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Computational strategy for the segmentation of the aortic annulus in cardiac computed tomography images

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Abstract. The purpose of this research is to segment the aortic annulus, present in cardiac computed tomography images, from a computational strategy generated using global similarity enhancement, vector least squares support machines and a segmentation technique named region growing. This enhancement is obtained by applying the following steps: a) Obtain an image of similarity by calculating the absolute value of the arithmetic subtraction that considers the original image and an image of contours. The image of contours is obtained by processing the original image with a filter based on the magnitude of the gradient. b) Is is processed with a Gaussian filter, generating a smoothed similarity image. On the other hand, considering the smoothed similarity image, the least squares support machines are used both to construct two cutting planes (that isolate the aortic artery) and to detect the coordinates of a seed voxel. In order to produce the morphology of the aortic valve annulus, the seed voxel initializes the technique of growth of regions during the segmentation process. From this morphology, some useful quantitative descriptors are calculated for the aortic ring characterization.

1. Introduction

In world wide, valve diseases represent the most relevant cardiac conditions in populations of elderly patients. Its prevalence, in subjects older than 80 years, exceeds 4%. In symptomatic patients, aortic valve replacement has been the treatment of choice for the last 40 years [1]. In 2002, a percutaneous aortic prosthesis (TAVI: transcatheter aortic valve implantation) was implanted for the first time [2].

On the other hand, the three-dimensional segmentation of the valves: a) facilitates the diagnosis of several valvulopathies, b) generates 3D models of the aortic annulus and c) allows the calculation of quantitative descriptors necessary to perform TAVI [3]. However, the segmentation of cardiac structures is a challenge due to the heart movement.

Although there are different modalities of medical imaging (see Figure 1), in this investigation, we chose to work with cardiac computed tomography (MSCT) images since, in the literature, it is the established modality for the detection of aortic valvular diseases and for the reconstruction of the 3D geometry of the valves [4].

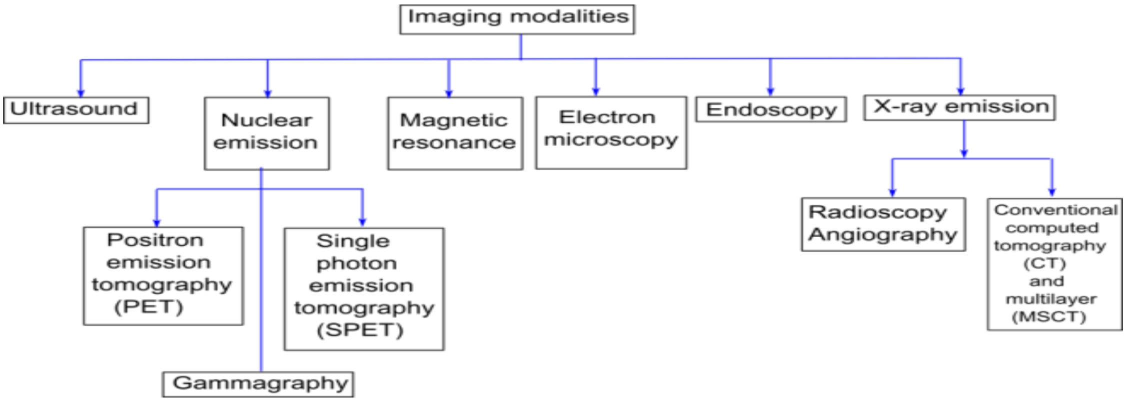


Figure 1. Medical imaging modalities.

The MSCT images present imperfections such as Poissonian noise, artifacts and low contrast through the cardiac cycle [5,6]. To deal with them we resort to the application of digital processing techniques which, usually, raise the quality of the information contained in an image.

The state of the art reflects the intense activity that has been developed in order to address problems related to the aortic valve of the human heart. In this sense, the majority of studies have been biased towards the production of computational models of the aortic valve apparatus using the following approaches: model based on atlas [7], marginal learning [8], deformable models [9], finite element method [10,11], mathematical morphology and fuzzy logic [12] and deep learning [13]. Additionally, other authors have carried out work focused on obtaining quantitative descriptors of the aortic annulus, especially necessary to perform TAVI [14-17].

