3D Modeling and Parameterization of the Left Ventricle in Echocardiographic Images Using Deformable Superquadrics

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Abstract

This paper proposes a new method for the quantitative analysis of the mobility of the left ventricle LV, based on a 3D dynamic model. One superquadric is used as the 3D global model. For data acquisition, an electro-mechanical device that allows acquiring the volume of images using 60 cross-sections in a rotational cylindrical 3D symmetry is adapted to an echograph. The images are filtered and later, they are segmented by a specialist. This processing provides images where the internal and external structures are already known. Finally, the 3D superquadrics model is used and we minimize the energy of the quadratic error using the method of descending gradient for several variables. We capture the geometrical and mathematical parameters when the model is adjusted to actual data. After, it is necessary to compute the medical parameters as: LVV, LV mass, stroke volume, ejection fraction, and cardiac output, etc. We propose new measures allowing the observation of the variations of the parameters in function of time. For example, in the calculation of the LVV, the results give a small error of 2% by respect on a manual segmentation made by the specialist. That demonstrates a good adjustment to the 3D volume images to the LV.

1. Introduction

The first cause of death in the United States is the Cardiovascular Disease CVD. More than 2600 Americans die every day victims of CVD, an average of one death each 33-sec. The Cardiovascular Disease kill every year around one million people in the United States, this quantity is bigger to the next seven leading causes of death combined and it affects the population who are between 35 - 74 years old. According to the most recent computations of the Control and Prevention of the National Center for Health Statistics (CDC/NCHS) [1].

The 3D imaging of the heart is a research area in continuous development. The new advances in hardware and the methods of space-temporal acquisition images of the heart have extended the frontiers in the clinical diagnosis and the research of Cardiovascular illnesses. The heart image is very important in the detection and diagnosis of the patient with cardiovascular illnesses and it is important in the therapeutic analysis and medical decisions.

The qualitative interpretation of echocardiographic images exists and provides an important information for the physician. However the quantitative echo cardiography will play a decisive role in the diagnosis, treatment and prognostication. Until today, each echocardiographic study gives their parameter values as the reference values [2,3].

The use of geometric models is not totally new to the analysis of cardiac images [4]. This models can be divided according to the information that you can extract from the images [4]. **1)** A global information obtained in order to extract the medical parameters that determine the functionality of the heart. **2)** A local information that allows the analysis of the movement and local deformations of the walls or the valves of the LV and RV. The main objective of this work is 1) to obtain some global parameters and 2) to compare these parameters obtained from the information of 2D images with respect to those obtained from the volumetric reconstruction of the LV.

2. Methodology

The detection and quantification of medical parameters for the medical diagnosis are the result of a long processing chain that begins with the radial acquisition of image sequences of the heart.

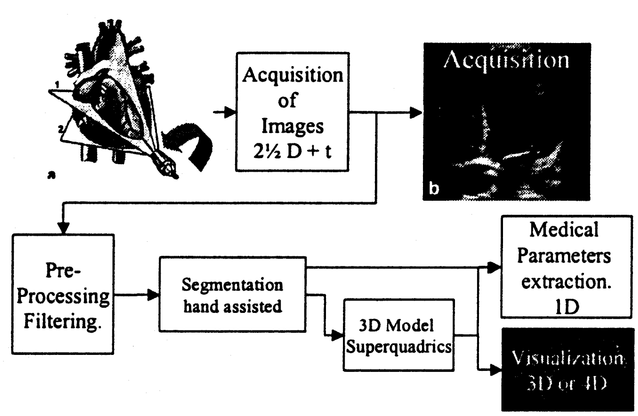

Figure 1. The chain of processing from ultrasound image sequences.

The problems of image acquisition and some solutions were published in [5]. The preprocessing and filtering were published in [6]. In this work, we will concentrate on the analysis and the extraction of the parameters from superquadric models. In figure 1, we can see the scheme proposed for the processing chain of echocardiographic images in order to obtain some useful parameters for the medical diagnosis.

