Cardiac Motion Quantification: A New Software Based on Non-rigid Registration

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Abstract

Evaluation of regional myocardial function using non-invasive techniques is an important goal in clinical cardiology. This work presents a new methodology and a software developed for this task. Its main features are the visualization and quantification of the motion and deformation of the myocardial wall along the cardiac cycle, using sequences of ultrasound or magnetic resonance images.

The software measures displacement of the different sections of the cardiac wall, and calculates velocity, strain and strain rate, in their radial and longitudinal or circumferential components. These parameters can also be displayed as a parametric image in color superposed to the original one.

To evaluate the software and method, a clinical trial has been carried out on 12 sequences of healthy subjects and 12 sequences of patients, showing that this application could be a useful tool for the diagnosis of cardiac ischemic disease.

1. Introduction

Cardiac motion and deformation have been traditionally studied with Tissue Doppler Imaging. This technique has the limitation of its inherent angle dependency, being able to measure just one velocity component. More recently, the use of Magnetic Resonance Imaging (MRI) allows the simultaneous measurement of all displacement components (radial, longitudinal and circumferential), for all myocardial segments [1,2]. However this modality is costly and requires long acquisition times.

This work proposes the assessment of myocardial motion using conventional (non-Doppler) 2D gray-scale echocardiographic images, by means of a novel methodology, based on non-rigid registration of the image sequence. That allows to compute the 2D displacement vectors, and from them, obtaining velocities as well as strain and strain rate tensor.

The software developed to use this methodology, allows quantifying myocardial motion and deformation providing simultaneously the radial and longitudinal components of myocardial displacement, velocity, strain and strain rate, and overcoming the limitations of the Doppler based techniques.

2. Method

Myocardial motion is computed using a frame to frame non-rigid registration technique on the whole sequence. The key feature of this method is the use of an analytical representation of the myocardial displacement field based on a semi-local parametric model of the deformation using Bsplines (Figure 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 [3,4].

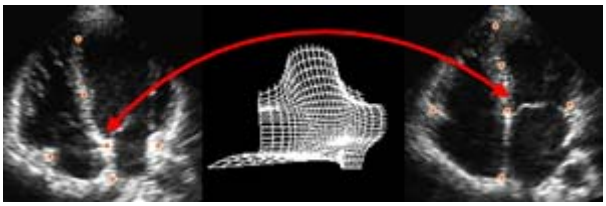


Figure 1. Deformation of the mesh *(centre of the image)* to obtain the displacement of every pixel from the frame t_0 of the cycle *(left)* to the frame $t_0 + t$ *(right)*.

Problem outline: Given an image sequence $f(t,\boldsymbol{x})$, the goal is to estimate a dense displacement field $\boldsymbol{g}(t,\boldsymbol{x})$ over the whole sequence. We choose to represent the movement with respect to the first frame of the sequence: a point at coordinate $\boldsymbol{x}$ in the first frame ($t=t_0$) will move to the location $\boldsymbol{g}(t,\boldsymbol{x})$ at time t. This objective is attained by means of non-rigid registration of consecutive pairs of images.

Consecutive Registration: This method computes $g(t,x)$ as a series of transformations between consecutive pairs of images $g'_t(x)$. Formulation is therefore defined as:

$g(t,x)=g_t(x)$ where $t \in \{0,1,...,T-1\}$ and $x=(x_1,x_2)$ (1)
$g_t(x)=g'(x_{t-1})$ where $x_{t-1}=g_{t-1}(x)$ and $g_0(x)=x$

The transformation between consecutive frames g'_t is defined as a linear combination of Bspline basis functions as previously introduced in [5].

$$g'_t(x) = \Sigma c_j \beta_r(x/h-j) \quad (2)$$

The solution to this problem is then formulated as an optimization procedure that minimizes a criterion E to find the coefficients c_j. E is defined as the squared differences between consecutive frames. This optimization is solved using a standard multidimensional optimisation algorithm with a multiresolution approach.

Strain (**S**) is calculated from the dense displacement field using a Green-Lagrange Strain Tensor:

$$\mathbf{S} = \tfrac{1}{2} (\mathbf{F}^T\mathbf{F} - \mathbf{I}) \quad (3)$$

Being **F** the deformation gradient tensor:

$$\mathbf{F} = \nabla_x \mathbf{g} + \mathbf{I} = \begin{bmatrix} \partial \mathbf{g}_1 / \partial \mathbf{x}_1 & \partial \mathbf{g}_1 / \partial \mathbf{x}_2 \\ \partial \mathbf{g}_2 / \partial \mathbf{x}_1 & \partial \mathbf{g}_2 / \partial \mathbf{x}_2 \end{bmatrix} + \mathbf{I} \quad (4)$$

As **g** is defined using Bspline functions its derivatives ($\partial \mathbf{g}_1 / \partial \mathbf{x}_1$) can be analytically computed [6].