In the present work, a strategy based on a variant of enhancement by similarity [18] is applied to cardiac MSCT images, with the aim of generating the 3D morphology of the aortic annulus. The variant consists of considering the anatomical structure of the aortic valve and replacing the morphological filters and the averager with a type of filters framed in the local similarity, which do not require intonation of the parameters that control their performance.

2. Materials and methods

2.1. Dataset

The database (DB) used, in the present investigation, of cardiac MSCT supplied by the Institute of Bioengineering and Development (IBIDSA), in Táchira-Venezuela, were acquired using a 64-slice CT-Toshiba Aquilion tomograph and contain in 10 instants the complete cardiac cycle. Each instant consists of images of 512x512 pixels and were sampled at 12 bits. Additionally, manual segmentation of the aortic annulus (reference segmentation) generated by a cardiologist is available, which will be used to evaluate the performance of the proposed technique.

2.2. Method

The cardiac moment corresponding to the systole phase of the aforementioned images belongs to a 79-year-old male patient with failure heart. This phase was processed with a computational strategy based on a variant of enhancement by similarity [18] consisting of the application of the following stages: pre-processing of the original image (filtering + generation of a region of interest), segmentation of the aortic valve (region growing) and calculation of quantitative descriptors of interest (diameter and area of the aortic annulus). Figure 2 shows the general structure of this strategy.

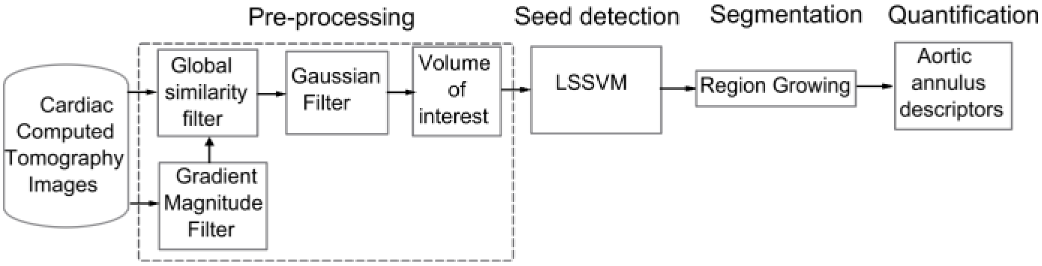


Figure 2. Diagram of the proposed strategy.

2.2.1. Pre-processing. This phase is divided into two stages. a) Filtering and b) Definition of a region of interest (VOI). During filtering, the systole image is processed with a technique that minimizes Poisson's noise and enhances the edges of the anatomical structures. In this sense, an image of similarity (Is) is generated by calculating the absolute value of the arithmetic subtraction that considers the original image (OI) and an image of contours (BI). The image of contours is obtained by applying, on OI, a filter called gradient magnitude [19]. To finish the filtering stage, the similarity image is smoothed with a Gaussian filter [20] that reduces the noise produced when the edges are detected.

To define the VOI, using least squares vector support machines (LSSVM), two planes are constructed that isolate the aortic valve. To do this, during training, a cardiologist selects the points that the LSSVM must recognize when the detection process is executed. With respect to the first plane (ventricular plane), the points are made to coincide with: the apex of the left ventricle (p1) and the union of that ventricle with the aortic valve (p2). For the second plane (aortic plane), p2 is considered and an additional point constituted by the centroid is the aortic artery (p3), which is located in the first layer of the heart base of the DB considered. Using these points are constructed, within the DB, two planes that isolate the aortic valve.

2.2.2. Segmentation. The images pre-processed in the previous phase are considered to segment the aortic ring and the aortic root using a method based on the technique called growth of regions [18]. These segmentations allow us to calculate the descriptors that characterize the aortic annulus.