2.1. Parameters extraction

The traditional methods to obtain parameters such as LV Volume and LV Mass from echocardiography were based on a simple geometrical models. For example, the formula used by the physician to obtain the volume of the ventricles in 2D echocardiography is: $0.85 * A^2/L$ [7]. This formula supposes that the LV is similar to an ellipsoid. This basic geometrical model was motivated by the necessity of extracting 3D parameters from 2D information. However, these approaches were always susceptible to errors and their accuracy was limited.

In practice, the indices of the cardiac function are linked to the volumetric measures such as: LVV, LV mass, and Ejection Fraction (EF). Five of the most used parameters for the medical diagnosis are described in the following section:

LVV - Left Ventricular Volume is a basic parameter required to obtain other LV indexes, for example: EF. At the beginning, some 3D models were used to approach the value of the LV volume. 1) A volume model with a simple shape (e.g. a truncated ellipse); 2) A model as the sum of small volumes of similar configuration (e.g. the Simpson's method) [7]; and 3) As the combination of different shapes. The accuracy in the computation of the LVV with echocardiography depends on the model used to represent the LV. In summary the volume of the LV represents the quantity of blood (ml) in the ventricle, and it depends of the electro-mechanic activation of the heart.

LVM - Left Ventricular Mass is a predictor of cardiovascular risk and higher mortality. The hypertrophy is characterized by an increment of the ventricular mass. The ventricular hypertrophy, sometimes caused by the high tension. LVM can be determined by two factors [7]: the chamber volume and the wall thickness. In the computation of LVM, the interventricular septum is assumed as a part of the LV. The volume of the myocardium, V_m, is the difference between the total volume among the epicardial borders of the ventricle, $V_t(\text{epi})$, and the chamber volume, $V_c(\text{endo})$; the LVM is the value V_m multiplied by the density of the muscle tissue, $1.05\, gr/cm^3$. The formulae are shown in table 1.

SV - Stroke Volume, is defined as the volume ejection between the end of diastole and the end of systole.

EF - Ejection Fraction, is a global index of LV fibers reduction, and is considered as one of the most important measures of the LV pump function. It is defined as the ratio between the SV volume and the volume of the end of the diastole.

CO - Cardiac Output, is defined as the product of the activity of pumping SV by the Heart Rate, HR. The role of the heart is to distribute an appropriate quantity of oxygenated blood to the body. This blood flow is known as the cardiac output and is expressed in liters per minute.

In this study, we will make a comparative analysis between the parameters calculated on each one of the 2D images and the parameters calculated directly on the 3D segmentation using the model.

The equations used to obtain the cardiac parameters can be seen on the table 1.

Table 1. A global cardiac parameters.

Parameters	Equations
Left Ventricle Volume. LVV.	$\frac{0.85 * A^2}{L}$
Left Ventricular Mass. LVM.	$V_m = V_t(\text{epi}) - V_c(\text{endo})$ $\text{LVM} = 1.05 \cdot V_m$
SV - Stroke Volume.	$SV = Dia.Vol(EDV) - Sys.Vol(ESV)$
EF - Ejection Fraction.	$\text{EF} = \frac{\text{SV}}{\text{EDV}} \cdot 100\% = \frac{\text{EDV - ESV}}{\text{EDV}} \cdot 100\%$
CO - Cardiac Output.	$\text{CO} = \text{SV} \cdot \text{HR}$

Actually, the quantitative analysis of the echocardiographic images was made in 2D with the formulae showed previously. The practician must know the exactly anatomy and all the standard echocardiographic windows. The second proposed method consists in a manual segmentation of each slice in order to make a 3D reconstruction and to obtain the volumetric parameters.

In this work, a third method is proposed for the quantitative analysis based on the deformable superquadrics. It is possible to make in the same time: a 3D global reconstruction of the LV, the visualization, the analysis of the global movement of the LV, and the extraction of the quantitative parameters that allow the evaluation of the cardiac function.