Constraints. This method is constrained using prior knowledge about the cardiac motion field: 1) the motion at the reference frame $f(0,t)$ must be zero, 2) motion must be cyclic: $g(0,x)=g(T-1,x)$.

3. Program Features

The program has been developed in the programming environment IDL 6.0 (Interactive Data Language, Research System Inc.), which offers advanced tools for the representation and treatment of images, and easy development of user interfaces.

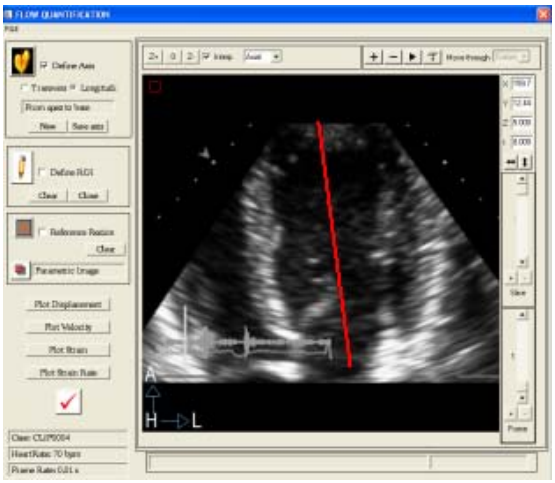
Following sections describe the principal operations that the user performs with the program: sequence selection, axis definition, parametric analysis, ROI definition and measure and quantification.

3.1. Sequence selection

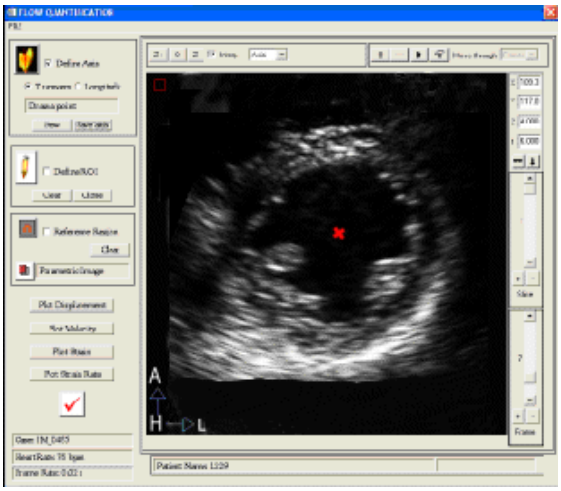
The program can visualize and process sequences of three different modalities: echocardiography, magnetic resonance and tagged magnetic resonance (Figure 2). It includes standard visualization tools, such as zoom/pan, cine loop, window level, etc.

3.2. Axis definition

As the orientation of myocardial walls changes depending on the cardiac view, myocardial and transducer axis are rarely aligned. The user has to manually define the myocardial axis (two-chamber view) (Figure 3) [7], or the center of the left ventricle (short axis view), references used to obtain radial, longitudinal or circumferential components.



(a)



(b)

Figure 2. Axis definition. (a) Long axis (four-chamber view) and (b) short axis echocardiographic images.

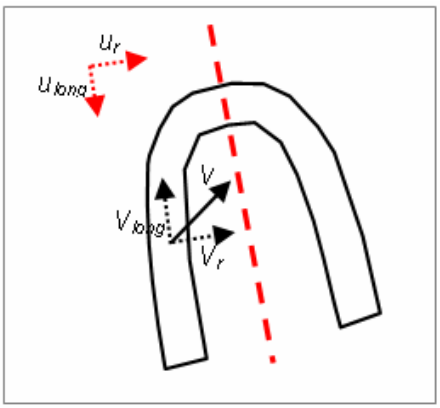


Figure 3. Velocity projection, V is the calculated velocity (derivate of the displacement), V_{long} and V_r, represent longitudinal and radial components respectively, according to the defined axis.

3.3. Parametric images

The different parameters (displacement, velocity, strain and strain rate) can be represented overlaid on the original image, enabling the user to check the registration and validate the parameter estimation. Two different kinds of overlays have been developed: parametric color images and arrow plots.

Parametric color images are displayed via translucent overlays, allowing the simultaneous visualization of the selected parameter and the original image (Figure 4).

Arrow plots display the displacement or velocity fields on a previously defined region of the myocardium. The arrows change along the cardiac cycle, indicating the direction and quantity of the displacements or velocities (Figure 5).