2.3. Choice of the values of the parameters linked with the techniques included in the strategy

The adequate performance of the techniques considered requires obtaining the values linked to their parameters that control the performance of the techniques described. In this sense, using the database considered, the following considerations are made:

a) The parameters for the filter based on Gaussian smoothing, in the 3-D domain, are: a) The standard deviations of each direction in which the filtering is intended. b) The size of the Gaussian core. During smoothing, the size of the Gaussian filter neighborhood was arbitrarily set to $(3 \times 3 \times 3)$; while for the values of its standard deviation an isotropic approach is assumed. This approach allows the deviations of each direction to be equal to the standard deviation of the similarity image obtained during the filtering phase. In this way, it is not necessary to intone the parameters of the Gaussian filter.

b) The magnitude filter of the gradient is implemented with an approach based on finite differences that can be backward, centered or forward. For purposes of the present investigation, this filter is applied with centered differences. So, this technique does not require tuning.

c) In [18], the tuning process of a vector support machine is described in detail. In this work an analogous process is developed in order to obtain the optimal values for the LSSVM.

d) During the optimization process of the parameters of the RG, each of the automatic segmentations of the aortic annulus, corresponding to the described database, is compared with the respective manual segmentation, generated by a cardiologist, considering the similarity index of Jaccard (JSI) [21]. The JSI can be modeled by Equation (1).

$$\mathrm{JSI} = \frac{|\mathrm{MS} \cap \mathrm{AS}|}{|\mathrm{MS}\ \mathrm{U}\ \mathrm{AS}|} \tag{1}$$

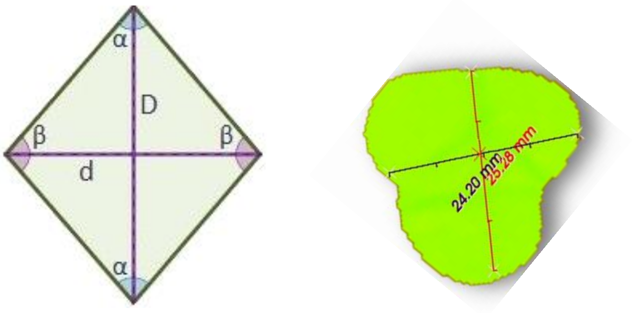
where: MS and AS represent the manual and automatic segmentations, respectively.

The optimal values for the parameters of RG, size of the initial neighborhood (*r*) and multiplier of the voxel acceptance range (*m*) are identified from the maximum value for the JSI. For *m* values between 0 and 10 are considered, with step size equal to 0.1 and for r integer values between 1 and 20 with step size of one unit.

2.4. Descriptors calculation

The value of the diameters (major and minor) and the area of the aortic annulus is calculated considering the cross section of an image in which the segmented valve is fully open. The value of the area is matched to the number of pixels contained within the contour surrounding the aortic annulus of the described cross-section; while the diameters assume a geometric hypothesis, which establishes an analogy between the aortic ring and a rhombus. In this sense, the diameters are made to coincide with the longest segments, in the two fundamental directions, selected from all the rays, perpendicular to each other, drawn on said cross section.

In Figure 3, a good geometric correspondence between the rhombus and a reference section that represents the aortic ring, of a real database is appreciated.



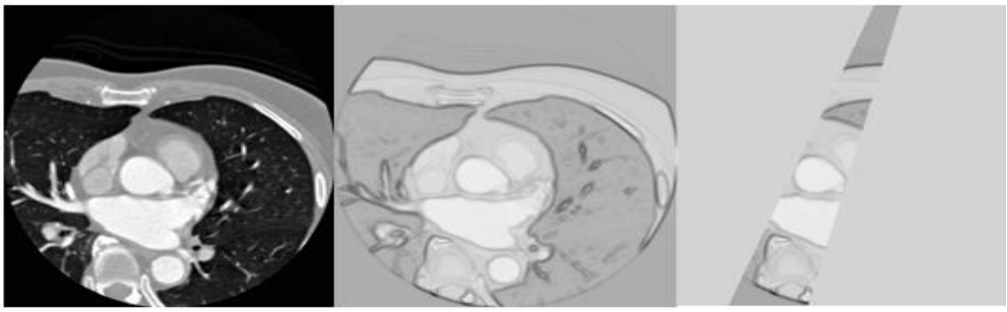
(a) (b)

Figure 3. Analogy between geometric hypothesis and aortic annulus. (a) Diamond, and (b) aortic annulus section.