3. Deformable model: superquadric

The superquadrics are a family of parametric surfaces that were used by Terzopoulos and Metaxas [8] to model a complex 3D shapes. The deformable superquadrics are defined in a parametric form as following :

$$\text{S}(u,v) = \begin{bmatrix} x(u,v) \\ y(u,v) \\ z(u,v) \end{bmatrix} = \begin{bmatrix} a \cos^{e1}(u) \cos^{e2}(v) \\ b \cos^{e1}(u) \sin^{e2}(v) \\ c \sin^{e1}(u) \end{bmatrix} \qquad (1)$$

where: $-\pi/2 \le u \le \pi/2$ and $-\pi \le v < \pi$

The parameters u and v corresponds to the angles of latitude and longitude respectively expressed in a spherical coordinated system centered in the object. The scale values: ***a, b*** and ***c*** define the size of the superquadric in a Cartesian Coordinate System. The exponents e_1 and e_2 produce an effect of square ness of the ellipsoid. The implicit equation of superquadric is the following:

$$\left[\left(\frac{x}{a}\right)^{2/e_2}+\left(\frac{y}{b}\right)^{2/e_2}\right]^{e_2/e_1}+\left(\frac{z}{c}\right)^{2/e_1}=1 \qquad (2)$$

3.1. Minimization Algorithm

We minimized the energy of the quadratic error for the adjustment of the model's parameters using the method of descending gradient for several variables. The expression of error between the model and data is the following :

$$Err(a_i)=\sum_{p_n}\left[1-F(p_n:a_i)\right]^2 \qquad (3)$$

where : p_n are the points obtained from the segmentation of the ventricle, a_i are the parameters of the model, and $F(p_n{:}a_i)$ is the implicit equation of the superquadric with all transformations.

The gradient vector of the error function ($\vec{\nabla}Err$) indicates the direction of growth of the objective function. Therefore, the a_i parameters are modified in small increments in the opposite direction. The following adjustment is made, in an iterative form, to each one of parameters:

$$a_i^{k+1}=a_i^k-\lambda_i\frac{\partial}{\partial a_i}Err \qquad (4)$$

All parameters are simultaneously adjusted and the magnitude of the modification is determined by the constant of adjustment λ_i, that is chosen independently for each a_i parameter.

4. Adjustment of the model

We used the sequence acquired by the trans-thoracic rotational sweep method [5]; and for each time interval, we make sixty (60) radial sections of the ventricle (figure 2a). A cardiologist manually segments these sections (figure 2b) and the extraction of the LV's internal and external walls (figure 2c) is obtained. We store the spatial data of the position of each point forming the edges of the ventricular walls as vectors and this cloud of points is used for the subsequent adjustment of the model.

5. Results

When the model's adjustment is completed, the parameters : position, orientation, size, torsion and shape of the LV are recovered. The model adjusts to all the sequence of volumes of actual cardiac data.

The evaluation of three different results is obtained in this paper : **1)** Using the formulae previously presented on the 2D images. **2)** Using the 3D calculation from manual segmentation and **3)** Using the 3D superquadric model.

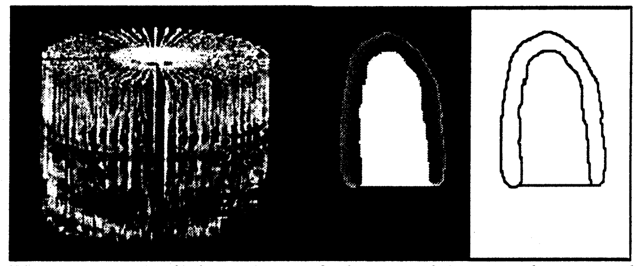

Figure 2. a) Radial sections of ultrasound images. b) Manual segmentation by a specialist. c) Ventricle edges extraction.

5.1. Results - global parameters extraction

The evaluations of the 2D and 3D results were independently made, without knowledge in the previous results. The 3D results were classified as the reference results. Five clinical parameters were evaluated: LVV, LV mass, SV, EF, and CO, which have been previously described.

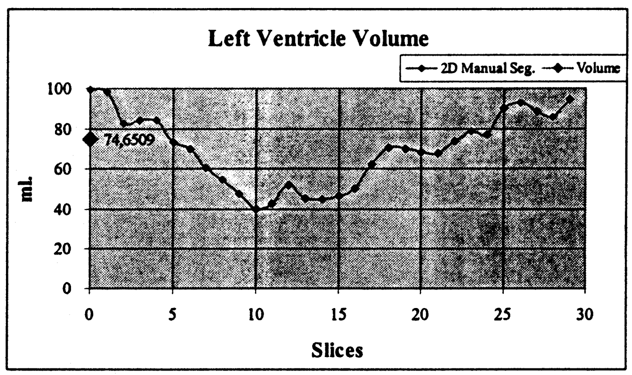

Figure 3. Comparative graph of the volume trend, calculating the 2D formula on each slice, on the actual volume.

