Age-Dependency of Left Ventricular Shape Measured from Real-Time 3D Echocardiographic Images

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Abstract

Combined assessment of left ventricular (LV) shape and function could provide new insights into the process of LV remodeling. Real-time 3D echocardiography (RT3DE) allows rapid and accurate semi-automated extraction of LV endocardial surfaces. Our aims were to quantify LV morphology both globally, using conical (C) and spherical (S) indexes, and locally, studying the mean curvature, in a large set of normal subjects in order to define normal values and test their age-dependency.

In each age group the LV became less spherical and more conical during systole. LV shape is the same among the age groups, except for young subjects in which the highest S and lowest C values were found, associated with a greater K at medial and apical inferior regions when compared to other age groups.

These results constitute a reference for future comparisons with serial follow up of patients during LV remodeling.

1. Introduction

The relationship between ventricular function and shape is well known in literature [1]. Evidences have been shown imposing functional or morphological changes and then assessing the induced modification in the other parameter [2,3]. This dynamic balance is achieved through the physiological process of remodeling, that aims to restore the normal LV function by inducing changes in its morphology.

In clinical routine the most widely used parameter to describe LV function is the ejection fraction, usually evaluated through standard echocardiographic examinations. Unfortunately there are not similar parameters to describe 3D ventricular shape, due to the inaccuracy of previously proposed indexes based on 2D images.

Recent improvements in ultrasound imaging techniques led to the availability of the acquisition of true three dimensional dataset, by real-time 3D echocardiography (RT3DE). In fact, RT3DE both allows the rapid acquisition of 3D datasets and provides the basis for an accurate estimation of LV size, function and mass [4].

Accordingly our aim was to quantify, from RT3DE datasets, the 3D LV shape, both globally and regionally, in a large group of normal subjects over a wide range of age, using a previously developed method, in order to define normal values and test their age-dependency.

2. Methods

Normal volunteers were enrolled at the University of Chicago Medical Center, Chicago, IL. A population of 147 subjects (93 M and 54 F, age 3-88 years, mean age: 37.7±18.8 yrs) was studied and subjects considered to be healthy after standard echo examination. The population was divided into six groups according to age decade (Table 1). Subjects younger than 20 or older than 60 were grouped respectively in the 1st and in 6th groups.

Table 1. Number of subjects included in each age decade.

Age	<20	<30	<40	<50	<60	>60
# subjects	25	26	30	26	22	18

Imaging was performed using a Philips iE33 ultrasound system equipped with the X3 probe (Philips Medical System, Andover, MA), that uses 3000 active elements to obtain a pyramidal volume dataset from a single transthoracic apical window. RT3DE datasets were acquired using the wide-angle mode, in which 4 wedge-shaped subvolumes were obtained over 4 consecutive cardiac cycles during a breath hold with R-wave gating. Poor quality 2D apical window, sinus arrhythmia and dispnea precluding 10s breath hold were considered as exclusion criteria.

LV endocardial surfaces were obtained semi-automatically from RT3DE datasets using commercial software (4D LV Analysis, TomTec, Unterschleissheim, Germany).

2.1. Shape indexes computation

Extracted LV endocardial surfaces were imported in Matlab (MathWorks, Inc) and filled using morphological operators to obtain binary datasets (1 inside, 0 outside). The 3D LV endocardial surface was then represented as a 1D signal by helical sampling, using the procedure described in [5]. Briefly, a cylindrical floating reference system was defined for each frame, with its unit vector **v** overlapping the axis associated with the minimum inertia moment (the LV long axis, LAX). The surface was then sampled along a helical pattern aligned with **v** from apex to base, using 64 windings and 36 samples per winding (Figure 1.A). The obtained signal $\rho(\theta)$, describing the Euclidean distance from LAX to the endocardial surface, was then normalized by LAX length (Figure 1.B) leading to signal $s(\eta)$. To obtain a shape descriptor with a constant number of samples, independent of LV dimensions, a variable pitch in the sampling helix was utilized.

