

● *Original Contribution*

## RADIAL VERSUS LONGITUDINAL MYOCARDIAL DEFORMATION FROM GRAY-SCALE ECHOCARDIOGRAPHY

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**Abstract**—The objectives of this work are to evaluate a novel non-Doppler-based echocardiographic method that makes it possible to simultaneously obtain the radial and longitudinal components of myocardial velocity (V) and strain (S), and to assess whether left ventricular fiber architecture affects the net function of the myocardium. Previous reports state that differences in the estimation of regional function between septum and lateral walls can be related to the anatomic disposition of myocardial fibers. In this work we measure and compare in 21 healthy volunteers longitudinal and radial peak systolic velocity V ( $V_{\text{long}}$ ,  $V_{\text{rad}}$ : cm/s), peak systolic strain S ( $S_{\text{long}}$ ,  $S_{\text{rad}}$ : %) and time-to-peak S and V (T-Smax, T- $V_{\text{max}}$ : ms) at the midsegments of the septal and lateral walls. Results show that V was higher, both in the radial and longitudinal components, in the lateral wall than in the septum ( $V_{\text{rad}}$ :  $4.77 \pm 0.26$  cm/s vs.  $3.77 \pm 0.20$  cm/s,  $p = 0.007$ ;  $V_{\text{long}}$ :  $5.60 \pm 0.48$  cm/s vs.  $4.13 \pm 0.11$  cm/s,  $p = 0.01$ ). Radial strain was higher in the septum ( $S_{\text{rad}}$ :  $28.63 \pm 2.25\%$  vs.  $22.54 \pm 1.5\%$ ,  $p = 0.015$ ), and longitudinal strain, in the lateral wall ( $S_{\text{long}}$ :  $-25.89 \pm 1.43\%$  vs.  $-22.20 \pm 0.87\%$ ,  $p = 0.02$ ). There was a significant delay in longitudinal T-Smax between the lateral and septal medial segments (mean: 14.5 ms; CI 95%: 0.3–28.6 ms;  $p = 0.04$ ), with no difference in radial T-Smax ( $277.1 \pm 8.6$  ms vs.  $277.2 \pm 12.4$  ms,  $p = 0.93$ ). The assessment of regional myocardial function by this new method enables the simultaneous analysis of its radial and longitudinal components. These measurements correlate well with previous anatomical knowledge of the architecture of myocardial fibers, emphasizing its functional significance in regional myocardial function analysis. (E-mail: [desco@mce.hggm.es](mailto:desco@mce.hggm.es)) © 2007 World Federation for Ultrasound in Medicine & Biology.

**Key Words:** Cardiac motion, Nonrigid registration, Myocardial fibers, Myocardial strain, Myocardial velocity.

### INTRODUCTION

The usefulness of strain (S) quantification for the assessment of regional myocardial deformation using Doppler-based techniques has been demonstrated widely (Sutherland 2004). However, the estimation of this parameter through Doppler imaging is clearly limited by angle dependency, which implies that not all the strain components (radial, longitudinal and circumferential) can be measured simultaneously for all the myocardial segments. Consequently, the development of 2-D methods for the assessment of regional deformation analysis is warranted. In this work, we have used a novel non-Doppler-based echocardiogra-

phy method that computes the 2-D strain tensor from gray-scale 2-D echocardiographic sequences by applying nonrigid registration techniques (Ledesma-Carbayo 2006). This software simultaneously measures the radial and longitudinal components of myocardial velocity, strain and strain rate.

Three-dimensional myocardial deformation is the result of a complex interaction of the cardiac fiber orientation throughout the left ventricle (LV). Histologic studies evaluating the regional differences in the myocardial fiber structure suggest that the septal wall shows fewer longitudinal fibers than the LV free wall, which has a predominance of longitudinal and circumferential fibers (Greenbaum 1981). The present study was designed to present the results of our method when applied to the assessment of regional myocardial function and to elucidate whether left ventricular fiber architecture may influence the regional myocardial deformation parameters.

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## MATERIALS AND METHODS

### Study subjects

Twenty-one healthy volunteers were studied after informed consent. The protocol was approved by the Institutional Ethics and Research Boards of the Hospital General Gregorio Marañón. All volunteers were not taking medication and had no evidence of cardiac disease based on medical history, physical examination, electrocardiogram and standard echocardiogram.

