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Use of computational realistic models for the cardiac ejection fraction calculation

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Abstract. Ejection fraction is one of the most useful clinical descriptors to determine the cardiac function of a subject. For this reason, obtaining the value of this descriptor is of vital importance and requires high precision. However, in the clinical routine, to generate the mentioned descriptor value, a geometric hypothesis is assumed, obtaining an approximate value for this fraction, usually by excess, and which is a dependent-operator. The aim of the present work is to propose the accurate calculation of the ejection fraction from realistic models, obtained computationally, of the cardiac chamber called right ventricle. Normally, the geometric hypothesis that makes this ventricle coincide with a pyramidal type geometric shape, is not usually, fulfilled in subjects affected by several cardiac pathologies, so as an alternative to this problem, the computational segmentation process is used to generate the morphology of the right ventricle and from it proceeds to obtain, accurately, the ejection fraction value. In this sense, an automatic strategy based on no-lineal filters, smart operator and region growing technique is propose in order to generate the right ventricle ejection fraction. The results are promising due we obtained an excellent correspondence between the manual segmentation and the automatic one generated by the realistic models.

1. Introduction

In cardiology, the most frequently used estimator to assess cardiovascular function is the ejection fraction (EF). In this paper, the EF is considered as the global index of the shortening of the fibers of the cardiac chambers. The right ventricle (RV) is a chamber of the heart, the EF for this cardiac chamber is considered as a global index of RV fiber shortening [1].

Additionally, the medical imaging modality accepted by the cardiologists' community for EF estimation is ultrasound in its two-dimensional and three-dimensional versions [2]. Particularly, for the measurement of the EF of the RV, considering cardiac ultrasound images, the protocol that is usually applied is the following:

a) It is assumed as a geometrical hypothesis that the RV has a triangular-spheroidal shape and a pyramidal-semi-lunar base.
b) Usually, a cardiologist expert draws certain ventricular contours belonging to the phases of final diastole and final systole.

c) Through the use of a numerical method, for example, the Simpson's rule, the diastolic (FDV) and final systolic (FSV) volumes are estimated.
d) The percentage value, of the EF, is estimated by the mathematical model given by Equation (1).

$$\mathrm{EF}(\%) = \frac{\mathrm{FDV}-\mathrm{FSV}}{\mathrm{FDV}} * 100 \tag{1}$$

This protocol exhibits the following limitations:

a) The assumed geometric hypothesis is not always fulfilled, especially if it is a subject with cardiac complications.
b) The protocol is a dependent-operator with the implications that this entails.
c) The EF is measured by taking two-dimensional considerations, despite the fact that the RV is a three-dimensional structure.
d) This protocol does not allow calculating the EF only generates an estimate of its value. Normally, this value is underestimated.

The aforementioned limitations have opened the stage for various researchers to generate strategies aimed at EF calculation but, unfortunately, the classical strategies created for this purpose are cumbersome due to the time required for their implementation and exhibit as a common feature that of being an operator-dependent.

Additionally, it is important to point out that the orientation of this research revolves around the generation of realistic model about RV that allow us to consider the possibility of modifying the described protocol, which is routinely applied in both clinical and surgical contexts.

A realistic model of an anatomical structure is a tangible or real representation generated, usually, using three-dimensional printers [3].

In order to generate the realistic model, segmentation strategies based on artificial smart operators are designed and applied. Hence, it is necessary to identify: What does mean segmentation? and What are the main smart operators considered in the literature?

In this sense, the images segmentation techniques can be interpreted as a digital image processing technique that allow obtaining an accurate description of the shape of the objects present in a scene [4]. Additionally, the main artificial intelligence operators (smart operators) that have been most frequently used, in the context of digital medical image processing, are artificial neural networks, classical support vector machines and least squares support vector machines (LSSVM) [5-7].

These operators are considered as paradigms of statistical learning [8] and they are algorithms with the capacity to learn from experience, with respect to any kind of tasks and a measure of performance.

