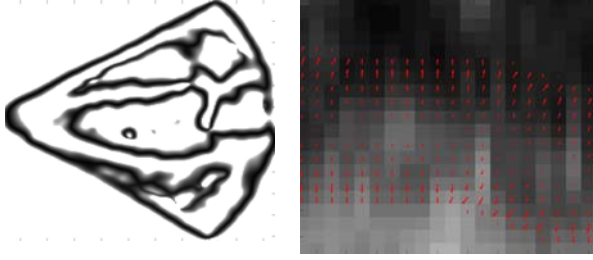


Figure 1. Left panel: example of the FA based edge indicator; right panel: zoom of the vector field computed as the gradient of the edge indicator, pointing towards the edges of the data.

2.2. Image analysis

The first step of the RT3DE processing procedure is the computation of the monogenic signal, by using a set of band-pass filters, one even filter for the real part of the monogenic signal, and three odd filters for the three components of the Riesz Transform in the 3D domain at different scales (s) [5].

$$H_1 = i \frac{u_1}{\sqrt{u_1^2 + u_2^2 + u_3^2}}; \quad H_2 = i \frac{u_2}{\sqrt{u_1^2 + u_2^2 + u_3^2}};$$

$$H_3 = i \frac{u_3}{\sqrt{u_1^2 + u_2^2 + u_3^2}};$$

$$c = n_c r^\alpha e^{-sr}$$

$$f_M(x, y, z, s) = (c * f, c * \mathbf{h} * f) = (c * f, c * f_R)$$

Starting from the monogenic signal, feature asymmetry (FA) is computed as:

$$FA_s = \frac{|odd_s - even_s - T_s|}{\sqrt{odd_s^2 + even_s^2 + \varepsilon}}$$

$$T_s = \frac{1}{V} \sum_V \log(|odd^2| + even^2)$$

FA contains the structural information of the signal, which is independent from its local energy [6].

To perform LV segmentation we apply a modified version of the Malladi-Sethian algorithm [7].

Instead of using an edge indicator based on the modulus of the intensity gradient of the image we use the phase information contained in the FA measurement as proposed by Wang [6]:

$$g = 1 - FA^\alpha$$

The level-set method implicitly defines a function

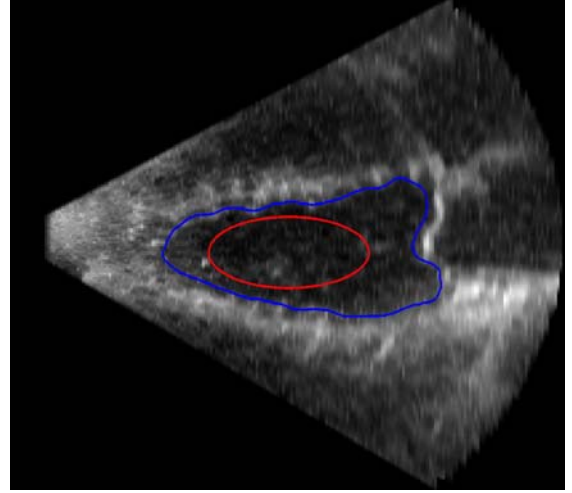


Figure 2. Example of initial condition setting for the LV segmentation procedure; in red the initial ellipsoid automatically derived from a manually selected point inside the LV chamber, in blue and the final result.

$\phi(x, y, z, t)$ whose zero level $\phi(x, y, z, t) = 0$ is the iper-surface to be guided by the level-set function evolution driven by the following partial differential equation:

$$\frac{d\phi}{dt} = \left[\lambda g K + \nu g + \mu \nabla g \cdot \frac{\nabla \phi}{|\nabla \phi|} \right] |\nabla \phi|$$

λ, ν, μ are three constants that weigh the three term.

The first term is a curvature flow aimed at surface regularization. The second term is a free expansion term weighted by the edge indicator; this term moves the surface until it reaches an edge, where the value of the edge indicator goes to 0. The third term is an advection term, driven by the vector field defined by the gradient of the edge indicator; it points towards data edges allowing the evolving surface to be attracted by them (Figure 1). When the three terms balance and convergence is reached, we extracted the zero level isosurface representing the LV surface.

The algorithm requires the user input for the initialization of the modified Malladi-Sethian edge-based level-set evolution. The user selects a point inside the LV chamber and an ellipsoid is automatically defined by exploiting gray level intensity information of the image along three orthogonal direction starting from the selected point, to compute the lengths of the ellipsoid axes (Figure 2).

