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Fast segmentation of the left ventricle in cardiac MRI using dynamic programming

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ABSTRACT

Background and Objective: The segmentation of the left ventricle (LV) in cardiac magnetic resonance imaging is a necessary step for the analysis and diagnosis of cardiac function. In most clinical setups, this step is still manually performed by cardiologists, which is time-consuming and laborious. This paper proposes a fast system for the segmentation of the LV that significantly reduces human intervention.
Methods: A dynamic programming approach is used to obtain the border of the LV. Using very simple assumptions about the expected shape and location of the segmentation, this system is able to deal with many of the challenges associated with this problem. The system was evaluated on two public datasets: one with 33 patients, comprising a total of 660 magnetic resonance volumes and another with 45 patients, comprising a total of 90 volumes. Quantitative evaluation of the segmentation accuracy and computational complexity was performed.
Results: The proposed system is able to segment a whole volume in 1.5 seconds and achieves an average Dice similarity coefficient of 86.0% and an average perpendicular distance of 2.4 mm, which compares favorably with other state-of-the-art methods.
Conclusions: A system for the segmentation of the left ventricle in cardiac magnetic resonance imaging is proposed. It is a fast framework that significantly reduces the amount of time and work required of cardiologists.

1. Introduction

The diagnosis of cardiomyopathies is recognized primarily as a fundamental requirement for the patient throughput. A crucial step in the analysis of cardiac function is the identification of the endocardium, the inner border of the left ventricle (LV). With this information, important medical features can be determined, namely, the left ventricular volume and the ejection fraction, which are amongst the most used parameters in the diagnosis and prognosis of heart diseases.

Quantitative assessment raises as a natural stage towards the diagnosis, in which magnetic resonance imaging (MRI) is considered the gold standard in the assessment of left ventricular function as a non-invasive image modality. However, to accomplish such quantitative assessment in MRI, an accurate segmentation of the LV is mandatory.

In the majority of the clinical setups, the segmentation of a magnetic resonance (MR) volume is manually performed by cardiologists, in a time consuming and demanding process. A typical magnetic resonance (MR) volume comprises 8–15 slices, and requires roughly 13–17 landmark points to delineate the LV contour. Furthermore, this manual intervention is required in the *end-diastolic* and *end-systolic* phases of the cardiac cycle [1], which means a total of more than 200 points have to be manually introduced by cardiologists in order to proceed with the diagnosis. This means that a (semi)automatic segmentation method that reduces the amount of work required is highly desirable.

In this paper, we address this problem using a fast dynamic programming (DP) methodology inspired in [2,3]. This approach is based on two main assumptions about the LV border: (1) that it is approximately circular in each MR slice; and (2) that it is (at least partially) associated to edges in the image. The segmentation of each MR slice is performed in polar coordinates and involves the following steps. First, an edge map is built so that its valleys roughly correspond to location of the LV border. Second, a Dynamic Programming algorithm is applied to determine the optimal path along the edge map, which corresponds to the delineation of the LV contour.

The paper is organized as follows. Section 2 describes related work in the field. Section 3 details the methodology and the con-

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tributions herein proposed. Section 4 describes the experimental setup and a comparative study with state-of-the-art related approaches is performed. Concluding remarks are addressed in Section 6.

2. Related work

Although there are several methods dedicated to the MRI segmentation, the problem is still open, motivating not only several surveys available in the literature [4,5], but also several challenges, *e.g.*, MICCAI 2009 and 2011, resulting in a LV segmentation challenge consensus paper [6]. In fact, the automatic endocardial delineation is a task that is far from being straightforwardly accomplished. In the following, we describe the challenges of this task and how they have been tackled in the related literature.

2.1. Challenges in the MRI segmentation of the LV endocardium

One of the main challenges associated with this problem is the fact that some parts of the LV border may not always be associated with image edges. This caused by the presence of the gray level inhomogeneities, due to the blood flow, and by the presence of papillary muscles and trabeculations, or wall irregularities, inside the heart chambers, that have the same intensity profile as the endocardium. As such, some image features such as intensity and gradient do not represent the real contours near the papillary muscle. Motivated by the fact that clinicians consider the papillary muscle trabeculations within the LV cavity [1], this could be a source of inaccuracies in automatic segmentation algorithms. Several works have been published to tackle this issue, *e.g.*, by computing the convex hull of the contour [7,8] or by adopting morphological operations [9,10].