In this paper, we develop a proposal for the transformation of RV protocol for EF calculation considering realistic model, obtained through LSSVM and computational segmentation strategies and considering multislice computed tomography (MSCT) images.

2. Materials and methods

2.1. Dataset

One three-dimensional MSCT cardiac dataset was used and it was supplied by the "Instituto de BioIngeniería y Diagnóstico S.A., Venezuela". Additionally, RV manual segmentation (ground truth) generated by a cardiologist, is available.

2.2. Computational strategy proposed

Figure 1 shows a block diagram of the automatic computational strategy (ACS), proposed in this paper, for segmenting the RV.

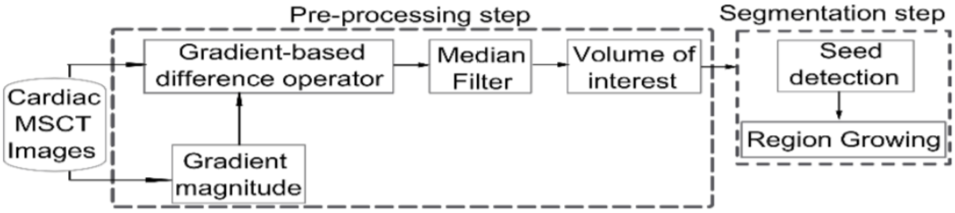


Figure 1. Block Diagram of the proposed strategy [10].

2.2.1. Pre-processing. At this stage, initially, a filter bank is applied to the dataset described in 2.1 section. Then, smart operators based on least square support vector machines (LSSVM) are applied in order to define a volume of interest and seed point. A brief explanation of these filters is found below.

- Gradient magnitude filter (GMF). In this work, an approach based on finite differences was used for GMF computational implementation [9]. This filter generates a smoothed version (I_{GM}) of original image (I_0) calculating the three-dimensional gradient magnitude of I_0, using the mathematical model given by Equation (2).

$$I_{GM} = \left(\left(\frac{\partial I_0}{\partial i}\right)^2 + \left(\frac{\partial I_0}{\partial j}\right)^2 + \left(\frac{\partial I_0}{\partial k}\right)^2\right)^{1/2} \tag{2}$$

  being: i, j, k the spatial directions in which the gradient is calculated and $\left(\frac{\partial I_0}{\partial i}, \frac{\partial I_0}{\partial j}, \frac{\partial I_0}{\partial k}\right)$ the partial derivatives of I_0.
- Gradient-based difference operator. A gradient image (I_g) is calculated by the absolute value of the arithmetic subtraction of I_0 and I_{GM} [10].
- Median filter. This filter computes a smoothed image (I_m) of the image I_g using the median of an arbitrary neighbourhood of each voxel into I_0. In this paper, an isotropic approach is considered for the size of this neighbourhood, which is a tuning parameter that varies between (1x1x1) and (7x7x7), with a step size equal to 1 [11].
- LSSVM for volume of interest definition (VOI). Due to the high similarity about intensity information into both right atrium and the RV, it is necessary to establish a volume of interest (VOI) in order to address the low contrast problem. A detailed explanation of the how the LSSVM are used in VOI definition, can be found in [10-12].