In addition, to avoid the leakage of the surface out of the LV chamber through the mitral valve when it is open, the user needs to choose two points on the leaflet junctions on the four-chamber view, and then two additional points on a plane orthogonal to the segment

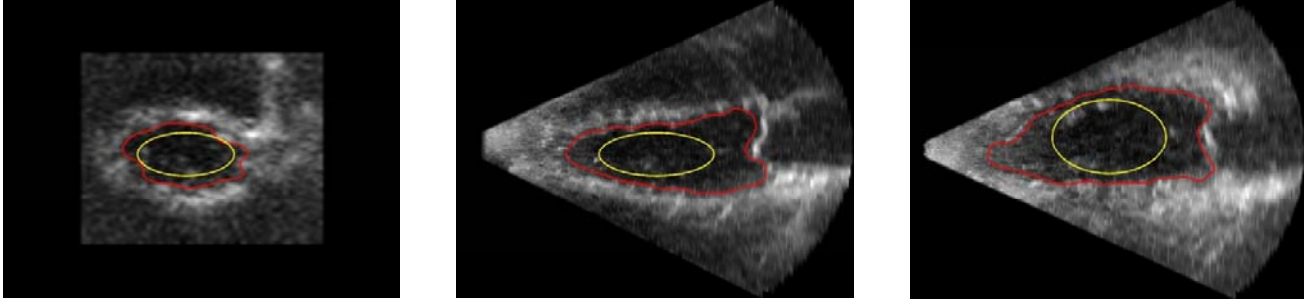


Figure 3. Example of the initial surface (in yellow) and of the final result of the LV segmentation (in red) on three orthogonal planes of the volumetric data.

connecting the previous two points, passing through the midpoint of the segment. Given these four points the algorithm finds the valvular plane by means of the method of least squares.

2.3. Statistical analysis

Statistical analysis is performed using the online platform MIDAS and Microsoft Excel. Correlation and Bland-Altman analysis are computed for EDV, ESV and ejection fraction (EF). LV surfaces are compared by mean absolute distance (MAD), Hausdorff distance (HD) and Dice coefficient (D) defined as in the following:

$$MAD = \frac{1}{2} [d(S, S_{ref}) + d(S, S_{ref})]$$

$$H_D = \max \{d(S, S_{ref}), d(S, S_{ref})\}$$

$$D = 2 \frac{(V \cap V_{ref})}{V + V_{ref}}$$

where S is the detected surface, S_{ref} the reference surface, V and V_{ref} the corresponding volumetric regions.

3. Results

Time required for the segmentation of a RT3DE volume depends on its size and on LV morphology. Average time, considering a cube of 200 voxel side, is about six minute.

Figure 3 shows an example the results along different planes of the segmentation of the LV with papillary muscles and trabeculae included in the detected surface.

A volumetric example of the detected surfaces compared to the reference surfaces at ED and ES in one patient is shown in Figure 4.

Linear regression analysis between the proposed algorithm and manually traced reference for the EDV and ESV values showed very good correlation coefficients and regression slopes (EDV: $y=0.9x-13.2$; $r=0.98$; ESV: $y=0.9x-10.4$; $r=0.99$; EF: $y=0.8x+5.9$; $r=0.94$). Bland-Altman analysis showed biases between the automated

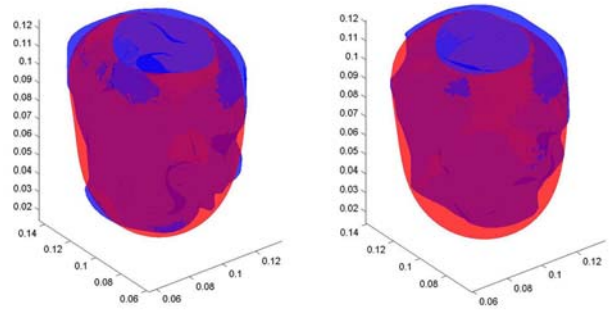


Figure 4. Example of detected surfaces (in blue) compared to the reference surfaces (in red) at ED (left panel) and ES (right panel).

measurements and the manual reference technique for EDV and ESV (EDV: bias: 36.2 ml, SD=20.9 ml; ESV: bias=25.3 ml, SD=13.9 ml; EF: bias= -1.2%, SD=5.2%).

Mean error measurements between the detected surfaces and the manually traced references confirm the previous results (MAD=2.58 mm; $D=0.88 \pm 0.028$; $HD=11.9 \pm 2.15$ mm).