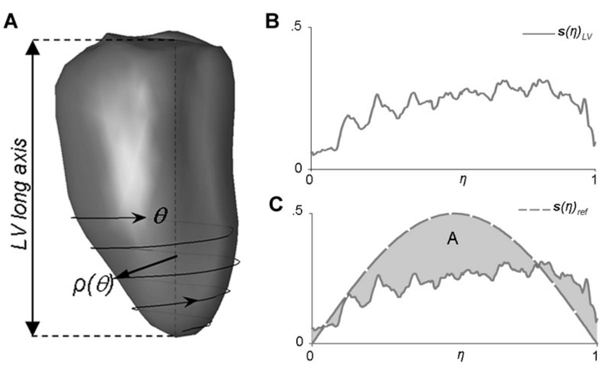

Figure 1. A) the LV endocardial surfaces and the sampling helix; $\rho(\theta)$ represents the Euclidean distance between LV long axis (LAX) and endocardial surface. B) the 1D signal obtained by the helical sampling; the signal $s(\theta)$ is obtained by normalizing $\rho(\theta)$ by LAX, while η normalizing the angular coordinate θ. C) the area A between $s(\theta)$ and a reference signal $s(\theta)_{REF}$ measures the degree of dissimilarity between the two signals.

Starting from this representation, a 3D shape index (SI) can be defined by measuring the degree of similarity between $s(\eta)$, computed from the LV ($s(\eta)_{LV}$), and that obtained using the same procedure for a reference 3D shape ($s(\eta)_{REF}$) by:

$$SI = 1 - A/A_{max} \quad (1)$$

where A is the area between the $s(\eta)_{REF}$ and $s(\eta)_{LV}$, and A_{max} is the total area in the (s,η) plane, equal to 0.5 (Figure 1.C).

We defined two different shape indexes: sphericity (S) and conicity (C). The corresponding signals $s(\eta)_S$ and $s(\eta)_C$ were obtained from LV inertia moments in each frame, thus preserving the LV aspect ratio.

2.2. LV endocardial surface curvature

LV endocardial curvature was evaluated in each point starting from the wireframe of the extracted surface, as described in [6]. First, the normal unitary vector ($\mathbf{N}_i$) in each node i was evaluated, then a local Cartesian reference system ($\mathbf{U}_i,\mathbf{V}_i,\mathbf{N}_i$) was created. The tangent vector $\mathbf{U}_i$ was calculated by imposing two components to be unitary and the scalar product with $\mathbf{N}_i$ to be equal to zero:

$$\mathbf{N}_i \cdot \mathbf{V}_i = 0 \quad (2)$$

and then normalizing by $|\mathbf{N}_i|$.

The tangent vector $\mathbf{V}_i$ was calculated as the cross product between $\mathbf{N}_i$ and $\mathbf{U}_i$:

$$\mathbf{N}_i \text{x} \mathbf{U}_i = \mathbf{V}_i \quad (3)$$

Then, the coefficients of a full quadric polynomial function $h_i(u,v)$

$$h_i(u,v) = a \cdot u + b \cdot v + c \cdot u^2 + d \cdot u \cdot v + e \cdot v^2 + f \quad (4)$$

were determined by least-squares fitting it to the neighbourhood of the node i. The hessian matrix $\mathbf{H}_i$ of the function $h_i(u,v)$ was then diagonalized: the eigenvectors of $\mathbf{H}_i$ are the principal directions, while the associated eigenvalues are the principal curvatures k_1 and k_2 in the node i. The mean curvature K_i in each node was defined as the arithmetic mean value of k_1 and k_2. The curvature mean value for each of the 17 standard myocardial segments, in which the LV endocardial surface was divided [7], was calculated as the average curvature of the nodes belonging to same segment. The apical segment, the 17^{th}, was not considered in the following analysis.

2.3. Statistical analysis

Separately for each decade, a paired Student t-test ($p<.01$) was applied to test for global shape and regional curvature changes through the cardiac cycle, considering the end-diastolic (ED) and the end-systolic (ES) values.