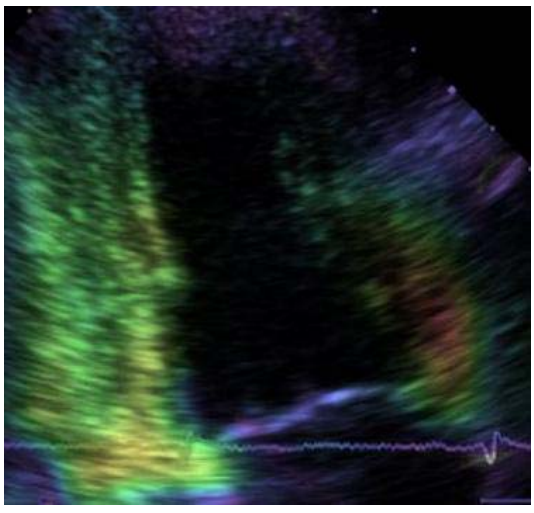


Figure 4. Parametric color image showing systolic displacement overlaying on the original image.

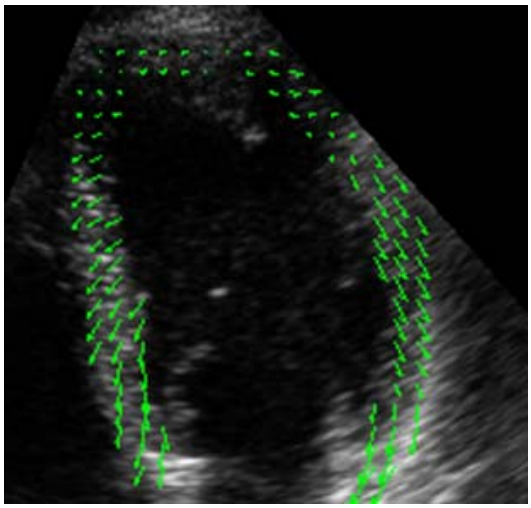


Figure 5. Arrow plot of the velocity field over the original image.

3.4. ROI definition

Regional function evaluation of the left ventricle (LV) is performed analyzing the motion of a predefined set of ventricle segments. LV is divided into 16 segments following the recommendations of the American Society of Echocardiography [8], based on the coronary arteries that irrigate each segment (Figure 6) [9].

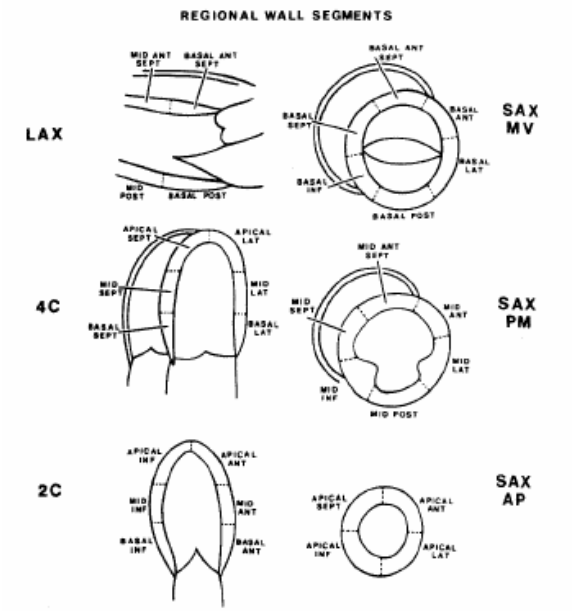
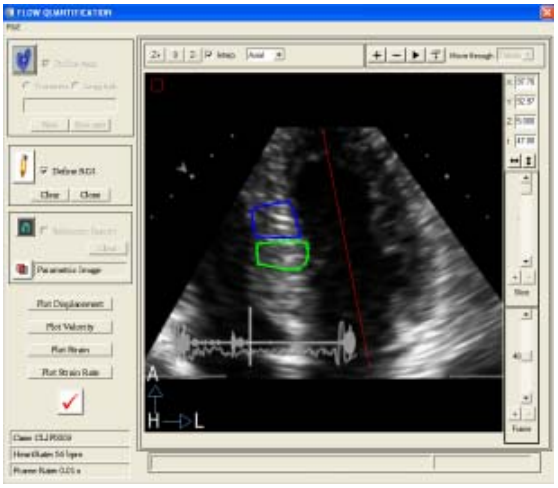


Figure 6. Segments division of the left ventricle and its correspondence with the tributary territories of the principal coronary arteries.

The program allows the user to draw ROIs along the myocardial wall in the first frame of the sequence. The ROIs are automatically re-positioned and deformed in each frame of the cycle according to the computed

movement and deformation of the myocardium (Figure 7).