### Echocardiography

All studies were performed with a 2.0- to 5-MHz transducer using a Sequoia 512 system (Siemens AG, Munich, Germany). Standard gray-scale 4-chamber apical views were obtained with simultaneous recording of the electro and phonocardiogram signals at a frame rate of at least 90 frames/s. Three independent cardiac cycles were stored digitally in a cine-loop format for subsequent off-line analysis. Left ventricle dimensions and ejection fraction were calculated from standard M-mode and Simpson's modified biplane method.

### Processing and analysis

Images were transferred to a PC workstation and analyzed off-line using dedicated software, described later.

### Dense displacement field computation

Myocardial motion was computed using a nonrigid registration technique across the whole sequence on a frame-to-frame basis (Ledesma-Carbayo 2001, 2006). The key feature of this method was the use of an analytical representation of the myocardial displacement field based on a semilocal parametric model using B-splines (Fig. 1). The strain tensor is therefore obtained from the analytical expression of the spatial gradient of the displacement field. Robustness and speed are achieved by introducing a multiresolution optimization strategy.

This method has been previously validated against Doppler tissue imaging (Ledesma-Carbayo 2006) by applying linear regression to assess the relationship between the velocity calculated from the proposed method and the Doppler measurement. The results of the validation showed a good agreement between both methods.

### Strain calculation

Given an image sequence  $f(t, \mathbf{x})$ , the registration method estimates the dense displacement field  $\mathbf{g}(t, \mathbf{x})$  over the whole sequence. Briefly, we choose to represent the movement with respect to the first frame of the sequence: a point at coordinate  $\mathbf{x}$  in the first frame ( $t = t_0$ ) will move to the location  $\mathbf{g}(t, \mathbf{x})$  at time  $t$ . The strain

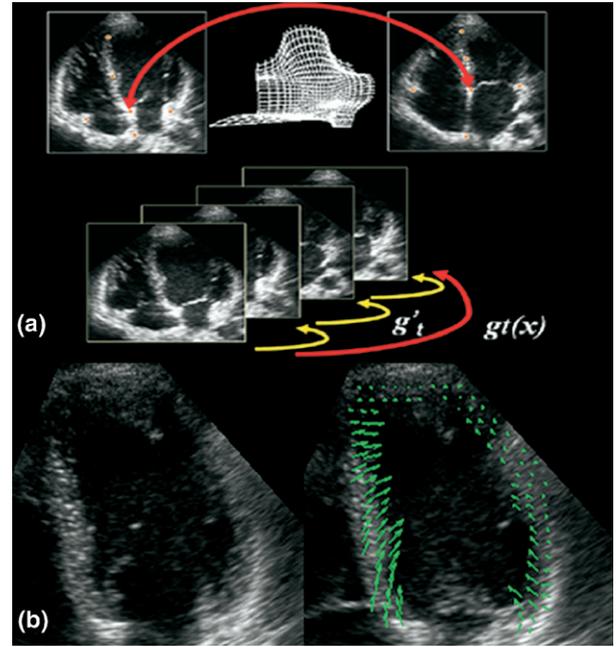


Fig. 1. (a) Deformation of the mesh (center of the image) to obtain the displacement of every pixel from the frame  $t_0$  (left) to the frame  $t_0 + t$  (right). (b) Accumulated displacement field at the time of maximum contraction.

( $\mathbf{S}$ ) is calculated from the dense displacement field using a Green-Lagrange Strain Tensor:

$$\mathbf{S} = 1/2 (\mathbf{F}^T \mathbf{F} - \mathbf{I}) \quad (1)$$

$\mathbf{F}$  being the deformation gradient tensor:

$$\mathbf{F} = \nabla_{\mathbf{x}} \mathbf{g} + \mathbf{I} = \begin{bmatrix} \partial \mathbf{g}_1 / \partial \mathbf{x}_1 & \partial \mathbf{g}_1 / \partial \mathbf{x}_2 \\ \partial \mathbf{g}_2 / \partial \mathbf{x}_1 & \partial \mathbf{g}_2 / \partial \mathbf{x}_2 \end{bmatrix} + \mathbf{I} \quad (2)$$

As  $\mathbf{g}$  is defined using B-spline functions, its derivatives ( $\partial \mathbf{g}_1 / \partial \mathbf{x}_1$ ) can be analytically computed.

