Ultrasound Echocardiographic Assessment of Transmural Inhomogeneity of the Left Ventricular Contraction during the Heart Cycle

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Abstract

Functional echocardiographic imaging, based on speckle tracking, has recently gained widespread use. It provides valuable clinical information, but only the longitudinal or circumferential strains are provided. Assessing these measures across the wall has immense diagnostic information. The purpose of this study was to employ a novel technique that allows measuring the left ventricular transmural kinematics in normal subjects.

A novel smoothing technique was developed for a speckle tracking imaging program, called 2D-strain, to achieve spatial transmural resolution analysis, and then applied to standard echocardiographic cines. The results show heterogeneity of the left ventricular rotation and circumferential strain across the wall, with large values for the inner layer, and smaller ones for the outer layer.

Using standard echocardiography, transmural analysis is feasible, and it may provide early diagnosis of different pathologies that were difficult to attain before.

1. Introduction

The left ventricle (LV) is composed of mayo-fibers that create a complex three-dimensional structure. The mayo-fibers are oriented circumferentially, with a well-ordered distribution of fiber angles versus the LV circumferential direction, from about -60° at the epicardium to about 60° at the endocardium. The macro-structure of a normal LV can be described as a cone [1]. During contraction the conical LV shrinks, and due to the incompressibility of the myocardium the circumferential strain becomes larger in the endocardium than in the epicardium. This transmural gradient of the circumferential strain was measured by tagged MRI [2-5].

The transmural gradient of the sarcomere shortening could have been much larger unless the fibers at the inner and outer layers of the myocardium were oppositely oriented. This opposite orientation causes the base and apex to rotate in opposite directions and creates torsion. The LV torsion, which is also non-uniform across the transmural direction [6-10], tends to equalize the sarcomere shortening and the mechanical loading between the endocardial and epicardial layers [11-14], thus equalizing the energy demand distribution across the myocardium [7].

The purpose of this study was to measure in normal subjects, by echocardiography, the transmural gradient of the circumferential strain and LV rotation at three short axis levels, thus allowing the calculation of the torsion across the wall.

2. Methods

The study included 10 healthy adult human subjects. The subjects underwent standard 2D ultrasound scan by VIVID VII system (GE Healthcare Inc). Subjects were included in the study if the clinical examination, the 2D-echo and the echo-Doppler examinations were all normal.

In this study, 3 levels of short axis acquisitions were analyzed, to evaluate the myocardial velocities during the heart cycle along the circumferential direction, across the wall and at different levels. The circumferential strain and the rotation were estimated off-line, for three myocardial layers.

The method is based on ‘2D-strain’, a speckle tracking imaging program on which a commercial product exists (UFI, GE Healthcare Inc.). The ‘2D-Strain’ algorithm tracks reflectors imaged by standard 2D echocardiographic cines, which are provided by a VIVID VII ultrasound system. By tracking the strong reflectors in the B-mode images from frame to by frame [15], it assigns the processed/filtered values in each region to a ‘tracking point’. The method imposes a grid of such tracking points on the imaged cross-section of the myocardium. It evaluates the velocity of each tracking point on the grid, according to the region surrounding it.

Thus a velocity function for each short axis slice is obtained: it has 3 dimensions, one along the circumferential orientation (with 50-60 samples), one across the myocardial wall (the radial orientation, with 4 samples), and one along time (along one cardiac cycle, 50-70 samples according to the frame rate). This velocity function serves as the raw-data for the novel. In order to achieve high spatial resolution, a new smoothing procedure of 3D wavelet de-noising was applied [16]. The rotation of every myocardial layer was evaluated as described by Notomi et al. [17], and the circumferential strain was evaluated as described by Rappaport et al. [15].

3. Results

3.1. Computerized phantom results

A computerized rotating phantom was modified to perform an inhomogeneous movement (of 0.5 sec duration) with different angular velocities: the angular velocity was maximal in the outer layer (0.2 rad/sec) and was linearly reduced with the radius, towards the inner layer (Fig. 1). The measured rotation and circumferential strain were estimated and compared with the theoretical values for 6 layers (Table 1 and Fig. 2). The mean absolute error of the maximal rotation, measured in the last frame, was 0.85 [Deg] and the mean absolute error of the circumferential strain in the last frame was 1.1 [%].