Table 2. Computed parameters with three different methods.

Parameters	2D basic method	3D manual segmentation	3D Super Quadrics	Units
LVVED	69.8 ± 17	74.65	74.46	ml
LVVES	32.8 ± 13	33.89	35.04	ml
LVM		84.75	84.18	gr
SV	37 ± 17	40.76	39.42	ml
EF	53 ± 9	54.6	52.9	%
CO	3.0	3.3	3.2	Lit/min

The figure 3 shows the results that correspond to a manual segmentation. The volume average using all the slices on the graph (figure 3) is 69 ml, with a standard deviation of 17, that is a big variation. The maximum error in the determination of the LVV will be obtained if the slice #10 (40 ml) is chosen. So, the 2D calculation of parameter is extremely dependent of the chosen slice.

Table 3. Computed parameters made by several authors.

Parameters	Angelini et al. [2]	Lorenz et al. [3]	Web-Site. *	Suggested Approach	Units
LVVED	90.6±20		68.9±13	74.46	ml
LVVES	41.5±9.9		27.1±7.8	35.04	ml
LVM		2.4 ± 0.3	91.6±3.2	84.2	gr
SV	49.1±10	45 ± 8	41.8±10	39.42	ml
EF	54 ± 3	67 ± 5	60 ±11	52.9	%
CO		2.9 ±0.6		3.20	lit/min

* http://www.mri.jhu.edu/~dbluemke/Cardiac%20Parameters.html

Lorenz et al. [3] computed some normal values for the Ejection Fraction using MR, which is 67 ± 5% (see table 3), while the maximum ranges are among: 57% - 78% for the LV and 61 ± 7% for the RV. In our case, we obtain 52.9% which is a smallest value by respect to the other methods.

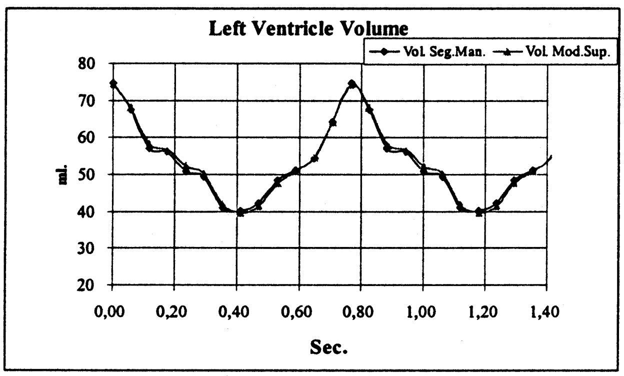

Figure 4. a) Comparison between the actual volume and the volume of the superquadric model in function of time.

The quatitative comparison between the volume of the LV and the volume of the superquadrics (figure 4) in function of the time shows a small error around 2% in the volume calculation.

Figure 5 simultaneously shows the LV and the model in the telediastole (ED) and telesystole (ES) instants.

6. Conclusions

The parameters extraction using only bi-dimensional slices has the following drawbacks: a) it is extremely dependent of the chosen slice to make the analysis, and b) it is dependent of the variability between one observer and another.

In conclusion this work presents a parametric model based on the superquadric for the quantitative analysis of the 3D movement of the LV. The developed model provides the necessary shape parameters to obtain the results "clinically useful" for the cardiologist. It helps to guide the diagnosis and the therapy adapted for each particular patient.

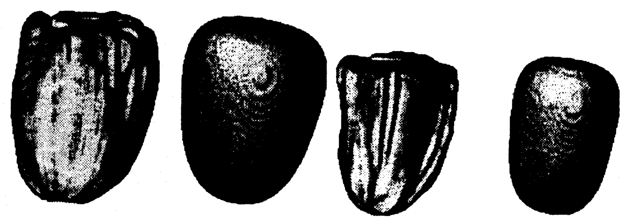

Figure 5. Comparison between the LV reconstruction and the model a) telediastole (ED) and telesystole (ES).

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