Left Ventricular Segmentation In MRI images

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Abstract

We present an original method of segmentation of the left ventricle from time varying cross-sectional slices. This segmentation method is based on a split and merge algorithm. The endocardial and the epicardial contours in the first image of the sequence are drawn manually, the other contours of the sequence are computed automatically. This algorithm integrates the topological and geometrical characteristics of the left ventricle over time. This method is robust despite noise, artifacts and time varying contrast.

1. Introduction

Cardiac MRI is a non-invasive technique developed to image the heart with good spatial and temporal resolution. An MRI examination includes a set of temporal sequences. Each sequence corresponds to a set of grey level slices acquired in a given plane and varying with time over the cardiac cycle. Quantitative analysis of the cardiovascular system requires identification of the boundaries of structures. These boundaries are the endocardial and the epicardial contours.

In clinical applications, the borders are drawn manually which is time consuming for the operator. Moreover, manual segmentations lead to substantial inter- and intra-observer variabilities. To reduce the variability and time constraints inherent in manual segmentation, many image processing methods of segmentation have been developed. Some methods are based on a contour approach: active contour models [2, 7], graph searching [10], deformable templates [8], fuzzy logic [3]; and some others on a region approach: region growing [6].

The methods based on active contours models provide interesting results. However, these methods are quite sensitive to the initialization process [1]; moreover the active contours can be attracted by some incorrect contours with high gradients in the cavity. In fact, the turbulence of the blood pool creates two very contrasted zones in the cavity and the active contours converge to this artificial separation.

Therefore, we propose a method totally dedicated to the heart that takes into account the problem raised by the turbulence of the blood flows, the artifacts and the noise inherent to cardiac examinations. This method is constrained by the cardiac properties. We propagate the epicardial and endocardial contours from one slice to the next. The regions delimited by these contours are modified by a split and merge algorithm in order to compute the new contours, and the process is iterated.

Section II describes the characteristics of the heart. Section III presents the method. Section IV details the criteria of the method. Section V presents results and conclusions.

2. Characteristics of the heart

As mentioned above, our method is directed by the properties of the left ventricle. In this section, we briefly present the main characteristics of the left ventricle. The region inside the endocardial contour is the cardiac cavity denoted $R_c$. The region situated between the endocardial and the
epicardial contours is the myocardial wall or the muscle denoted \( R_{mw} \). We introduce a last region corresponding to the exterior of the epicardial contour. This region is named the exterior and is denoted \( R_e \) and permits us to reduce the segmentation area. We establish the following notation:

- \( R_{ec} \) is a heterogeneous region, the turbulence of the blood flow induces a large colorimetric distribution,

- \( R_{mw} \) is made of muscular fibers and is homogeneous,

- \( R_e \) is composed of the right ventricle, lungs and air so it is a heterogeneous region.

The muscle is always surrounding the entire cardiac cavity. In slices, the blood flow appears bright and the muscle has mid-gray intensities. In the first image of the sequence, the cavity is in a telediastolic phase; the contrast between the cavity and the muscle is well defined. Along the cardiac cycle, the cavity undergoes a phase of contraction followed by a phase of dilation. During the contraction, the quality of contrast between the cavity and the muscle decreases due to signal loss from turbulent blood flow. After telesystole, the extension of the cavity causes contrast loss and noise. The last slice of the sequence is similar to the first.

Therefore, the endocardial contour evolves along the cardiac cycle. In contrast, the epicardial contour is quite constant. In fact, while the cardiac cavity contracts, we can observe a thickening of the myocardial wall.

Many of these observations will help us to establish appropriate criteria.

3. Presentation of the method

To obtain the segmentation along a sequence of slices, we automatically deduce the contours of the \((i-1)^{th}\) slice from the previously segmented contours of the \((i-1)^{th}\) slice (see figure 1).

Our method proceeds slice by slice starting with a manually segmentation on the first slice. This method is based on an algorithm of split and merge. The merge conditions depend strongly on the cardiac properties (small deformation between two consecutive slices, topological condition).

