Analysis of Tagged Cardiac MRI Sequences

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Abstract. The non invasive evaluation of the cardiac function presents a great interest for the diagnosis of cardiovascular diseases. Tagged cardiac MRI allows the measurement of anatomical and functional myocardial parameters. This protocol generates a dark grid which is deformed with the myocardium displacement on both Short-Axis (SA) and Long-Axis (LA) frames in a time sequence. Tracking the grid allows the estimation of the displacement inside the myocardium. The work described in this paper aims to make the automatic tracking of the grid of tags on cardiac MRI sequences robust and reliable, thanks to an informational formalism based on Extreme Physical Informational (EPI). This approach leads to the development of an original diffusion pre-processing allowing us to increase significantly the robustness of the detection and the follow-up of the grid of tags.

1 Introduction

The non invasive assessment of the cardiac function is of major interest for the diagnosis and the treatment of cardiovascular pathologies. Whereas classical cardiac MRI only allows to measure anatomical and functional parameters of the myocardium (mass, volume...) tagged cardiac MRI makes the evaluation of the intra-myocardial displacement possible. For instance, this type of information can lead to a precise characterization of the myocardium viability after an infarction. Moreover, data concerning myocardium viability allows to decide of the therapeutic : medical treatment, angiopathy, or coronary surgery and to follow the amelioration of the ventricular function after reperfusion.

The SPAMM (Space Modulation of Magnetization) acquisition protocol [22] we used for the tagging of MRI data, displays a deformable 45°-oriented dark grid which describes the contraction of myocardium (Figure 1) on the images of temporal Short-Axis (SA) and Long-Axis (LA) sequences. The 3D+T follow-up of this grid makes the evaluation of the intra-myocardial displacement possible.

Nevertheless, tagged cardiac images present particular characteristics which make their analysis difficult. More precisely, images are of low contrast compared with classical MRI, and their resolution is only of approximately one centimeter.

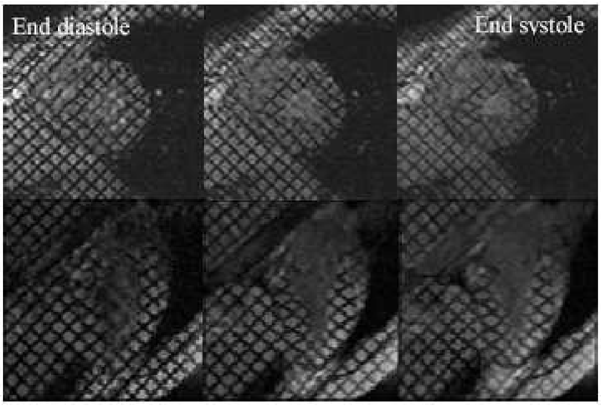

Fig. 1. SA and LA tagged MRI of the Left Ventricle.

Numerous studies were carried out concerning the analysis of the deformations of the grid of tag on both SA and LA sequences: These methods can be divided into two major families:

- direct estimation of the displacement field of the myocardium (optical flow [3], analysis of the Harmonic Images [13, 7], image registration [15]);

- undirect estimation of the displacement field (active contours [11, 21, 6, 1, 2], use of the spectral information [23, 5]).

The common disadvantages of those approaches are their sensibility to noise and to the fading of the grids of tags, their poor adaptation when tags are close to myocardial boundaries and their bad adaptation to important deformations of the grid between two consecutive instants. Moreover, manual interventions are often needed to obtain precise results and execution time can sometimes reach high values [10].

Moreover, the clinical validation of the different methods often shows a lack of robustness and reproducibility which is incompatible with a medical application.

In order to avoid these problems, we propose in this article, an original method for the detection and the follow-up of the grid of tags, based on active contours and image diffusion. More particularly, we will show that the integration of an adapted external energy in a simple contour active model allows to avoid the usual problems encountered by the different technics presented in literature. We will also show that our approach allows to obtain precise and robust results of detection.

We present in a first part the principle of the detection and follow-up method, to continue with the description of our diffusion process based on a recent theory developed in [4] called Extreme Physical Information (EPI). In a second part, we present the application of the resulting diffusion process to our particular topic. In a last part, we present results of detection and follow-up of the grid of tags on tagged cardiac MRI showing the robustness of the technic, and illustrating it with examples of quantification and representation of the extracted data.

2 Method

2.1 Principle

The general principle of the technic we present here has been already described in a past article [9] : To detect and to follow-up the grid of tags on SA and LA sequences, we deform a virtual grid, modeled by B-splines and controlled by 44 nods P (the intersections of the grid), each one characterized by a particular energy, noted E, to minimize (Eq. (1)) :

$$E = w_{internal}.E_{internal} + w_{external}.E_{external} \quad . \tag{1}$$

The internal energy imposes the regularity of the whole grid to obtain thus a coherent result. For our application, we chose the weighted sum of two terms defined by [18] :

- the energy E_{esp}^{int} ensures a regular spacing between each intersection point (i,j) of the grid of tags.

$$E_{esp}^{int} = \sum_{i,j} \left[\left(\frac{1 - r_1^2(i,j)}{1 + r_1^2(i,j)} \right)^2 + \left(\frac{1 - r_2^2(i,j)}{1 + r_2^2(i,j)} \right)^2 \right] \tag{2}$$

  where $r_k(i,j)$ is the ratio among the distances which separate the intersection point (i,j) and its two related intersections in the k direction (k=1 for 45° and k=2 for 135°). We can note that this expression is equal to zero when $r_1(i,j) = r_2(i,j) = 1$ for all (i,j), *i.e.* when intersection points are regularly spaced.