### Application to the regional function analysis of the left ventricle

On each sequence, we defined the axis of the LV from the middle point of the mitral valve to the apex. The unit vector of the longitudinal axis served as a reference to define the unit vectors of the main directions of interest:  $\mathbf{U}_{\text{long}}$ , unit vector of the axis, defines the longitudinal direction, and  $\mathbf{U}_{\text{rad}}$ , unit vector perpendicular to the axis, the radial direction. These unit vectors were used to project the velocity (derivative of the displacement) and strain tensor, and both components of these parameters were obtained before being presented as time curves.

Two regions-of-interest (ROI) were delimited in the first image of each sequence, and positioned on the midsegment of the septum and lateral wall respectively. To correctly delineate these segments, the length of both

Table 1. Demographic and echocardiographic variables

Parameters	Mean $\pm$ SEM
Age, years	30 $\pm$ 1
Sex, male:female	11:10
Systolic blood pressure (mm Hg)	119 $\pm$ 3
Diastolic blood pressure (mm Hg)	71 $\pm$ 2
QRS duration, ms	90 $\pm$ 2
LV end-diastolic diameter, mm	46 $\pm$ 1
LV end-systolic diameter, mm	27 $\pm$ 1
Septum thickness, mm	9 $\pm$ 1
Posterior wall thickness, mm	9 $\pm$ 1
LV end-diastolic volume, cm <sup>3</sup>	83 $\pm$ 5
LV end-systolic volume, cm <sup>3</sup>	28 $\pm$ 2
LV ejection fraction, %	66 $\pm$ 1

LV = Left ventricle.

walls was divided into the three standard segments (basal, mid and apical), thus leading to ROI sizes ranging from 1.3 to 1.5 cm<sup>2</sup>. The estimated displacement field was used to re-position the ROI contours in the remaining frames of the sequence, thus avoiding tedious manual work and enabling a visual verification of the motion estimation. For each myocardial segment we analyzed, longitudinal and radial components of regional peak systolic velocity ( $V_{\text{long}}$ ,  $V_{\text{rad}}$ : cm/s) and peak systolic strain ( $S_{\text{long}}$ ,  $S_{\text{rad}}$ : %) were assessed. Time-to-peak velocity ( $t-V_{\text{max}}$ : ms) and peak strain ( $t-S_{\text{max}}$ : ms) were measured in both components using the onset of mitral closure as the reference point and excluding the cases with post-systolic strain peaks. The onset and the end of the systolic period were identified from the phonocardiogram signal and are marked with a vertical line in the presented figures. A total number of 126 measurements were performed (21 volunteers  $\times$  3 cycles/volunteer  $\times$  2 segments). All the measured parameters were averaged over the three cardiac cycles analyzed for each subject.

For evaluation of interobserver and intraobserver repeatability of  $S_{\text{long}}$  and  $S_{\text{rad}}$ , 21 cycles were examined by two observers and re-examined by the first observer following the same methodology.

### Statistics

Results are presented as mean  $\pm$  SEM. Frequencies are expressed as percentages. Comparisons were assessed using paired and unpaired Student's *t*-tests when appropriate.

Interobserver and intraobserver repeatability were evaluated by linear regression analysis and Bland-Altman plots.

## RESULTS

Table 1 shows the demographic and echocardiographic variables of the study population.

Table 2. Longitudinal velocity and strain parameters from septum and lateral wall

Segment	$V_{\text{long}}$ (cm/s)	$T-V_{\text{max}}$ (ms)	$S_{\text{long}}$ (%)	$T-S_{\text{max}}$ (ms)
Septum	4.1 $\pm$ 0.1	106.7 $\pm$ 7.6	-22.2 $\pm$ 0.9	292.9 $\pm$ 7.5
Lateral	5.6 $\pm$ 0.4*	68.9 $\pm$ 3.3*	-25.9 $\pm$ 1.4*	310.9 $\pm$ 10.9†

$V_{\text{long}}$  (cm/s) = Longitudinal systolic peak velocity;  $T-V_{\text{max}}$  (ms) = time to systolic peak velocity;  $S_{\text{long}}$  (%) = Longitudinal systolic peak strain;  $T-S_{\text{max}}$  (ms) = time to systolic peak strain.

Mean  $\pm$  SEM.

\*  $p < 0.05$  septum vs. lateral,  $N = 21$ .

†  $p < 0.05$  septum vs. lateral,  $N = 16$ .

All segments could be analyzed correctly. In normal myocardium, directional changes are characterized by longitudinal shortening and radial thickening. By convention, negative values indicate shortening/thinning and positive values indicate lengthening/thickening.

