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Simultaneous left and right ventricle segmentation using topology preserving level sets

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ABSTRACT

Cardiovascular Magnetic Resonance (CMR) has been successfully used in clinical practice to evaluate the cardiac function. Heart functional indexes, such as end-systolic volume and end-diastolic volume, are usually computed from manual segmentations performed by an expert using short-axis cine MR images. This process is tedious and time consuming. Despite semi-automatic methods have been proposed, including pixel-based, atlas-based, active contours and level sets, most of them allow the segmentation of only one ventricle at a time, and methods for segmenting both ventricles simultaneously tend to fail in the presence of abnormal anatomies.

We propose a method based on level sets with preserved topology that allows simultaneous, fast and accurate segmentations of the left and right ventricles. We compared our segmentation results of the left and right ventricles with those obtained with clinically validated software (Viewforum, Philips, Best and Segment, Medviso, Lund) using two-tailored paired *t*-test, Pearson's correlation, Bland-Altman plots of standard functional indexes and voxel-by-voxel analysis with Dice. Two-tailored paired *t*-test showed no significant difference between our method and gold standards ($P < 0.05$), Pearson's correlation showed a high correlation of our measurement with gold standards (over 0.98), Dice showed an average agreement over or equal to 0.90 and Bland Altman analysis showed that our method has a good agreement with the gold standard segmentations.

We were able to segment both ventricles simultaneously, without any training process and taking less than 15 s per cardiac phase. The process was semi-automatic with only minor manual corrections needed at the basal slices. Our results show high levels of accuracy considering functional indexes and also in a voxel-to-voxel comparison.

1. Introduction

The assessment of cardiac function is of highly relevance for several cardiovascular diseases. Cardiac performance is typically evaluated using Cardiovascular Magnetic Resonance (CMR) imaging since it has been shown to be accurate and reproducible for normal and abnormal hearts [1]. This technique allows computing accurately the Left Ventricle (LV) volume and has also shown to be a reliable tool to measure the Right Ventricle (RV) volume [2]. 2D multi-slice cine images of the heart, using balanced Steady-State Free Precession (SSFP) sequences, are the most widely used CMR technique for measuring ventricular volumes [3–5].

Once the cine images are acquired, they need to be processed by an expert. The expert has to identify the end-systolic and end-diastolic frames from the cine sequence, and then, perform manual image segmentation in order to compute the ventricular volumes, which are usually calculated using Simpson's method based on Simpson's rule [6], which in the case of CMR is defined as consists on the sum of the cross-sectional areas of each slice considering

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the slice thickness and the spacing between slices [7]. This is currently the most accurate and robust method [8]. Unfortunately, manual segmentation is a tedious and labor-intensive process and has high inter- and intra-observer variability. Promising alternatives has started to arise using different physical constraints and basis functions to model de cardiac volume [23].

In this scenario, a wide variety of image segmentation techniques exist in order to automate and speed up this process [2,14–21,23,24–31]. Those techniques involve methods based on pixel classification and active contours, with different degrees of prior knowledge.

Commonly used pixel classification techniques are region growing, clusters and atlas-based methods [2]. Region growing and clusters implementations are simple and fast. However, those techniques have several drawbacks: both of them are very sensitive to noise and therefore, they produce corrupted results; region growing methods depend on a parameter which is hard to determine for images with different contrast and intensities as usually occur in CMR images; and cluster-based methods do not consider spatial information and thus, they require an extra manual process to select the correct regions among those several structures that are commonly segmented. Atlas based methods consist in matching the image being segmented with a template generated from a big training data set created by experts. The main drawbacks of these methods are the need of a large training set and that they tend to fail with severely abnormal shapes. This is especially important in patients with congenital heart diseases (CHD), in which the anatomy is not well represented by standard templates.

Active Contour (AC) techniques have been extensively used in cardiac segmentation. They consist in an iterative process in which a curve is deformed in order to capture a specific feature (typically the edges) of an object of interest within an image. These techniques can be classified as explicit or implicit. Explicit (or parametric) AC [9] have the advantage of preserving the topology, i.e. keeping constant the number of contours defined during the initialization process, avoiding any merge or split of different structures. However, standard explicit AC can handle the deformation of only one curve, thus multiple boundaries are difficult to segment simultaneously [10].

