

Estimation of Right Ventricular Volume, Quantitative Assessment of Wall Motion and Trabeculae Mass in Arrhythmogenic Right Ventricular Dysplasia

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Abstract

The aim of this study was to gain a wide perspective of the arrhythmogenic right ventricular dysplasia (ARVD) by developing algorithms for Cardiac Magnetic Resonance Imaging. We developed a semi-automatic procedure to assess the Right Ventricle (RV) volumes and to quantify RV wall motion; moreover, with the increased visible details in a single MR image, a manual method to evaluate the trabeculae mass was performed. All the algorithms used were based on the level set theory which allows detecting both endocardial and wall surfaces, as well as the black parts characterizing the trabeculae. 6 normal subjects and 6 subjects with ARVD have been investigated. Our method and the standard manual method for volume estimation were significantly correlated ($y=0.92x+6.56$), ($r=0.92$ $p<0.001$). Wall Motion results showed a significant reduction of RV segmental function in patients with ARVD, Inferior Wall was the most involved with more than 80% reduction ($p<0.001$) compared with normal subjects, while RV outflow tract (RVOT) was the least involved with less than 50% reduction ($p<0.001$) compared to normal subjects. A repeatability test was executed on trabeculae mass assessment, which showed a high intra observer correlation, in fact the results were significant at 95% of the cases.

1. Introduction

Cardiac MRI is a non invasive imaging modality which can be perfectly customized for each patient; furthermore with the increased time and spatial resolutions, it provides good images for a complete overview of the right ventricle (RV) [1]. In fact it allows an anatomic, functional and morphologic approach, so that it is possible to detect several disorders despite the complex crescent shape of the RV. Cardiac MRI is now becoming the most valid imaging technique to diagnose arrhythmogenic right ventricular dysplasia (ARVD). ARVD is a progressive disease leading to right ventricular failure and several dysfunctions. In early

stages, the dysfunctions may be subtle and the diagnosis is quite difficult. On the contrary, in advanced stages, RV enlargement may be evident as well as various clear clinical signs [2]. It is important to suspect any disorder in the early stages since sudden death can occur, especially in the subjects who present premature ventricular complexes or ventricular tachycardia originating from the RV, particularly when the ϵ wave is present. Nowadays Cardiac MRI is the gold standard for assessing RV volume since the estimation is perfectly carried out by many tools which require a manual contour tracing, even if it cannot be standardized. The wall motion analysis, which is very important in the early stages, is still assessed visually and as a consequence is performed only qualitatively so that even experienced operators can miss subtle abnormalities [3]. Recently with the improved MRI techniques, more details are visible on a single image; therefore it is possible to detect both papillary muscles and trabeculae. Those little parts are suspected to become hypertrophied in case of ARVD [4]. In this study we applied level set techniques in order to segment RV in short axis view utilizing Matlab. We implemented a tool that performs a semi-automatic RV volume estimation without geometrical assumptions. We also performed a quantitative wall motion estimation that could distinguish normal subjects from ARVD patients by classifying each wall as Normokinetic, Dyskinetic or Akinetic. Moreover, a manual method to assess trabeculae mass was developed with the intention to demonstrate the feasibility.

2. Method

Our method for assessing RV volumes is based on the identification of the endocardial border by letting evolve a closed curve inside the RV cavity visible on MRI image for each slice corresponding to either End-Diastole (ED) frame or End-Systole frame (ES). Concerning the quantitative assessment of wall motion, the method is based on the superimposition of the ED and ES contours, both obtained by the evolution in time of a surface previously laid on the borders of RV walls. The method

used to assess trabeculae mass was based on the manual tracing of a little surface for each black part present on the ED images with the intent to calculate the area of a not connected surface.

2.1. Level set method

The Level Set idea was firstly introduced by Sethian and Osher in 1988 by modeling the propagating curve as a specific level set of a higher dimension surface. Since then, these techniques were applied to many issues, but a general model to image segmentation was given by Malladi who described the evolution of a surface Γ as the zero level of a function $\phi(x, y, t)$, whose relationship can be written as: $\Gamma(t) = \phi^{-1}(t)(0)$ [5]. The motion equation that describes the evolution of the curve is:

$$\phi_t + V \cdot \bar{\nabla} \phi = 0$$

Where V is the speed function while $\phi_t = d\phi/dt$. The speed function is formulated from the image $I(x)$ to be segmented as:

$$V = g\varepsilon K - \beta \bar{\nabla} g \frac{\bar{\nabla} \phi}{|\bar{\nabla} \phi|}$$

In which ε weighs the curvature term while β weighs the advection term. The parameter g is an edge location function for the image itself, given by the following formulation:

$$g = \left[1 + \left(\frac{|\nabla(G_\sigma \otimes I(x))|}{\alpha} \right)^2 \right]^{-1}$$

The parameter α weighs the contrast while G_σ represents a Gaussian kernel which the image is convoluted with. This convolution sets the level of visible details present in the image. This approach is well suitable for images that have a high image gradient defining the edge.

