Coronary Artery Segmentation in CTA Using the Distance Transform

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Abstract: This work consists in automating the segmentation of coronary arteries from three-dimensional images obtained from Computed Tomography Angiography (CTA) studies. The method uses mathematical morphology to segment hyperintense regions, snakes to extract the heart contour and finally a tube detection filter to extract the coronaries. The advantages of the distance transform are used in the heart contour segmentation as well as in the tube detection filter.

1 Introduction

According to the American Heart Association’s 2007 statistical report [7], an estimated 79 400 000 (1 in 3) Americans suffered from cardiovascular disease (CVD) making it the most prevalent cause of death in the United States. CVD include high blood pressure, coronary heart disease (CHD), stroke, and congenital cardiovascular defects among others. CHD accounts for approximately 20% of all CVD. CHD is the result of the accumulation of atheromatous plaques in the arteries that supply blood, nutrients, and oxygenation to the myocardium (atherosclerosis). With the rise of CTA as the gold standard to evaluate heart disease, the segmentation of the coronary arteries has become an integral part of the analysis of the disease.

Many different methods to segment the coronary arteries have been described in literature (e.g. [2], [3], [4], [8], and [9]). The method we present consists of 3 main steps: the segmentation of the heart chambers, the segmentation of the heart from the lungs, and the tube-detection filter. Our method started as a combination of the methods presented by [4] and [2] to segment the coronary arteries and [1] to extract the heart chambers. We did replicate the work presented by [1] to segment the blood pools; however, we applied modifications to the work presented in [4] and [2] to perform the other steps. The motivation behind modifying the methods mentioned above is to reduce computational complexity and to provide a scale independent vessel filter. There is a significant computational complexity difference between calculating the distance transform and Gradient Vector Flow (GVF). Both the GVF and the distance transform are crucial in creating vector fields that drive our segmentation processes.

Funk-Lea et al in [4] present a method to isolate the heart from the lungs in CT. Their approach consists of making an ellipsoid grow inside the heart towards its boundaries, resembling a balloon being inflated inside the heart in 3D. We decided to take a similar approach but on a slice by slice basis in 2D. Kitslaar et al take a similar approach in [3], where they inflate a balloon in 2D. For the vessel-extraction filter, the method presented by Frangi et al [2] is scale dependent. Therefore, the success of the method depended on the choice of the scales since there is no real heuristic that can automatically detect a specific human’s vessel diameters. Bauer et al in [6] presented a scale-independent method based on (GVF). This method is computationally intensive so we decided to use a modified version of their algorithm to segment the coronaries. The method we present uses the distance transform as an alternative to the GVF algorithm to produce a similar vector field that is used in the heart segmentation as well as the vessel filtering steps. This is done to reduce the computational complexity of the calculation of GVF to the simplicity of the distance transform.
2 Methods

The method for the automatic segmentation of the coronary arteries includes four main processes: an initial pre-processing step, the segmentation of the blood pools, the segmentation of the heart, and finally the extraction of the coronaries using a vessel filter.

In the pre-processing step of the procedure, the original volume in DICOM format is read in and the window parameters are extracted. These parameters are used to create a windowed volume that is characterized by the enhancement of the hyperintense regions (bones and blood pools). This volume is later used as an initial step to segment the blood pools. Also, a binary volume is obtained in this step by selecting all the voxels that have a value greater than zero and setting them to 1. This volume is used as an initial step in the segmentation of the heart’s contour.

The second step consists of the segmentation of the heart’s blood pools. In order to do so, we start with the windowed volume we calculate in the pre-processing step. We then iterate through the whole volume in a slice by slice basis. For each slice, we first create a binary image by setting all the pixels not equal to the maximum to zero. This creates an image that contains both bones and blood pools. We then apply a hole-filling algorithm to reduce noise from the previous step. Finally, to segment the blood pools, we apply a method similar to what Cline does in [1]. The process consists of mathematical morphological erosion followed by a dilation applied to the binary image. The resulting image is a slice that only contains the blood pools and bones. We can subtract this image from the windowed image to obtain a slice without the blood pools and bones but with the coronary arteries.

The third step is performed to segment the heart from everything else (bones, lungs, etc.) in each slice. This is done to have a final image with only coronary arteries and myocardium in them. In order to do so we start with the binary volume obtained in the pre-processing step. Again, we perform a slice by slice operation to segment the heart’s contour. For each slice, the first step consists of applying a median filter for noise reduction. We then find the centroid of the image to have an initial contour that later will be deformed. The contour is found using a traditional snakes algorithm [5][11]. The snakes algorithm contains an external energy field that will drive the initial contour (created around the centroid) to the heart’s boundary. The steps to calculate the external energy are the following:

1. Calculate the magnitude of the gradient of the windowed function.
2. Multiply the image in (1) by -1 (calculate the negative image).
3. Find the distance transform of the image in (2).
4. Calculate the normalized gradient of the image in (3).

The image obtained in (4) is a vector field that points towards the heart’s boundary. Finally, to segment the heart, we apply the snakes algorithm recursively and deform the initial contour created.

The final step of the process is to apply a vessel filter that is based on the work previously done by Frangi in [2] and Bauer in [6]. Unlike the work by Bauer, that uses Gradient Vector Flow (GVF) our approach consists of an analysis of the second order structure of the vector field obtained using the distance transform of the magnitude of the derivative of the volume. The results are similar in the sense that they both produce vector fields that point towards the center of the vessel.

To find the vesselness of each voxel in the initial windowed volume (using Frangi’s vesselness definition), we first need to calculate two different Hessian matrices. The first Hessian is calculated by first taking the normalized gradient of the input image and then constructing the Hessian using the derivative of the normalized gradient field. The second Hessian is computed by first calculating the magnitude of the first derivative of the initial volume and then calculating its distance transform. The second Hessian is then constructed by taking the derivative of this second normalized vector field. The final vessel filter response consists using Frangi’s measure (for details on...
this calculation please refer to the cited paper) with default values on both Hessians and for each voxel choosing the greater value of the two.

The results of the calculations performed on a slice are shown in Figure 1. To the right we see the initial slice that has been windowed using the parameters in the DICOM file and to the left we see the final slice after the four steps of processing.

Figure 1. (a) Original windowed image. (b) Final result.

3 Conclusions

The objective of this paper was to implement a method to extract the coronary arteries from images obtained in CTA. By combining and modifying previously published methods, we were able to develop our own and unique method. We chose to take advantage of the computational simplicity of the distance transform as opposed to the complexity of the GVF (Gradient Vector Flow) proposed by Bauer et al. This was a key to our process since it is used in two of the four steps that we need to segment the coronaries. In the future we plan on adding noise reduction techniques to get cleaner results.
References