The segmentation of the apical and basal slices also faces additional challenges [11]. The apical slices are difficult to segment because the MRI resolution is too coarse to provide detailed and good visualization of small structures at the apex. Regarding the basal slice, there exists large LV shape changes near the base of the heart due to its vicinity to the atria.

Other issues include: unpredictable end of the LV cavity, vicinity of the diaphragm, large shape variability, and tissue motion and haziness [4].

2.2. Image based methodologies

As mentioned above, the presence of papillary muscles, as well as the trabeculations provide gray level inhomogeneities in the endocardium contour. To tackle this challenge several works have been published in the attempt to segment the endocardium of the LV. One class of approaches is based on a threshold operation [12] to separate outer and inner regions of the contour. However, DP is one of the most common choices for data-driven endocardial/epicardial border detection. This class of approaches is rooted in the work of Geiger et al. [13] and used in several works, *e.g.*[2,7,14–17]. It searches for the optimal path (*i.e.*, the contour) by using a cost matrix that assigns a low cost to the object boundary. The design of the cost matrix itself is a challenging task and plays a core role in DP based approaches, which motivated research on this subject. In [7], a threshold based approach is presented, in which the optimal threshold is found by computing the mean gray value of the maximal edge pixels. These pixels are found by generating orthogonal lines radiating from the epicardial center and collecting, for each line, the gray intensity of the pixel with highest edge value (*i.e.*, maximal edge) within the epicardial contour. A methodology termed *iterative multigrid dynamic programming* (IMDP) is introduced in [2]. Here, the contours of the LV in ultrasound image sequences are assumed to be one dimensional noncausal first order Markov random fields. The DP is run in a multigrid fashion, *i.e.*, first with a coarse resolution, followed by a refining stage that estimates the segmentation by searching in a smaller range, using a thinner resolution. To obtain the cost matrix, they model the intensity values of the tissues surrounding the ventricle border. DP has also been used to extract the myocardium region in [17]. First, they identify the endocardium border by using a classifier to label the LV cavity pixels and applying a convex hull operation on that region. Then, the image is converted to polar coordinates and transformed into a cost matrix based on the gradient along the radial direction. Finally, DP is applied to determine the epicardial border. In order to obtain a closed contour, they iteratively extend the cost matrix by replicating the initial part until they find an end point that intersects with the contour.

In [18] a threshold based operation is also used, where the binary masks (*i.e.*, thresholded images) are jointly used with the *Global Circular Shortest Path algorithm* (GCSP). It is shown that an improved method is achieved by combining the advantages of the two above techniques together. Fuzzy logic is used in [14] that comprises two stages. The first stage accounts for the pixel gray values and presence of edges, while the second stage comprises the determination of cardiac contours that is based on fuzzy logic with DP. With these two ingredients, a degree to which each pixel belongs to the cardiac contour is computed, allowing the image to be represented by a membership degree matrix. The final step comprises a graph search on the cost matrix to determine the cardiac contour. In [15] histogram equalization followed by wavelet transform is used to build the cost matrix. The branch-and-bound algorithm is used [16], where the main focus is to reduce the complexity of finding the optimal path that represents the endocardial border. In [10], the endocardial border is obtained for each volume independently using a region growing technique called geodesic dilations [19]. The idea is to merge two regions inside the LV cavity: one located close to the LV center that has a higher intensity, and another one located closer to the border, whose intensity is lower due to the proximity to the muscle tissue. A shortest path algorithm is also used in [20], which averages all the phases over one cardiac cycle, and contours in each image can be recovered using minimum surface segmentation. Spectral decomposition is another image based approach that has been used to segment the LV in [21]. It allows them to represent the images independently of the imaging modality and specifications, from which they employ a clustering step that divides the images into superpixels of similar appearance and their corresponding labels.

2.3. Deformable models

Another class of approaches regarding object segmentation is the active contours (or deformable models). The seminal approach is rooted in [22], which consists of an optimization problem that moves a parameterized curve toward image regions with strong edge information. Related approaches concerning this trend are characterized by a geometric representation that covers a large variability of shapes, and is currently used in medical image segmentation (*e.g.*, [23,24]).

The deformable model designation stems from the use of elasticity theory within a Lagrangian dynamics setting. The above setting, is characterized by forces that are internal to the model, which are called *internal forces* (related to the prior), and the external potential energy functions that are defined in terms of data of interest in the image (*e.g.*, boundary of the object to be segmented). These potential energies are associated to the *external forces* that are able to deform the model to fit the desired data. The energy of the deformable model is supposed to be minimal when two conditions are reached: (i) the model is located at the