2.2. Volume assessment

Volume estimation was executed by detecting endocardial contours in previously selected slices of the dataset. The procedure is semi-automatic; for either ED or ES images, the user initially places some points inside the RV cavity defining the initial condition. In fact, the software joints the points making a polygon that afterwards starts evolving outwards up to the RV endocardial borders. All the detected contours are put together in a matrix so that they can be superimposed and then displayed as a surface in 3D view. At the same time as the 3D visualization is shown, the software displays the volume in [mL] exploiting the data stored in the DICOM files' header. In this regard the area of each segmented region is calculated in pixels, whose dimensions are known and multiplied by slice thickness. By adding up the single volumes the ventricular volume is obtained. A simple linear interpolation can be used in

case of missing slices. In order to avoid wrong estimates only the right ventricle outflow tract (RVOT) below the pulmonary valve was included in the assessment while the lower apical region contour was always difficult to detect for the uncertain endocardial border.

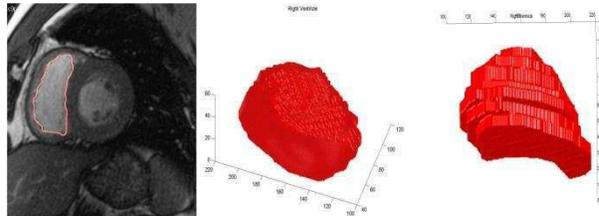


Figure 1. An extracted surface on the left, two lateral view of 3D visualization in the middle and on the right.

2.3. Quantitative wall motion

Wall Motion assessment is performed quantitatively by sectoring the superimposition of end-diastolic (ED) and end-systolic (ES) frames. Both contours are segmented semi-automatically on the wall borders, therefore not on the endocardium as seen for volume estimation. In fact, through an increasing of the contrast, the edge detector g becomes the overriding factor in the speed function formulation, which means that the propagating speed decreases as well as the global evolution of the closed curve. It follows that by placing some points where are supposed to be the RV walls; the tool easily detects the wall borders. The anatomical segmentation of the RV was defined in 7 segments on 3 levels along the long axis and known as basal level (BL), mid level (ML) and apical level (Apex). For each level, after having superimposed the corresponding frames, the resulting images are sectorized in segments without considering the septum. The BL was sectorized in RVOT wall, anterior wall; lateral-basal wall; inferior-basal wall. The ML was divided in anterior-mid wall and inferior-mid wall; whereas the apex is considered as a single segment (Figure 2.).

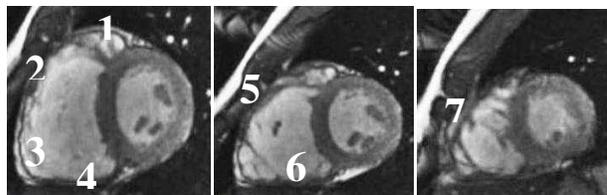


Figure 2. 1- RVOT, 2- Anterior Wall, 3- Lateral-Basal Wall, 4- Inferior-Basal Wall, 5-Anterior-Mid Wall, 6-Inferior-Mid Wall, 7-Apex.

For each segment wall motion is calculated as the mean difference in pixels between ED and ES contours. The tool calculates the excursion for each segment at intervals, in other word it divides each segment in as many sectors as large is the segment. After having divided the segment it calculates the excursion in pixel

sequentially. The corresponding results are then multiplied by the pixel dimensions, so that the excursion can be displayed in [mm]. Geometrical correction factors have been used with the aim to keep the estimation precise. Normally the ES contour is surrounded by the ED contour, so that the tool considers as positive excursion the inwards motion, in other words when the exterior wall is ED contour. On the contrary, the tool considers the excursion as negative, when the motion is directed outwards, that is when the ED contour is partially surrounded by ES contour. After having computed each excursion, the results are shown in [mm] segment by segment; and moreover each one is classified as Normokinetic, Dyskinetic or Akinetic. A segment is classified as Normokinetic, if the mean excursion computed on all the sectors forming a segment is greater than 1.5 mm. A segment is classified as Akinetic, if the mean excursion computed on all the sectors forming a segment is included in [0,1.5] interval. A segment is classified as Dyskinetic if there is a sector that has reported a negative excursion. The tool segments the RV semi-automatically but works automatically to compute the quantitative data of motion for each wall.