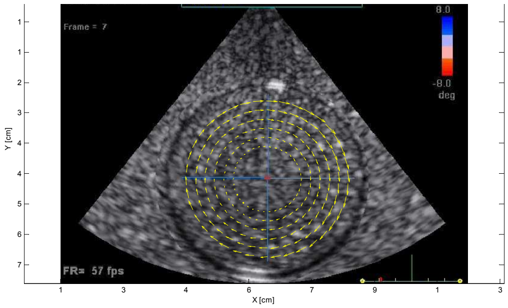

Figure 1 – The arrows represent the velocities of the rotating phantom. The inhomogeneity in the radial direction is preserved while using Wavelet de-noising.

radius	0.79	1.02	1.22	1.45	1.66	1.88
real rotation	-9.1	-12.2	-15.3	-18.4	-21.5	-24.5
measured rot.	-10.3	-12.6	-16.1	-19.2	-22.5	-25.4
real circ strain	0	0	0	0	0	0
measured circ st.	-3.4	-1.6	-0.5	-0.2	0.6	0.3

Table 1 – Theoretical and measured rotation [Deg] and circumferential strain [%] at different layers (radii in cm).

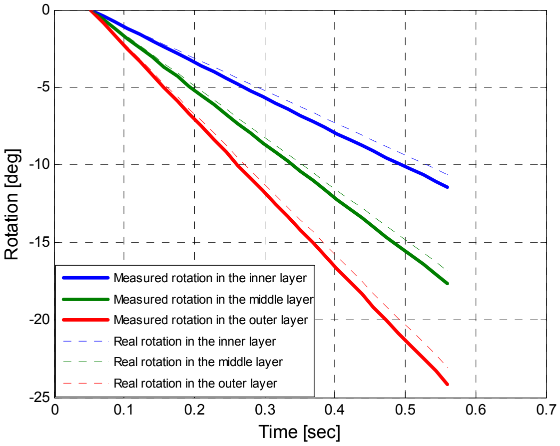

Figure 2 – Theoretical (dashed line) and measured (smooth line) rotation [Deg] and circumferential strain [%] at different layers (radii in cm). The mean value of rotation error, at the last frame, is 0.85 degrees.

3.2. Clinical results

Results from 10 normal subjects are presented below. Some cines loops were not at good enough quality, and could not be analyzed due to low tracking quality. It can be seen in Tables 2 and 3 that the rotation, torsion and circumferential strain obtain the largest values at the endocardium and their values are smaller towards the epicardium. The bar plots in Figs. 3-5 show the peak rotation, torsion and circumferential strain and their standard deviations, respectively. Table 4 summarizes the results of paired T-test that was done for every pair of layers.

Layer	Rotation [Deg] AP (N=7)	Rotation [Deg] PM (N=10)	Rotation [Deg] MV (N=9)	Torsion [Deg] (N=7)
Endo	9.0±3.3	1.3±2.4	-5.1±1.8	12.9±3.5
Mid	6.4±2.4	1.4±2.0	-3.7±1.3	9.0±2.7
Epi	4.7±1.8	1.5±1.7	-2.8±1.4	6.1±2.6
Aver	6.6±2.4	1.4±2.0	-3.8±1.3	9.3±2.8

Table 2 – Peak Rotation for three myocardial layers and the average value in three levels of short axis cross-sections – Apex (AP), Papillary muscles (PM) and Mitral valve (MV). The last column represents the torsion that was calculated between the AP and MV levels. N = number of analyzed subjects. Values are mean ± standard deviation.