### Longitudinal left ventricle function

Systolic parameters of regional longitudinal velocity and deformation are shown in Table 2. Peak longitudinal strains resulted postsystolic in six cases and these were excluded from the time analysis to strictly assess normal and synchronous systolic behavior. Assessment of longitudinal LV function showed that peak systolic velocity and longitudinal strain were significantly higher in the lateral wall than in the septum. Time-to-peak of longitudinal strain, measured from the mitral closure, showed a statistically significant delay of the lateral peak strain (mean: 14.5ms; CI 95%: 0.3–28.6 ms;  $p = 0.04$ ). An example of an apical 4-chamber view image is shown in Fig. 2 and the corresponding  $V_{\text{long}}$  and  $S_{\text{long}}$  are shown in Fig. 3a.

### Radial left ventricle function

Radial regional systolic function results are shown in Table 3. Peak systolic velocity was also significantly

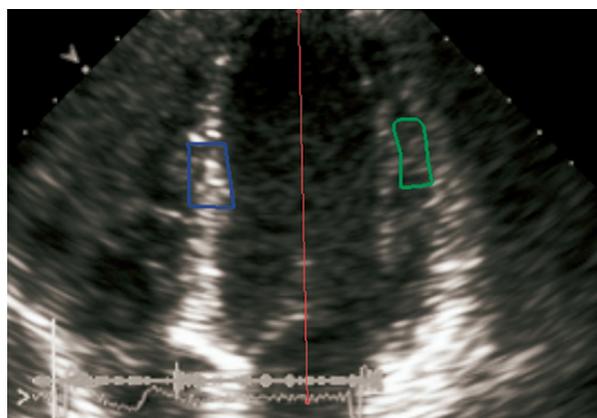


Fig. 2. Definition of two regions-of-interest in the septum (blue) and lateral wall (green) from an apical 4-chamber view of a healthy volunteer.

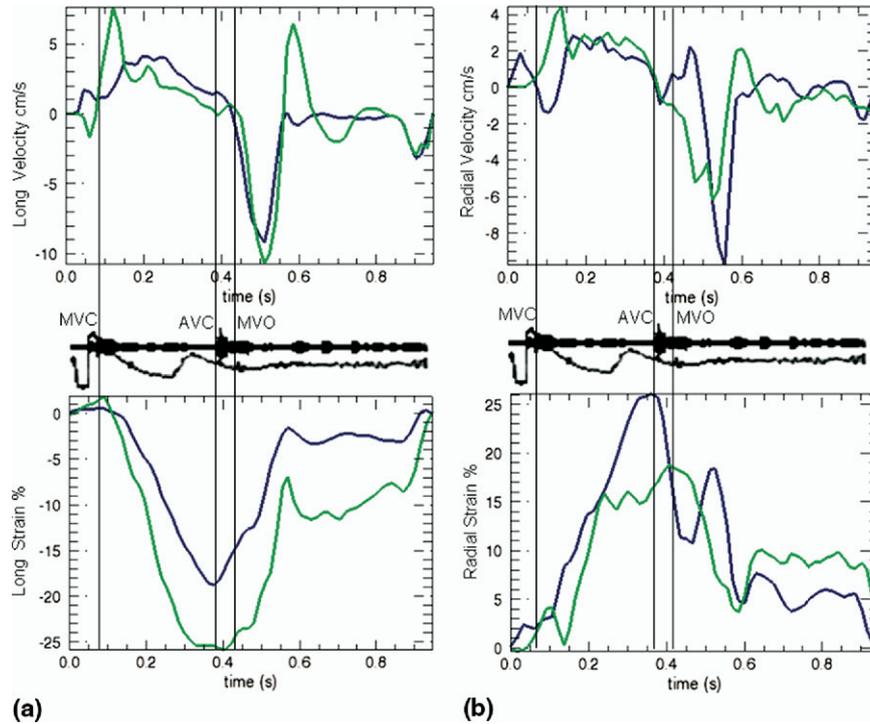


Fig. 3. (a) Longitudinal and (b) radial velocity and strain curves obtained from a healthy volunteer using the regions-of-interest defined in Fig. 2 (septum [blue] and lateral wall [green]). Time-aligned electro and phonocardiogram are also represented. The three vertical lines correspond to the mitral valve closure (MVC), aortic valve closure (AVC) and mitral valve opening (MVO), respectively.

higher in the lateral wall than in the septum. With regard to the radial strain, the septum showed more radial strain than the lateral wall. Nevertheless, there was no difference in time-to-peak of radial strain between segments.