(a)

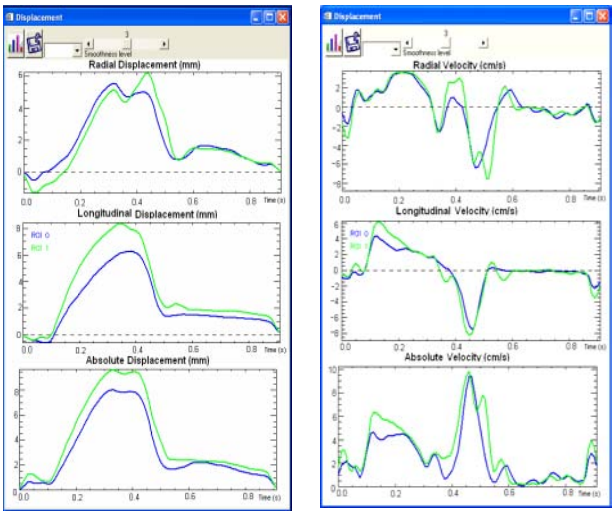


(b)

Figure 7. Definition of two ROIs in the septum at end-diastole (a). Same ROIs at end-systole (b). In normal myocardium, the regions should move towards the apex, and deformations changes are characterized by longitudinal shortening and radial thickening.

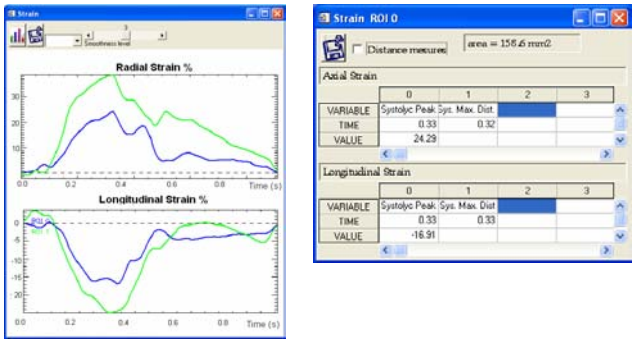
3.5. Measurements and quantification

After ROI definition the system plots time curves of the different parameters, for the longitudinal (circumferential in short axis views), radial and absolute components (Figure 8). Curve values can be displayed and saved for later processing (Figure 9).



(a) (b)

Figure 8. Curves corresponding to two ROIs placed in the septum wall. (a) Displacement time curves. (b) Velocity time curves. From top to bottom, radial, longitudinal and absolute components are represented.



(a) (b)

Figure 9. (a) Radial and longitudinal strain components of two ROIs placed in the septum wall. (b) Table of strain values.

4. Clinical applicability

The clinical applicability of the proposed methodology and the program has been evaluated with a total of 24 ultrasound sequences (46 myocardial segments) from 6 healthy volunteers, and 6 patients with contraction and motion abnormalities. Longitudinal and radial displacement and strain parameters were extracted and compared with the functional score as assessed by an expert [6].

To verify the difference between normal and damaged segments we performed an ANOVA statistical analysis followed by multiple comparisons between groups (with a post hoc Scheffé test). Results showed significant differences ($p<0.05$) between normal (N=24) and pathological segments (N=22), thereby

illustrating the clinical applicability of the proposed method.

Figure 10 shows the dense displacement field for a healthy volunteer (*left*) and an ischemic patient with a previous inferior infarct (*right*).

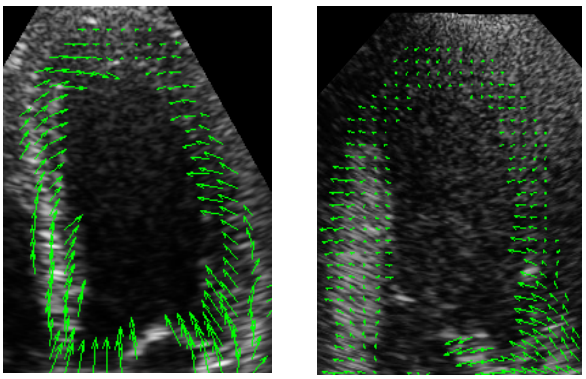


Figure 10. Displacement field during systole for a healthy volunteer (*left*) and an ischemic patient (*right*). Four-chamber view.

5. Conclusions

The program presented implements a new tool for regional cardiac motion quantification, featuring the measurement of displacement, velocity, strain and strain rate.

The algorithm performs a frame to frame non rigid registration of ultrasound sequences. It is fully automatic and provides motion detection, exploiting a priori knowledge of cardiac motion. Overcoming the limitations of the Doppler based techniques, it allows quantifying every component, radial, circumferential or longitudinal. An evaluation with real ultrasound sequences supports the clinical applicability, although further clinical validation is warranted.

Acknowledgements

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6. References

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