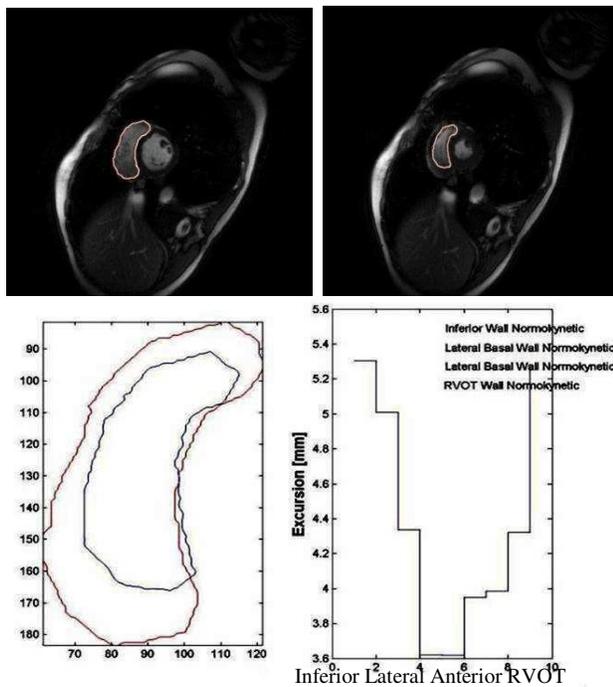


Figure 3. ED contour on the top left, ES contour on the top right, Superiosition on the bottom left and result displaying on the bottom right of the figure.

2.4. Assessment of trabeculae mass

The attempt of assessing trabeculae mass was carried out using a manual procedure to segment all the visible black parts inside the RV cavity for each ED image of the

dataset (figure 4). The most difficult part in developing the tool was to find an edge detector that was able to highlight the trabeculae without distorting their forms. The process to obtain the mass estimation is similar to the one we used to determine areas in the volume estimation and the distances between ED and ES contours in the quantitative wall motion assessment. Precisely, this time the tool sums the single little areas of each contour traced making an area of a non connected surface. Each single little volume is obtained by multiplying the area for the slice thickness as already seen for the volume estimation. The global volume is computed by adding up all the little volumes present. The mass in [g] is displayed after a multiplication by the mass density.

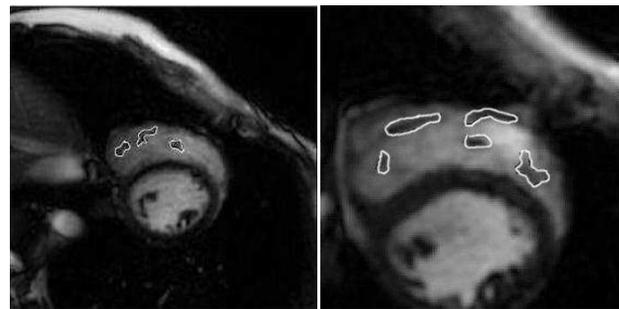


Figure 4. Detection of Trabeculae at 2 different Mid Levels.

3. Results

We applied these three tools to 6 normal subjects and 6 subjects with ARVD. 2 patients had a much enlarged RV, a maximal QRS duration greater than 120ms, epsilon wave as well as all the cardiac functions evidently reduced. The images analyzed were taken from a 1.5T scanner performing a CINE-FIESTA acquisition. The voxel dimensions for every image was 1.25x1.25x8 mm, the spacing between slices was 1mm, while the number of pixels was 256x256. The volume estimation using our tool was compared to volumes obtained by doctors applying the multi-planar Simpson's rule after a manual contouring. The wall motion assessments were carried out by analyzing the motion features between the normal subjects and the ARVD patients. The feasibility of trabeculae mass estimation was performed by a single user measuring consecutively 3 times the all dataset, keeping the same detecting criteria. The volume estimation, through a linear regression analysis, showed a good correlation between our method and the manual method ($y=0.92x+6.56$), ($r=0.92$ $p<0.001$), standard error of the estimate $SEE=6.56$ ml, Mean Error \pm Standard Deviation $\Delta \pm SD = 7.03 \pm 6.56$ (Figure 5.). The wall motion assessment showed a significant reduction of RV segmental function in patients with ARVD, Inferior Wall was the most involved with more than 80% reduction ($p<0.001$) compared to normal subjects and was usually resulted much classified as akinetic and at intervals as