In order to investigate differences in LV shape with age, ANOVA with Bonferroni correction was performed, separately for ED and ES, and for each index and regional segment. Significant differences were found applying Tukey HSD test ($p<.05$).

In addition, for a subgroup of 50 subjects the LV surface detection and the morphological analysis were performed by two different operators. The interoperator variability both for volume and shape indexes was investigated. The coefficient of variation (CV%) between

N measurements *x* performed by two operators A and B was defined as:

$$CV(\%) = \frac{1}{N}\sum_{i=1}^{N}\frac{\sigma(x_A, x_B)}{\bar{x}} \cdot 100\% \qquad (6)$$

where $\sigma(x_A, x_A)$ is the standard deviation and $\bar{x}$ the mean value.

3. Results

3.1. Shape changes in the cardiac cycle

The mean values for each decade, separately for ED and ES, are presented in Table 2.

Table 2. End-diastolic (ED) and end-systolic (ES) values for spherical (S) and conical C indexes. Values are expressed as mean±SD (t-test, *: p<.01 ED vs ES).

	S		C	
age	ED	ES	ED	ES
<20	.64±.05*	.59±.05	.79±.03*	.82±.03
<30	.62±.03*	.57±.04	.80±.02*	.83±.02
<40	.63±.04*	.56±.04	.80±.02*	.83±.02
<50	.61±03*	.56±.04	.81±.02*	.84±.02
<60	.62±.04*	.56±.04	.80±.02*	.84±.02
>60	.61±.03*	.57±.04	.81±.02*	.83±.03

Independently of age, the LV resulted to be less spherical and more conical during systole; conversely, a more spherical morphology was restored during diastole.

3.2. Intergroup shape differences

The results of the comparison of S and C indexes among the considered age groups are shown in Figure 2.

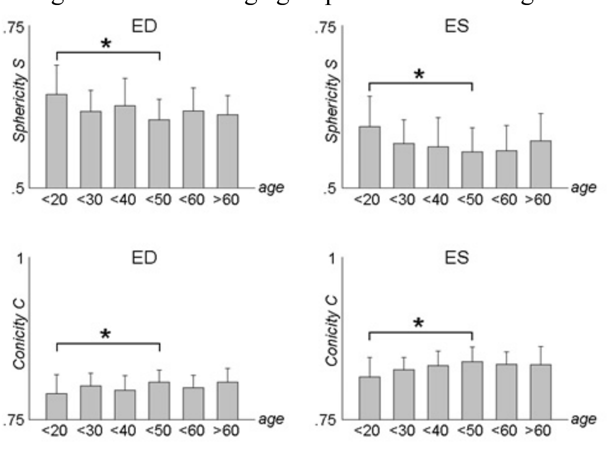

Figure 2. Results of sphericity S (top) and conicity C (bottom) according to age decade at end-diastole (ED, left) and end-systole (ES, right). Values are expressed as mean±SD. (HSD test, *: p<.05)

The highest values in S (ED:.64±.05; ES:.59±.05) and the lowest values in C (ED:.79±.03; ES:.82±.03) were found in young subjects (age<20 yrs), with significant difference from the 40-49 years age decade, where the lowest S (ED:.61±.03; ES:.55±.04) and the highest C (ED:.81±.02; ES:.84±.02) were noticed.

3.3. Endocardial curvature

In figure 3 the polar plots for the mean value of curvature for each segment are presented, separately for ED and ES.