In order to modify the contours, we proceed in four stages:

- Projection of \( R_{ec}^{i-1} \), \( R_{mw}^{i-1} \) and \( R_e^{i-1} \) on the \((i)^{th}\) slice. (cf figure 2.a)
- Split of the three regions (cf figure 2.b) into homogeneous sub-regions,
- Classification of the obtained sub-regions (cf figure 2.c),

Figure 1. a: contours computed on the \((i-1)^{th}\) slice. b: projection of previous contours in the \((i)^{th}\) slice. c: the new contours of the \((i)^{th}\) slice.

Figure 2. (a): The regions \( R_{ec}^{i-1}, R_{mw}^{i-1} \) and \( R_e^{i-1} \) are projected on the \((i)^{th}\) slice. (b): Splitting of these regions. (c): After the direct assignment, only small sub-regions around the contours (see (a)) remain. (d): The regions \( R_{ec}^i, R_{mw}^i, R_e^i \) computed by the segmentation.
• Building of the new regions $R_c^{i}$, $R_m^{i}$, and $R_e^{i}$ by merging the sub-regions according to the classification of the stage 3 (cf figure 2.d).

The region are split according to a homogeneity criterion. It ensures that all the sub-regions obtained are homogeneous. We have to respect two constraints: (i) geometrical deformations on the epicardial and the endocardial contours must be small and (ii) initial topology of the first slice must be preserved. The sub-regions that induce an important deformation of the region area or of the contour perimeter have to be kept in their initial region. For instance, let $r$ be a region resulting of the split of $R_c^{i-1}$. The region $r$ must be assigned either to $R_c^{i}$ or to $R_m^{i}$. The assignment of $r$ to $R_m^{i}$ is possible under two conditions: the region $R_c^{i}$ is still simply connected, and the endocardial contour undergoes small geometrical deformations. If these conditions are not validated, the region $r$ must be assigned to $R_c^{i}$.

The previous conditions (i) and (ii) directly allow to assign some sub-regions. The unassigned sub-regions have the following properties: (i') they share the contours of the regions $R_c^{i-1}$, $R_m^{i-1}$ (ii') they have insignificant area. The next stage is the sub-region assignment.

Let us consider a sub-region $r$ that share the endocardial contours. The neighboring regions of $r$ are $R_c^{i}$, $R_m^{i}$. We select the assigned region of $r$ according to an evaluation function $F$. The function $F$ valuates the deformation resulting of the merge of the sub-region $r$ with $R_c^{i}$ or $R_m^{i}$. To assign $r$, we compute $F(r, R_c^{i})$ and $F(r, R_m^{i})$. Then, $r$ is merged with the region which minimizes the function $F$. We apply a similar function for a sub-region whose neighbors are $R_c^{i}$ and $R_m^{i}$.

The last part consists of obtaining the endocardial and the epicardial contours by merging all the regions according to their assignment.

4. Details of the method

In this paragraph, we explain in more detail each step of the algorithm.

4.1 Splitting the three regions

After the contour projection, the three regions are split. Before an effective split, the histogram of each region is clustered. The algorithm of clustering minimizes the global squared error. This split produces sub-regions which are homogeneous. The predicate used to measure the homogeneity of the region depends on its squared error and on its surface.

4.2 Classification of the obtained sub-regions

The constraint of small deformation reflects the fact that the surface and perimeter of the heart do not substantially change over time. This constraint includes topological and geometrical criteria.

4.2.1 Topological criterion

The muscle is always surrounding all the cardiac cavity. The cavity is a simply 4-connected region (it has no hole). The muscle has one and always one that corresponds to the cavity. Therefore, the sub-regions that do not intersect the boundary of the regions $R_c^{i-1}$, $R_m^{i-1}$ and $R_e^{i-1}$ have to be directly classify according to the condition 1.