diskinetic, while RV outflow tract (RVOT) was the least involved with less than 50% reduction with no diskinesy ($p < 0.001$) compared to normal subjects (Figure 6.). A repeatability test was executed on trabeculae mass assessment, which showed a high intra observer correlation between the measures (Correlation coefficients: $\mathcal{R}_{12} = 0,98, \mathcal{R}_{23} = 0,97, \mathcal{R}_{31} = 0,98$), in fact the results were significant at 95% of the cases (Figure 7).

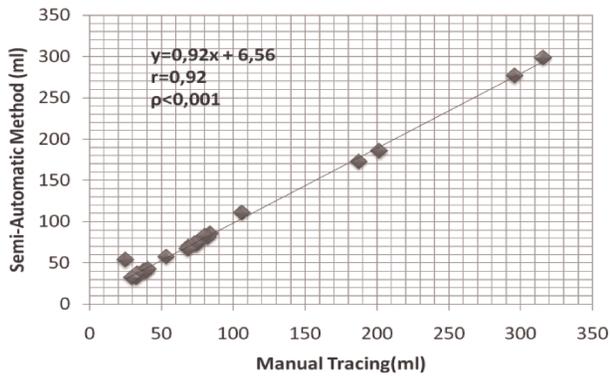


Figure 5. Volume estimation

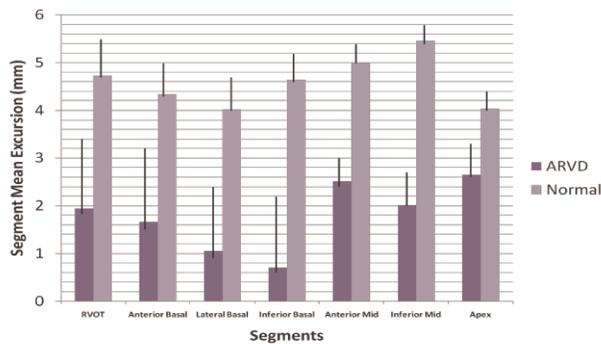


Figure 6. Wall motion, contraction by zones

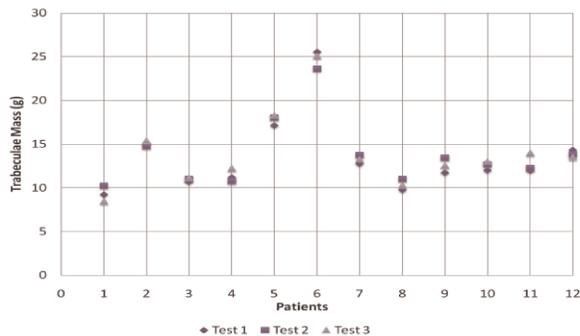


Figure 7. Trabeculae measures correlation

4. Discussion and conclusions

MRI is becoming a more and more important helpful mean in diagnosing ARVD since it allows a complete analysis of disorders and abnormalities caused by ARVD, which are both morphological and functional. Level set

techniques are by now well known and used in many tools, in fact it is possible to segment complex shapes as RV without making geometrical assumptions. As a consequence, RV volume assessment and in general RV segmentation are perfectly performed with MRI even if the procedure is still not automated. Our volume estimation results were good and were able to distinguish an ARVD heart in advanced stage, hence enlarged, from a normal heart. Wall motion assessment was performed in order to quantify the regions with abnormal wall motion in patients with ARVD compared with normal subjects. The evident finding was that the inferior wall, at mid and basal levels, was the most involved. As regards of the estimation of trabeculae mass, it showed a clear repeatability, but we have to mention the small amount of cases analyzed, as well as being performed by only one user. In the next future a faster segmentation, possibly with a shorter number of points for the initial surface, will be developed. The segmentation procedure might become completely automated. Wall motion analysis needs improving in speed besides defining rules to be compared by different doctors on different patients. With the sophisticated scanners existing nowadays, more details are visible on single MR images so that it might be possible that the detection of trabeculae might become semi-automatic soon.

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