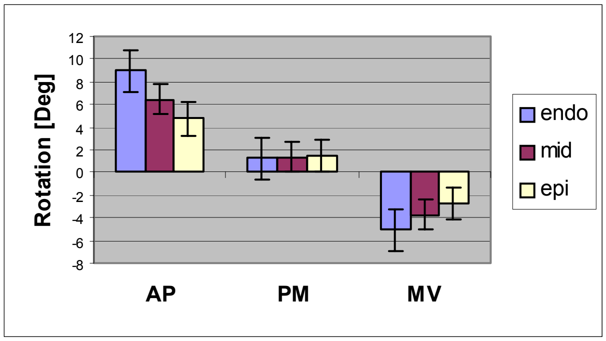

Figure 3 – Peak rotation of the myocardial layers, acquired at three levels of short axis cross sections.

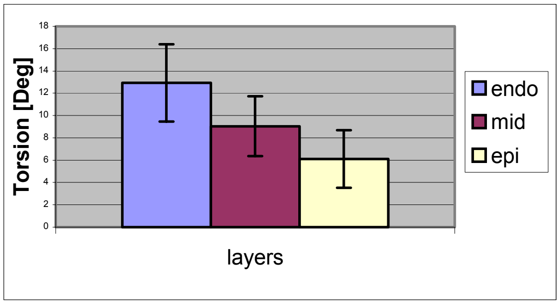

Figure 4 – Mean peak torsion of myocardial layers, measured between the AP and MV short axis cross section.

Layer	Circ Strain [%] AP (N=7)	Circ Strain [%] PM (N=10)	Circ Strain [%] MV (N=9)
Endo	-30.9±9.6	-26.0±9.8	-23.3±8.1
Mid	-21.3±6.6	-19.1±5.2	-17.1±5.6
Epi	-14.1±5.2	-13.2±7.0	-11.5±3.7
Aver	-21.8±6.8	-19.3±5.3	-17.2±5.7

Table 3 – Peak circumferential strain for three myocardial layers and the average value in three levels of short axis cross-sections – Apex (AP), Papillary muscles (PM) and Mitral valve (MV). N = number of analyzed patients.

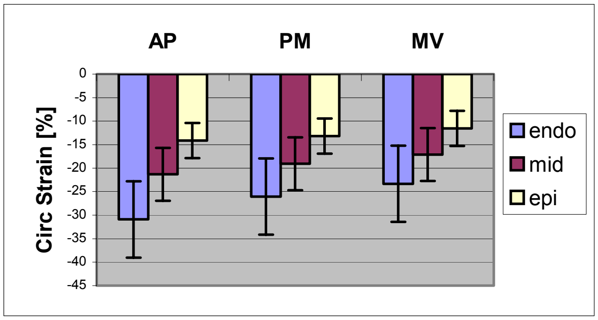

Figure 5 – Peak circumferential strain of the myocardial layers at three levels of short axis cross sections.

Short axis slice	Layers	P value for rotation difference	P value for circ strain difference
AP	Endo-Mid	0.001	0.005
	Mid-Epi	0.005	0.0005
	Endo-Epi	0.005	0.001
PM	Endo-Mid	NS	0.01
	Mid-Epi	NS	0.05
	Endo-Epi	NS	0.05
MV	Endo-Mid	0.005	0.0005
	Mid-Epi	0.01	0.0005
	Endo-Epi	0.005	0.0005

Table 4 – Results of paired T-test for every pair of myocardial layers. NS = not significant.

4. Discussion and conclusions

In this study it is demonstrated that it is possible to achieve strain analysis at high spatial resolution, based on the common B-mode echocardiography.

The information that is gained from the transmural gradient measurements is important for both diagnosis and therapy. For example, aortic stenosis patients suffer from left ventricular hypertrophy. In some cases, after valve replacement the hypertrophy is reduced, and the LV returns to its normal function. Mathematical models reported by Art et al. [6], show that left ventricular hypertrophy increases the transmural gradient of the LV torsion; thus measuring this gradient may provide information regarding the patient's condition and the probability of success or failure of the therapy. Another interesting case is LV ischemia. It may be feasible to distinguish between transmural and non-transmural ischemia by utilizing the method presented here.

The method is limited, though, by the image quality. In some cases it is impossible to obtain satisfying image quality, even when an experienced technician scans the patient, limiting the applicability of the method.

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