Condition 1 Let $r$ be a sub-region previously assigned to $R_c^{i-1}$, if $\partial r \cap \partial R_c^{i-1} = \emptyset$ then $r$ is assigned to $R_c^{i}$

The cavity is never in contact with the exterior. Then, a sub-region establishing a bridge between the cavity and the exterior (see condition refcond2) has to be directly assigned to the muscle (illustrated in figure 3).

Condition 2 Let $r$ be a sub-region previously assigned to $R_m^{i-1}$, if $\partial r \cap \partial R_c^{i-1} \neq \emptyset$ and $\partial r \cap \partial R_e^{i-1} \neq \emptyset$ then $r$ is still assigned to $R_m^{i}$.

Figure 3. The shaded region establishes a bridge between the cavity and the muscle

4.2.2 Geometrical criteria

Despite the conditions 1 and 2, some unassigned sub-regions may induce important geometrical deformation. In terms of surface and perimeter the cavity and the muscle are quite constant from slice to slice. Then, to avoid important geometrical change, we establish two geometrical conditions, the first one is based on the surface and the second one on the shape of each sub-region.
The surface criterion The sub-region displaying in figure 4.a represents a significant percentage of the region $R_{cc}^{i-1}$. If its assignment changes, then the region $R_{mew}^{i}$ undergoes an important surface modification (in comparison with $R_{mew}^{i-1}$). Conversely, the sub-region displaying in figure 4.b previously included in $R_{cc}^{i-1}$ may be assigned either to $R_{cc}^{i}$ or to $R_{mew}^{i}$ without important surface change. To avoid important surface change, the sub-regions that have a surface rather than a given percentage no not change (see condition 3). In that way, the surface of the regions $R_{cc}, R_{mew}$ and $R_{e}$ does not significantly increase or decrease from one slice to the next.

The endocardial contour undergoes more deformations than the epicardial contour. Therefore, the percentage $e_{1}$ associated to the surface of the subregion close with the endocardial contour is greater than the percentage $e_{2}$ associated with the surface of the subregion close to the epicardial contour.

Condition 3 Let us consider a sub-region $r$ that shares the endocardial contour and is included in $R_{cc}^{i-1}$ ($\alpha \in \{ec, mew\}$). If $\frac{|r|}{|R_{cc}^{i-1}|} \geq e_{1}$ then $r$ is assigned to $R_{cc}^{i}$.

Let us consider a sub-region $r$ that shares the epicardial contour and is included in $R_{mew}^{i-1}$ ($\alpha \in \{mew, e\}$). If $\frac{|r|}{|R_{mew}^{i-1}|} \geq e_{2}$ then $r$ is assigned to $R_{cc}^{i}$.

The sub-regions that are not already assigned have a surface smaller than a given percentage of $R_{mew}^{i}$ and are close to the previous endocardial or epicardial contours.

The shape criterion A last criterion dedicated to the perimeter variation must be considered. A significant increase in perimeter without an important change of surface can be interpreted as the presence of an asperity in the endocardial or the epicardial contours. Let us consider the case displayed in figure 5.a. The shaded sub-region shares a little percentage of its border with the previous endocardial contour. If this sub-region is later assigned to the muscle, the endocardial contour will lose its natural circular shape. In the opposite case, whether the sub-region of the figure 5.b is assigned to the cavity or to the muscle, the endocardial contour keeps its circular shape.

In order to avoid these defects of contours, we compute a criterion (see condition 4) based on the common perimeter of a sub-region with the previous endocardial or epicardial contours.

Condition 4 Let us consider a sub-region $r$ previously assigned to $R_{cc}^{i-1}$. If $\frac{|r||r^{c}+|r^{mew}|}{|r|} \leq t_{8}$ then $r$ is assigned to $R_{cc}^{i}$.

Using the previous conditions, we have eliminated all the sub-regions which can introduce some unacceptable deformations of the endocardial and the epicardial contours.

4.2.3 The last sub-regions assignment

Now, the remaining sub-regions can be assigned to anyone of their neighbouring regions while respecting the topological and geometrical conditions.