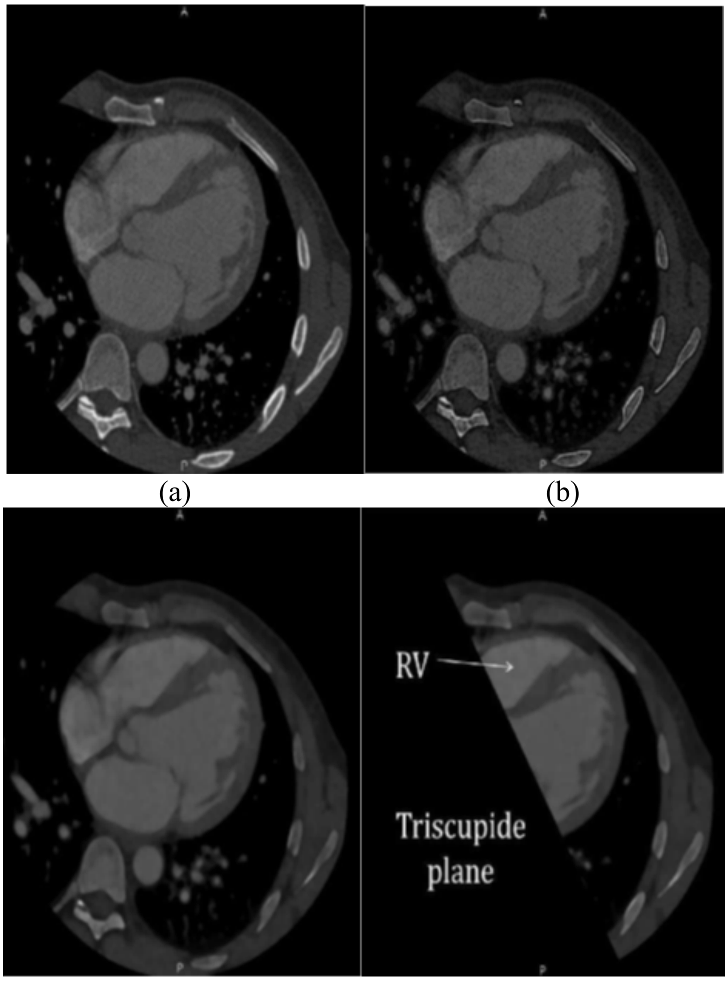
2.2.2. Segmentation. This stage involves two steps: seed point detection and RG segmentation technique. These steps are presented at next.

- Seed point detection. In the dataset, a LSSVM detect the seed voxel using the procedure explained in [10].
- Region growing technique (RG). In the RG, the coordinates of the seed voxel are detected using LSSVM and they are used as the initial position for starting RG using the initial neighbourhood, which has an arbitrary size (*s*). The criterion for including new voxels in the region is defined by an intensity range around the mean value of the voxels existing in this region. The extent of the intensity information interval is computed as the product of the variance image and an arbitrary multiplier (*m*) [13].

During the tuning process, the RV segmented is compared with the ground truth traced by a cardiologist. The dice score (Ds) is used in order to estimate the difference between these structures [14].

3. Results

A maximum Ds of 0.89 is obtained from the tuning, which generated the optimal parameters for RG technique (m = 9.50 and s = 10.00). The LSSVM optimal parameters were 2.00 for penalty error parameter and 0.50 for the radial base function deviation parameter; while the best size of median filter was (7x7x7). Figure 2 shows an axial view of an original image and the images linked to digital processing developed with the ACS.



(a) (b) (c) (d)

Figure 2. Effect of the ACS using a 2D view of RV. (a) Original. (b) Difference operator. (c) Median filter. (d) VOI definition.

Additionally, for an improved observation of the three-dimensional morphology of segmented RV an amplified version of this ventricle is shown in Figure 3.

Figure 3. Three-dimensional representation of segmented RV.

Also, Figure 4 represents the step by step for the RV realistic model generation.