4. Discussion and conclusion

RT3DE is going to become the technique of choice for fast, non-invasive, precise measurements of ventricular volumes and assessment of cardiac function. The availability of automatic or nearly-automated tools for accurate detection of LV surfaces from which accurate clinical indexes could be estimated, is essential to allow the widespread of volumetric echocardiographic systems.

In clinical practice, the analysis of LV volumes is still performed by manually tracing LV endocardial contours frame-by-frame and by the application of geometric modeling; consequently derived clinical parameters are affected by not negligible intra and inter-variability.

Recently several approaches have been proposed for LV segmentation from RT3DE data (<http://www.creatis.insa-lyon.fr/Challenge/CETUS/index.html>) with encouraging results.

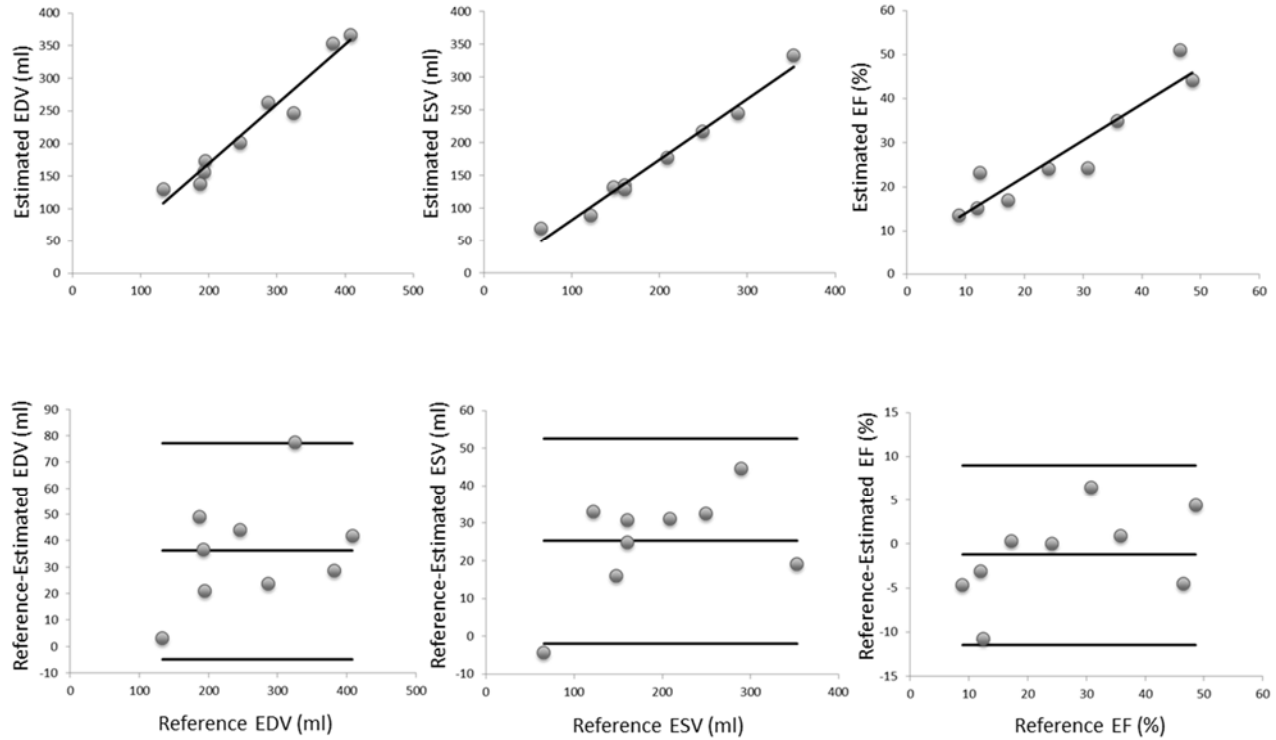


Figure 5. Linear regression (top panels) and Bland-Altman analysis (bottom panels) between estimated and reference values of EDV, ESV and EF (left, middle and right panels, respectively).

The proposed technique can be listed between them, considering the comparable results. In our method we exploit phase information, which gives better results compared to gradient intensity based methods. The proposed method is nearly-automated and the initialization step only requires the selection of one point inside the LV chamber and the computation of the valvular plane to constrain surface evolution.

The results of this study showed that the proposed technique is accurate compared to the standard reference methodology but further testing in larger groups of patients is necessary. If verified by further validation studies, this analysis holds promise for clinical applications.

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