Level set based algorithms [11] are a more elegant solution for the simultaneous segmentation of multiple structures. Since their creation, several authors have used them in cardiac imaging segmentation problems. Level sets are driven by a simple edge detector as an external force [12–14]. Other authors have chosen slightly different approaches using AC based on Gradient Vector Flow or modifications of it [15–21]. Those techniques have been applied to the LV with relative success, but they have not solved the simultaneous segmentation of the right and left ventricles.

Another level set based approach is STACS [22], which is a special formulation for cardiac imaging segmentation. This technique allows segmenting LV and RV ventricles, but through separated consecutive processes. Furthermore, the method tries to approximate the segmentation result to an elliptical shape, which may not always yield good results, particularly in patients with CHD. Comprehensive reviews of cardiac imaging segmentation methods can be found in [2,23].

Despite of the wide variety of approaches for segmenting automatically LV volumes, there is still no consensus about which is the most accurate one. Additionally, the problem of segmenting automatically RV volumes still remains unsolved [2], especially in patients with CHDs.

LV and RV segmentation has started to be explored with more attention [24–31], even as simultaneous processes. For example Mahapatra et al. [25] and Mahapatra [26] use mutual context information of both ventricles iteratively, fixing one of them and then optimizing the shape of the other. Grosgeorge et al. [31] used a level set based AC called Active Contours Without Edges (ACWE) [32] in order to simultaneously segment the left and right ventricles. The ACWE algorithm produced the segmentation of several structures of high intensity with different unconnected curves. For this reason, they proposed a second step in which the final segmentation only keeps the two largest components, assuming that those components corresponded to the ventricles. Although they reported interesting results, the authors did not evaluate the standard functional indexes. Additionally, they reported problems on the apical zone of the heart, due to the poor contrast obtained at the septum.

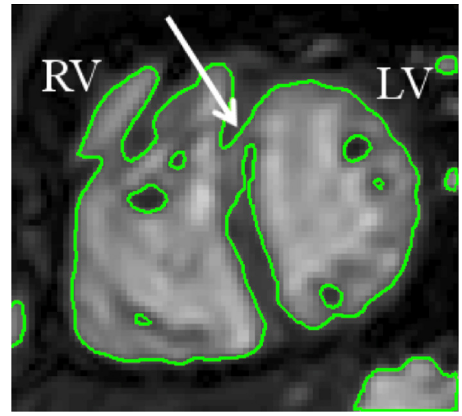

Fig. 1. Segmentation result using ACWE. Due to the presence of tetralogy of Fallot, both ventricles were erroneously segmented as a single structure.

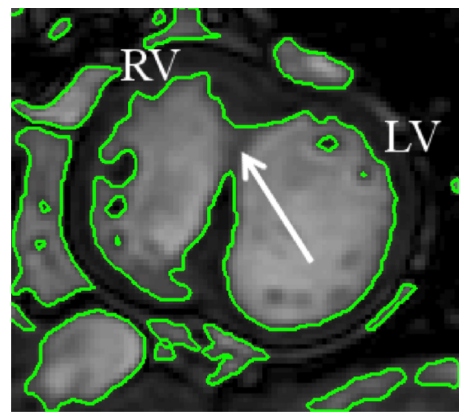

Fig. 2. Segmentation result using ACWE. This patient presents interventricular connection near the apex, causing that both ventricles were erroneously segmented as the same structure in several slices.

ACWE is a good option for segmenting structures with well-defined image contrasts and it has been previously used, showing interesting and promising results [31], but it tends to fail when those contrasts decrease. This problem commonly happens at apical slices, but it is even more serious in abnormal hearts, causing ACWE-like algorithms to fail. For example, in patients with repaired tetralogy of Fallot, a severe hypertrophied right ventricle can produce MR images in which the septum can be barely distinguished from the ventricles. The resulting ACWE segmentation can therefore consider LV and RV as a single structure (Fig. 1). This effect produces that simple rules, such as that proposed by Grosgeorge et al. [31] (i.e. selecting the two largest components) do not work anymore and important human intervention is therefore needed to correct the segmentation. Similarly, in the presence of ventricular septal defects, the separation between ventricles can be missed for several slices causing ACWE to fail (Fig. 2).

In this paper, we propose a new approach in which we include additional information into an ACWE-based segmentation tech-