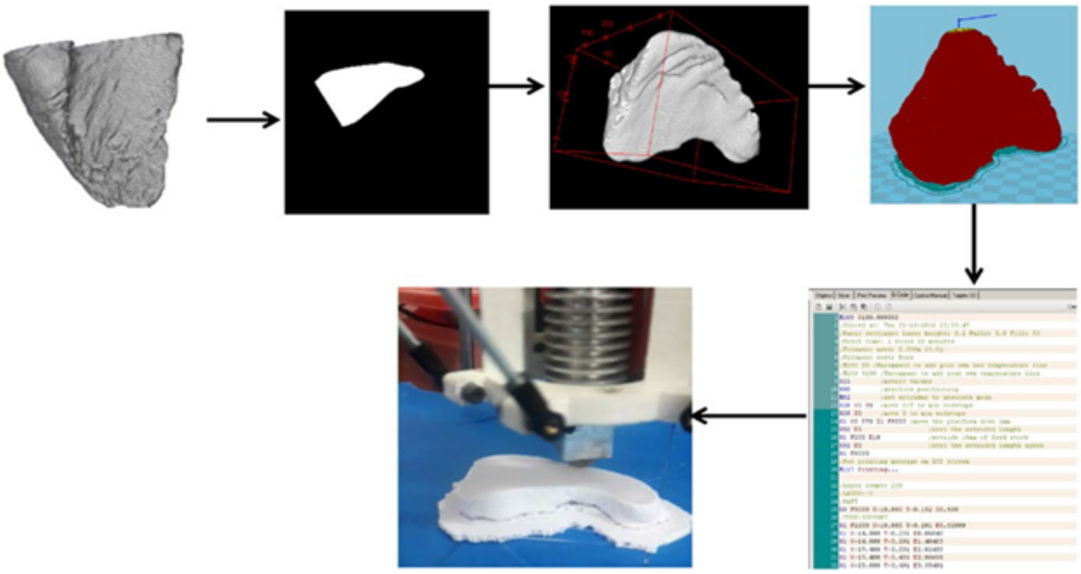


Figure 4. The RV realistic model generation using 3D printer [3].

At the beginning of Figure 4, it is showed the 3D RV segmentation, then its conversion to slices and the code necessary for the adequate interpretation by the 3D printer. Finally, it is presented an example of RV realistic model printing. Table 1 shows the volume values (voxel size multiplied by the number of RV voxels) considering its automatic segmentation in final diastole (FDV) and final systole (FSV).

Table 1. RV ejection fraction results by manual and automatic approach.

FSV (ml)	FDV (ml)	EF (%)
34.00	90.00	62.22 (manual)
44.00	103.00	57.28 (automatic)

Finally, in Table 2 we propose modifications to the RV ejection fraction protocol. Here, it is necessary pointed that the Ds is a metric with values between zero and 1. This metric is better when its value is closest to 1 [14]. In a medical image segmentation context, this means that the manual segmentation and the automatic one matching when the Ds is 1 and they no matching at all when the Ds is zero. In this sense, normally, values of Ds over 0.75 are okay, in the medical routine. In this sense and according with the results, the ACS had a good performance segmenting RV because the maximum Ds value obtained for the RV segmentation was 0.89.

Table 2. Limitations and modifications associated with EF protocol.

Limitations	Proposed modifications
The geometrical hypothesis assumed in the protocol is not fulfilled in all cases. The EF protocol is dependent operator. The protocol only estimates, by default, the value of the blood volumes contained in the cardiac chamber.	The volume can be calculated without to assume any geometrical hypothesis: Considering the digital segmentation of the RV, the volume is calculated by multiplying the voxel dimensions by the number of voxels that make up each structure. Considering the realistic model (MR) printed from the segmentations, the MR is introduced in a graduated cylinder which allows to directly calculate the volume of the RV.

4. Conclusions

The considered automatic segmentation technique allows generating the actual morphology of RV. It was verified that the aforementioned segmentation is useful not only to generate 3D computational RV representations, but also to obtain tangible realistic models, through the 3D printing process, which allow accurately calculate the value of the RV volume. Usually, in the clinical routine the volume occupied by the RV is of vital importance for the detection, diagnosis, monitoring and planning of treatments or behaviours to be followed when addressing RV pathologies.

It is hoped that the results of this research will be disseminated through appropriate mechanisms so that the medical community can be made aware of the importance of reviewing and updating the clinical protocols that depend on volume as a descriptor of the appearance or follow-up of diseases that affect the body of human beings.

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