*Velocity vs. strain*

When velocity parameters were used to estimate regional myocardial function, both radial and longitudinal components were higher in the lateral wall than in the septum. On the other hand, strain analysis showed higher radial strain in the septum than in the lateral wall and higher longitudinal shortening in the lateral wall than in the septum (Fig. 3b).

*Repeatability*

To analyze intra and interobserver variability, 42 measurements of the 126 obtained were selected randomly. Both radial and longitudinal components of strain were assessed. There was a good agreement for the same observer (ICC 0.89 and 0.84 for radial and longitudinal strain, respectively). The agreement between observers was lower for radial and longitudinal strain (ICC 0.48 and 0.79). Figure 4 displays Bland-Altman plots of differences between radial and longitudinal strain. The mean difference ± SD between observers was 1.6 ± 7.7 and -1.8 ± 5.7 for radial and longitudinal strain, respectively, and 0.3 ± 5.7 and -2.7 ± 6.9 for the same observer.

Table 3. Radial velocity and strain parameters from septum and lateral wall

Segment	V <sub>rad</sub> (cm/s)	T-V <sub>max</sub> (ms)	S <sub>rad</sub> (%)	T-S <sub>max</sub> (ms)
Septum	3.77 ± 0.2	131.4 ± 8	28.6 ± 2.6	277.1 ± 8.6
Lateral	4.77 ± 0.3*	76.2 ± 3.5	22.5 ± 1.6*	277.2 ± 12.4

V<sub>rad</sub> (cm/s) = Longitudinal systolic peak velocity; T-V<sub>max</sub> (ms) = time to systolic peak velocity; S<sub>rad</sub> (%) = longitudinal systolic peak strain; T-S<sub>max</sub> (ms) = time to systolic peak strain.

Mean ± SEM.

\*p < 0.05 septum vs. lateral, N = 21.

**DISCUSSION**

Since the introduction of ultrasonic Doppler strain imaging to quantify regional function (Fleming 1994; Heimdal 1998; Isaz 1998, 2000, 2002; Urheim 2000), the analysis of myocardial deformation has become part of clinical practice, despite its limitations. The primary limitation is the impossibility to simultaneously estimate deformation in different directions in the same segment (D’Hooge 2000). This problem is intrinsic to any Doppler measurement because only the component along the

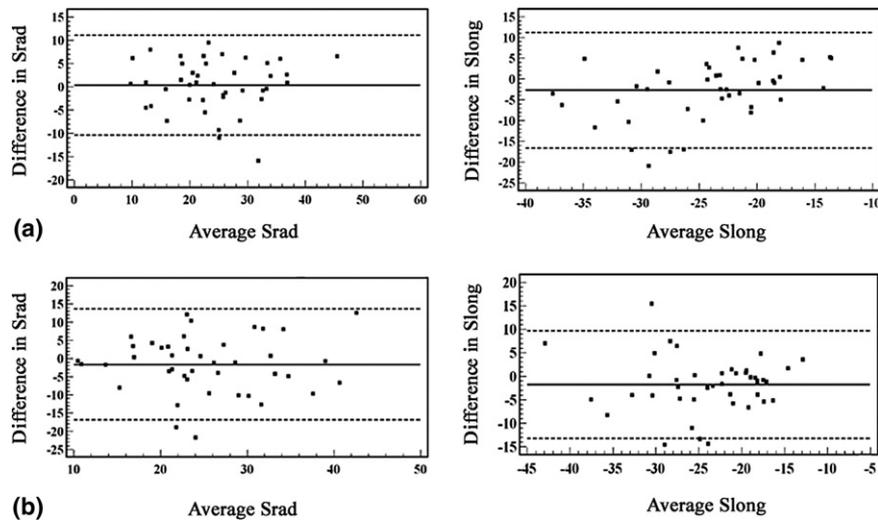


Fig. 4. Bland-Altman plots for (a) intraobserver and (b) interobserver variability. Dashed lines indicate mean  $\pm$  2 SD.  $S_{\text{rad}}$  = radial strain;  $S_{\text{long}}$  = longitudinal strain.

