Morphological Scale-Space Decomposition for Segmenting the Ventricular Structure in Cardiac MR Images

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Abstract. We propose a method for segmenting the endocardial contour of the left ventricle from magnetic resonance (MR) images, using morphological scale-space decomposition based on multiscale spatial analysis. This approach comprises a powerful tool which presents many advantages: the preservation of scale-space causality, the localisation of sharp-edges, and the reconstruction of the original image from the scale-space decomposition. An appropriate scale is defined as the scale that maximizes the response of the morphological filter through the scale-space at each point giving constant scale values in a region of constant width. The approach was able to separate the gray-level appearance structures inside the ventricular cavities from the endocardial contour, facilitating the segmentation process.

1 Introduction

Magnetic resonance imaging (MRI) has been shown to provide an accurate and precise technique for assessing cardiac volumes and function in a non-invasive manner. However, segmenting the endocardial boundary of the left heart ventricle has shown to be a difficult task. The major problems related to the boundary's detection are the typical shortcomings of discrete data, such as sampling artifacts and noise, which may cause the shape boundaries to be indistinct and disconnected. Furthermore, the gray-level appearance of structures inside the ventricular cavities, such as papillary muscles, are often indistinguishable from structures of interest for diagnostic analysis, such as the moving inner heart boundary. Thus, segmentation appears error-prone and often incomplete. There exit a number of different approaches that employ different models for segmentation. For example approaches are based on deformable models [3], specially the active contour models and their extensions but most of the applied techniques fails in over passing the appearance structures inside the ventricular cavities, since they are almost adjacent to the endocardial contour even if the initial position is near to the final position.

The presented method represent a bottom-up multiscale analysis based mainly on the idea presented by Köthe [1], taking advantage of using the morphological scale-space by decomposing the image into numbers of scales of different structure size, and defining an appropriate scale that maximizes the response of the band-pass morphological filter at each point in the image. This scale gives constant values in a region of constant width.

2 Methods

2.1 Image acquisition and pre-processing

Images were acquired using a 1.5T whole body scanner (Intera CV, Philips Medical Systems) with Master Gradients (slew rate 150 T/m/s, amplitude 30 mT/m) and a 5-element phased-array cardiac coil. Three short survey scans were performed to define the position and true axis of the left ventricle. Afterwards, wall motion was imaged during breath holding in long and short-axis slices using a steady-state free precession sequence, which provides an excellent demarcation of the endocardium. Cardiac synchronization was achieved by prospective gating. The cine images were recorded with 23 heart phases (23 frames per heart cycle). Each frame of 256x256 with a slice thickness of 10mm.

2.2 Morphological scale-space and Appropriate scale

Mathematical morphology is a nonlinear analysis of signals [2], using structuring elements. Two dual operations, erosion and dilation, are the most basic morphological operators. Erosion is shrinking operation while dilation is an expanding one. By combining dilation and erosion two new operations can be defined

$$\begin{aligned} \text{opening: } (f \circ d_s)(x) &= ((f \ominus d_s) \oplus d_s)(x) \\ \text{closing: } (f \bullet d_s)(x) &= ((f \oplus d_s) \ominus d_s)(x) \end{aligned} \tag{1}$$

The function $d_s(x)$ is called the *structuring function*, and $f(x)$ is the input image (i.e. morphological scale-space comes in variety opening-closing scale-space). The Morphological band-pass filter is defined according to [1], by the following formula (with limiting blob size $s = 0 < \ldots < n < n+1 = \infty$, where n must be chosen larger than the image diagonal):

$$\begin{aligned} \text{for closing: } & H_{n+1}(x) = f(x) \\ & B_k^{k+1}(x) = (H_{k+1} \bullet d_k)(x) \\ & H_k(x) = H_{k+1}(x) - B_k^{k+1}(x) \\ \text{for opening: } & H_{n+1}(x) = f(x) \\ & B_k^{k+1}(x) = (H_{k+1} \circ d_k)(x) \\ & H_k(x) = H_{k+1}(x) - B_k^{k+1}(x) \end{aligned} \tag{2}$$

where the resultingB_l^u represent a morphological decomposition of the image into ands of different structure sizes with light and dark blobs ($H_k(x)$) are intermediate high-pass filtered images).

Similar to the definition of Köthe, the appropriate scale is defined as

$$S(x) = \arg_k \left(\max_{k=1,\ldots,n} \left| \frac{B^k_{k+1}(x)}{k-(k+1)} \right| \right) \tag{3}$$

2.3 Algorithm

The algorithm was achieved by linking the appropriate scale, with the scale-space decomposition obtained from the close morphological operator, in order to distinguish between the inner cavity and the inner gray-level structures inside it, which facilitate the inner boundary segmentation. The algorithm goes as follow:

1. Calculate the morphological band-pass filter based on (2), using a disk as a flat structuring element of increasing logarithmically, obtaining a close scale-space and an open scale-space respectively. Applying (3) for both close and open scale-space, two appropriate scales are obtained, as shown in figure 1.

2. Based on the evaluation of the close scale-space and referring to the appropriate close scale, individual scales can be assigned a 'main scale' or a 'secondary scale', (figure 2a) as follows:

- 3 main scales. Scale 6: determines the inner region. Scale 4: determines the boundary. Scale 3: determines the inner structures.
- 3 secondary scales. Scale 1 and 2: determine tiny structures. Scale 5: determines large structures around the boundary.