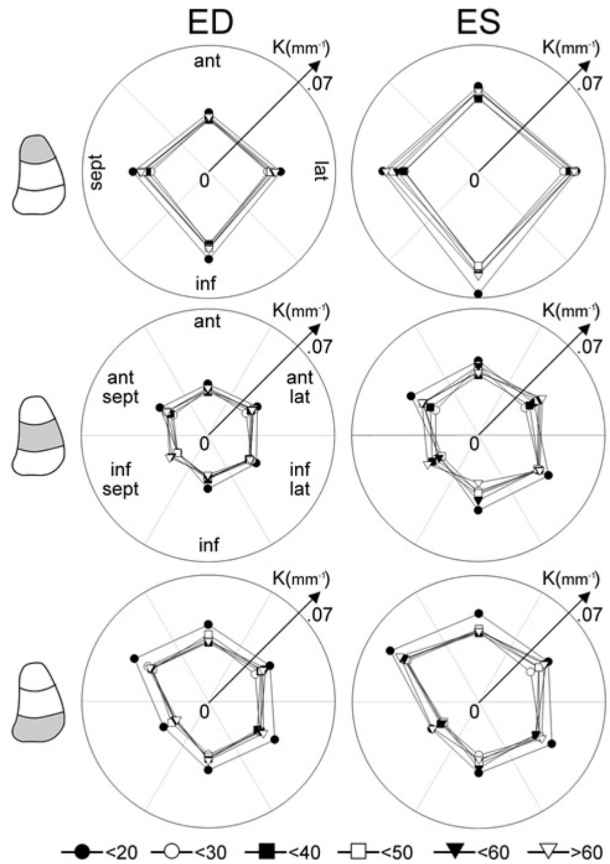

Figure 3. Mean curvature K for apical (top), medial (center) and basal segments (bottom) are shown for each of the 6 age groups at end-diastole (ED, left) and end-systole (ES, right). Nomenclature of each segment is given in the top left plots. The radial coordinate represents K, ranging from 0 to .07 (in mm^{-1}).

In each group, the mean curvature K was found larger at ES than ED (t-test, p<.01), corresponding to a lower systolic mean radius of curvature. For subjects aged less than 20 years, K was found greater at base and in the inferior segments of mid and apical LV endocardium at ED compared to the other age groups (HSD, p<.05).

3.4. Inter-operator variability

The coefficient of variation relevant to LV volumes, conicity and sphericity indexes are shown in Figure 4.

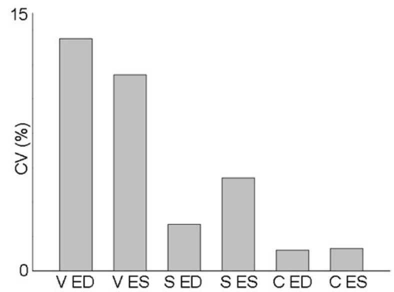

Figure 4. The coefficient of variation (CV%) relevant to end-diastolic (ED) and end-systolic (ES) values for LV volume (V), sphericity (S) and conicity (C) indexes. Values are expressed as %

Our results showed that LV volume estimation is more affected by operator subjectivity than C and S indexes computation. In particular C index value seemed the least affected by the inter-operator variability (ED: CV_C=1.2%; ES: CV_C=1.3%).

4. Discussion and conclusions

We evaluated both global and regional LV shape in a large population of normal subjects using a previously proposed methodology. The global 3D LV shape information was exploited by reducing the problem complexity to 1-D but considering the LV shape ratio.

Despite the high inter-operator variability in LV endocardial tracing, which influence LV volume computation, the computed sphericity and conicity indexes, independent of LV size, reflected only a minimal part of this variability. In all the examined age groups, consistent morphological changes were noticed during the cardiac cycle, reflecting ejection (LV more conical) and filling phases (LV more spherical). Interestingly, age differences in global shape were found only between subjects <20 yrs with subjects 40<age<50 yrs, with the LV more spherical and less conical in younger subjects. This may reflect the lower end-diastolic pressure in the right ventricle compared with the left ventricle, in younger subjects. Also, regional mean curvature analysis showed that in subjects <20yrs the whole basal region, and the apical and medial inferior segments were more curved compared to the other age groups. These results suggest than in young people the myocardium is still in evolution and that the process of growth is not simply a scaling process, but influences directly LV remodeling.

These observations are in agreement with [8], where an increase in roundness of the LV shape with age in infants, compared to newborns, is reported, and with [9], where a decrease in LV sphericity with age in adulthood in described.

In conclusion, 3D LV shape analysis of RT3DE images may provide useful information on LV morphology, both globally and locally, and help to better understand its relation with LV function. These results constitute a reference for future comparisons with serial follow up of patients during LV remodeling, or with patients with congenital heart disease.

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