This last assignment is done according to the measure of an heuristic function $F$. We establish two different functions: one for the sub-regions sharing the endocardial contour and one for the sub-regions sharing the epicardial contour.

The sub-regions sharing the endocardial contour

In this case, the sub-regions have to be assigned either to the cavity or to the muscle. The function $F$ measures the deformation induced by the sub-region merging with $R_{cc}^{i}$ and $R_{mew}^{i}$. The function $F$ is inspired by the Beveridge’s criterion [5]. But we must underline that the func-

Figure 4. (a) a sub-region that does not validate the surface criterion, (b) a sub-region that validates the surface criterion

Figure 5. (a) The sub-region does not validate the shape criterion, (b) the sub-region validates the shape criterion
A homogeneity function

A colorimetric function

A geometric function

A homogeneity function

This second function measures the perturbation of the grey-level distribution resulting from merging two regions, the evaluation varies from zero to one. The function takes a value near zero if the merge is favored. This function is not redundant with the previous colorimetric function. Because, when the colometric function is close to zero for the both regions $R_{cc}$ and $R_{mw}$, the minimal perturbation of the homogeneity has to be considered.

A geometric function

The geometric function computes an normalized evaluation of the common perimeter of two regions. The merge is favored if the function is close to one.

Final Function

This formula is weighted by three parameters. They have been fixed according some properties of the cardiac images. Therefore, the weighting parameters must be adapted to both images of good and bad contrast. In case of good contrast, it is the two first functions that are determinant. In case of bad contrast, since the previous functions are not selective, the geometrical function is preponderant to the sub-region assignment.

We consider that the geometrical function and the combination of the colorimetric and the homogeneity functions have the same contribution. Then, the weighting parameters are: $\alpha \approx \beta = 0.25, \gamma = 0.5$.

The sub-regions sharing the epicardial contour

We proceed in a similar way for the endocardial and the epicardial contours. Let us consider the sub-regions sharing the endocardial contour. First, the sub-regions are ordered according to the final function. This process is repeated until there is no sub-region sharing its border with the two regions.

At this stage, some sub-regions can be included in one of the regions. These sub-regions have to be directly merged with the region where they are included in order to preserve topology.

5. Results

Our algorithm has been tested on 33 temporal sequences of short axes MR images. Each of these sequences has been acquired from a different patient. The validation has been done for medium-plane sequences. The results have been qualified by hospital practionners: 12 excellent, 8 good, 8
medium, 4 insufficient and 1 mediocre segmentations of an entire sequence.

Despite the bad quality examination (bad contrast, noise...), the results seem satisfactory. The study of inter- and intra-observer reproducibility made for these sequences, shows that our algorithm corresponds to the expectations of the hospital practitioners; that is a decrease of the inter and intra variability.

![Image of results](image)

**Figure 6. Example of results**

This algorithm has also been tested in some basal and apical sequences. The base and the apex are the extremities of the heart. The basal sequences do not pose particular problems. However, the segmentation of the apical sequences is more difficult because the cavity totally disappears in the muscle. In order to segment an apical sequence, the topological condition must be modified. We consider that the muscle may have no hole.

In medium plane sequences, the papillary muscles may appear in the cavity. In this case, the topoly of the cavity is made of one or two holes. The same algorithm is applied but the number of considered regions is range from 3 to 5.

This algorithm shows a great robustness to contrast varying along a temporal sequence. This is performed thanks to the application of a constraint of small deformation and the use of geometrical criterion in the function of final merge.

Some local default exists in the epicardial contours, we investigate the asperity smoothing using active-contour models.

In conclusion, this algorithm is based on discrete geometric map model [4]. This model compute efficiently the region neighbouring, the split and merge operations. Moreover, it provides directly topological and geometrical information on regions and region boundaries (perimeter and surface, length of common region boundary,...). Using this model, our algorithm produces interactive segmentation.

is based on

**References**