From the previous evaluation and the observation of the behaviour of the data set, we can conclude the following:

- Scale 1, mostly represents tiny structures in the region of scale 6.
- Scale 2, mostly represents tiny structures in the region of scale 4.
- Scale 5, mostly represents structures of equal size around scale 4.

Assign the values of all scales in the appropriate close scale into only 2 main scales (4 and 6), representing the inner region and the boundary (figure 2b). Scale 3 appears in both the inner region and the boundary. Now we need to assign the value of scale 6 to the structure in scale 3, found in the area of the inner region, the remaining structures the same value of scale 4. This classification is obtained by applying the following algorithm.

a) Referring to the appropriate close scale determine the scale containing inner region (scale 6).

b) Apply a region growing algorithm to detect the region of interest.

- Calculate the centre of mass of the scale.
- Select the brightness intensity in 8-connected neighbours to represent the seed point for the region growing.
- Stopping criteria using a defined threshold value.

c) Calculate the centre of mass of the image.

d) Calculate the distance between the centre of mass and the farthest point which lies in the region of interest obtained from b.

3. Draw a circle with radius equal to the distance obtained from 2d on the appropriate close scale, for every value of scale 3 determine if it is inside the circle or not, and assign the value of scale 6 or scale 4 respectively (figure 3).

4. Apply an opening morphological operator on the result image for smoothing.

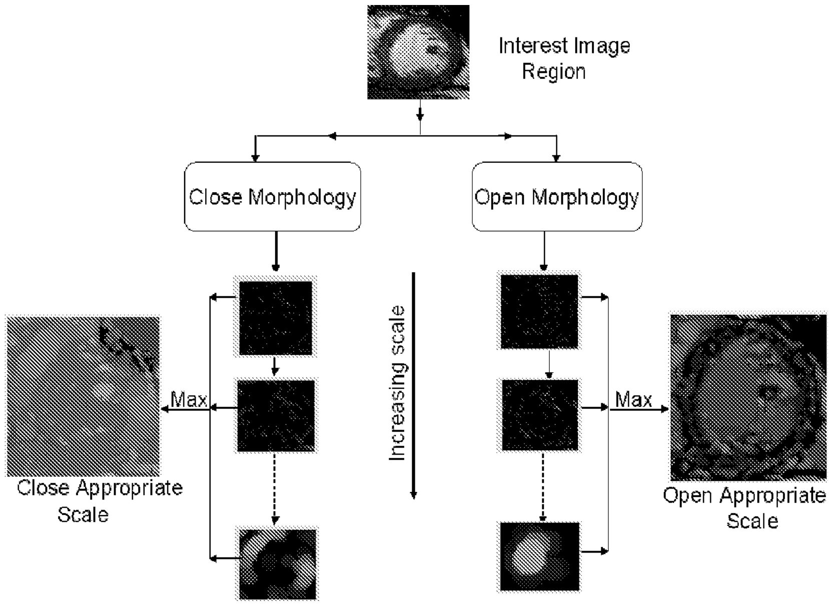

Fig. 1. Decomposition of an image with respect to structure sizes. Left: using the close morphology. Right: using open morphology, and obtaining the maximum response of the scale operators in each case.

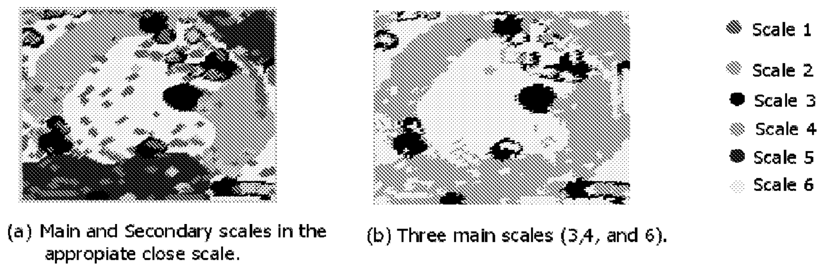

Fig. 2. (a) 6 scales marked in the appropriate close scale. (b) results from assigning the secondary scales the same values as the main scales (4 and 6), and showing only the three scales 3, 4, and 6.

3 Results and Conclusion

The proposed approach was tested on 150 MR images from different cases, each image of size 95x95 pixels, representing the interest region, which is extracted from 256x256 pixels as explained (section 2.1). The approach was able to correctly locate and classify the inner structures in 91% of the tested cases. The results were also recorded and compared according to the mean distance error between the drawn contour points and the contour obtained from the proposed method, the best result was of 0.1 mean distance error. We are working to modify the proposed method with respect to the following points: 1. Refine the way of selecting the best scale that represent the inner region, specially in the contraction phase. 2. Combine the proposed model with a top-down model to improve the performance of the segmentation.

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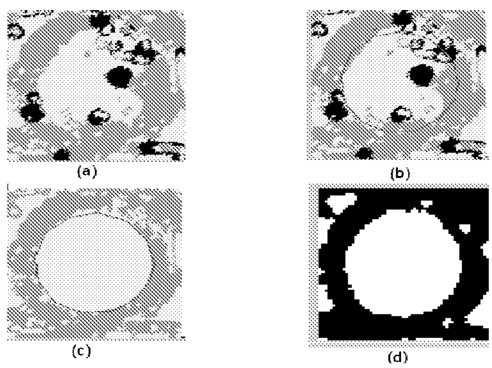

Fig. 3. (a) Appropriate scale with 3 main scales. (b) The drawn circle separates between the structures in scale 3 either assigned to scale 4 or 6. (c) Result after assigning scale 3. (d) Final smoothed result with strong inner boundary appearance.