3. Results

For the LSSVM the optimal values of its parameters were (γ=2, σ^2=3); while, for the RG, the optimal values were: (*m*=1, *r*=6.8).

It is presented, through Figure 4, the corresponding axial view relative to: Original image, filtered image and Image in which a region of interest for the aortic valve has been defined. These images show the detection of edges on the filtered image and the isolation of the aortic valve.



(a) (b) (c)

Figure 4. 2D view of the effect of the application of the proposed strategy. (a) Original, (b) filtered, and (c) VOI.

Additionally, Figure 5 presents the 3D segmentation model of both the aortic ring and the aortic root. In Figure 5, representative bulges of the aortic valve can be seen, and it is an excellent 3D representation of the aforementioned valve. The cut produced by the aortic plane is also clearly seen.

This segmentation allows us to calculate the area and diameter of the aortic annulus. The values obtained for the annulus were: 24.20x25.28 mm (smaller and larger diameters, respectively) and an area of 5.40 cm^2. Figure 6 shows the values for those diameters.

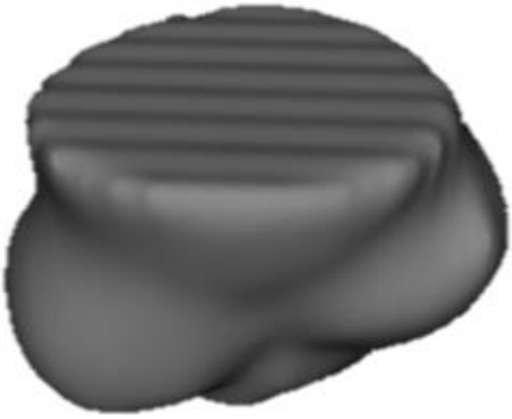


Figure 5. 3D view of segmented aortic ring.

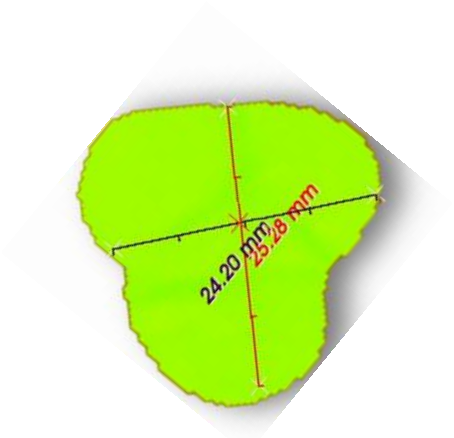


Figure 6. Diameters of the segmented ring.

The preprocessing and segmentation phases allowed to calculate, in a precise way, the diameters of the aortic ring, which allows to choose between one of the 6 prototypes of commercially available aortic valve prostheses. The aortic valve that could be used for TAVI is a commercial valve called CoreValve of 25 mm (see Figure 7).

Figure 7. Valve photography CoreValve type.

4. Conclusions

In this work, an automatic technique was developed which allowed a precise segmentation of the aortic ring, present in computed tomography images. The computational 3D model of the aortic valve allows calculating the necessary descriptors to perform the transcatheter aortic valve implant, particularly the diameter of the aortic annulus. The main contribution is the fact that segmentation of the aortic annulus was carried out without the need to develop a manual process that is usually made by cardiologists, called multiplanar reconstruction. In the immediate future, to establish the robustness of the proposed technique, it is planned to apply this strategy to a large number of databases and develop a process of comparative evaluation with other techniques reported in the literature.

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