ultrasound beam can be obtained. Most of the clinical studies that have validated the usefulness of deformation parameters are based on the estimation of the longitudinal strain, whereas the importance of the radial strain in the ventricular function is less known (Fortuin 1972). This type of quantification may provide relevant information about myocardial function (Storaa 2004), but it cannot yet provide a suitable description of the 3-D structure of the human heart with its complex ventricular fiber architecture (Torrent-Guaspa 2005). In addition to the development of tagged magnetic resonance imaging (Chandrasekara 2004), other approaches using ultrasound imaging, such as speckle tracking and elastographic techniques, have explored the possibility of obtaining multidimensional motion from echocardiographic data (D'Hooge 2002; Kaluzynski 2001). These methods process the radiofrequency signal to obtain the displacement of one or several consecutive lines of response, using correlation and phase shift techniques. Another family of methods assesses cardiac motion by combining image feature extraction with deformable and mechanical models (Papademetris 2001). Optical flow techniques also provide promising results (Suhling 2004).

This work presents the initial results obtained with a new method (Ledesma *et al.* 2005) to analyze myocardial mechanics from gray-scale 2-D echocardiographic sequences that simultaneously obtain radial and longitudinal components of velocity, strain and strain rate. Previous validation against Doppler tissue velocity showed a good correlation between both methods, overcoming the limitations of Doppler techniques (Ledesma-Carbayo 2006). The results obtained for radial strain are within the lower range of values reported previously (Bogaert and Rademakers 2001; Edvardsen 2002; Kowalski 2001;

Moore 2000). The main cause of these discrepancies could be related to the different measurement principles (D'Hooge 2003). Another important point is the effect of including trabeculae or papillary muscles in the regional measurement of strain because of low resolution imaging or poor visibility. As studied in Peters 2002, who used high-resolution magnetic resonance imaging, the influence of this inclusion could lead to an overestimation of 100%.

We observed a reasonable interobserver and intraobserver repeatability of strain measurements in both radial and longitudinal directions. Main differences could be related to placement of the region-of-interest, and to the effect of the poorer visibility and the papillary muscle when the lateral wall was analyzed.

The results of our study suggest that the radial and longitudinal components of velocity and strain of a segment could differ depending on the amount and disposition of the predominant fibers, and it could be an explanation for the differences in velocity and strain between the septal and lateral walls. As Peverill (2004) recently suggested, part of these differences are likely to be related to variations in the anatomy of the longitudinal fibers that run through the left ventricle. Thus, if the septum contains mainly cross-sectional fibers, its main systolic deformation should involve thickening, and if most of the fibers of the lateral wall have a longitudinal or circumferential orientation, it should involve longitudinal shortening and twist. For the estimation of longitudinal velocity, values given in Table 2 are comparable to previous measurements (Edvardsen 2002), and, according to velocity studies, the longitudinal component is higher in the lateral wall than in the septum (Peverill 2004). Nevertheless, when comparing systolic deforma-

tion in the radial and longitudinal directions, we found that radial strain was significantly higher for the septum than for the lateral wall, and shortening (longitudinal systolic deformation) was characterized by significantly higher values than thickening (radial systolic deformation) in the lateral wall, demonstrating the inhomogeneous behavior of the deformation parameters through the left ventricle.

Timing analysis of strain reveals a new and interesting fact. Although the measured difference in time-to-peak systolic longitudinal strain between the septum and lateral wall was similar to that reported in previous studies (Voigt 2003), no differences in time-to-peak radial systolic strain between the septum and lateral wall segments were found in our work. This could be explained by a homogeneous radial deformation of the healthy left ventricle, and could be potentially useful for the evaluation of asynchrony (Breithardt 2003), as recently suggested by Suffoletto 2006.

### Limitations

Our study focused on two opposite walls, the septum and lateral wall, because of their well-known different fiber disposition. An analysis of the whole LV and the circumferential motion component could provide more consistent information. Further studies to investigate other segments and parameters are warranted.

No attempt has been made to assess the robustness of the method against low-quality images. This problem, common in any echocardiographic technique, could limit a generalized use of the procedure.

## CONCLUSIONS

We present the results of a new image processing method that performs spatio-temporal registration of gray-scale 2-D ultrasound sequences. The method provides, in a fully automatic way, the simultaneous measurement of the radial and longitudinal deformation parameters in the same cardiac segment, avoiding the limitations of Doppler-based techniques. Results in our trial of healthy volunteers seem to match properly with the anatomical disposition of the fibers, emphasizing the functional significance of LV fiber orientation in the evaluation of regional myocardial function.

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