- the energy E_{align}^{int} ensures the alignement of the related intersection points on each lines of the grid of splines :

$$E_{align}^{int} = \sum_{i,j} \left[cos^2 \left(\frac{\theta_1(i,j)}{2} \right) + cos^2 \left(\frac{\theta_2(i,j)}{2} \right) \right] \tag{3}$$

  where $\theta_k(i,j)$ is the angle of the intersection point (i,j) and its two related intersection points in the k direction (k=1 for 45° and k=2 for 135°). We can note once again that this expression is equal to zero when $\theta_1(i,j) = \theta_2(i,j) = 180°$ for all (i,j), *i.e.* when two intersection points on a same line are aligned.

Concerning $E_{external}$, this term takes into account the tag information of the studied tagged MR image. Numerous proposition have been made since 1988 to extract the tag information (gradient of the image, extraction in the Fourier's domain), but no one of them appears to be really adapted to the problematic in terms of robustness regarding small variations of $w_{internal}$ and $w_{external}$.

As a consequence, it appears that an original definition of $E_{external}$ is essential for the implementation of a robust detection method of the grid of tags.

Thus, we propose to increase this robustness thanks to a method based on the enhancement of the tag information using a diffusion process which takes into account *a priori* data characterizing the grid.

2.2 Anisotropic diffusion

Regarding the existing fundamental anisotropic diffusion method presented in the literature [14, 19], it appears that their leading differential equations were not adapted to our application because of the impossibility to take into account particular characteristics of the information to enhance.

This is confirmed by the tests presented Figure (2) where we can see that, whereas an optimal parameterization of the diffusion process is implemented, the grid of tags is too much altered even for a small number of iterations.

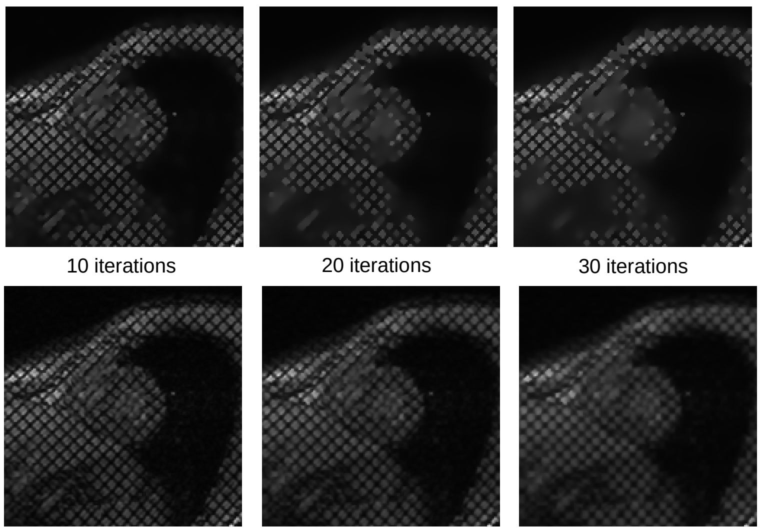

Fig. 2. Top sequence: Perona-Malik's Diffusion $dt = 0, 2$, bottom sequence: Weickert's Diffusion $dt = 0, 2$.

To integrate in the diffusion process the local orientations of the grid of tags, which will allow to preserve it from alteration, an enrichment of the fundamental diffusion equation (*i.e.* the heat equation (Eq. (4)), can be seen as a solution.

$$\begin{cases} \psi(r,0) = \psi_0(r) \\ \frac{\partial\psi}{\partial t} = \triangle u = div(\nabla\psi) \end{cases} . \quad (4)$$

Thus, we propose to introduce in equation (4) a new parameter noted **A** which is a potential vector :

$$\frac{\partial\psi}{\partial t} = (\nabla - \mathbf{A}).(\nabla - \mathbf{A})\psi \quad . \quad (5)$$

This integration allows to take into account particular properties of the structure to be enhanced through a judicious choice for **A**.

2.3 About A

As we have just said, the **A** potential allows to control the diffusion process and introduce some prior knowledge about the image evolution.

The choice we do for **A** is based on the fact that equation (5) allows to weight the diffusion process with the difference of orientation between the local gradient and **A**.

To explain the way we implement **A**, let us consider Figure (3):

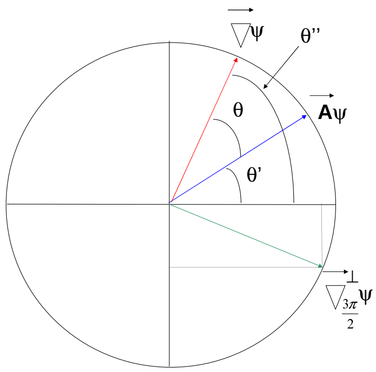

Fig. 3. Local geometrical implementation of **A** in terms of the local gradient $\nabla\psi$.

We can notice on this Figure that when angle θ is null (*i.e.* **A** and $\nabla\psi$ are colinear), the studied pixel will not be diffused. Thus, a precise local estimation of this angle can lead us to preserve particular patterns in the processed image for a given vector **A**.

Thus, a solution to the problem of enhancement of the grid would have been to impose particular orientations for **A**, considering the fact that the gradients to preserve are well known and correspond to the orientations of the grid-of-tag ones (45°, 135°, 225°, 315°). However, because the contraction of the LV induces a deformation of the tags, the local orientation of the grid for an instant of acquisition different from the initial one, can be no more characterized by imposed particular orientations. Moreover, because of the poor quality of MRI sequences, it appears that a calculation of the local orientation of **A** directly made on cardiac tagged images, would be strongly deteriorated by noise.

As a consequence, we propose to make a local estimation of the direction of **A** in the Fourier area, using the principle developed by Zhang *and al* [23] (Figure 4).

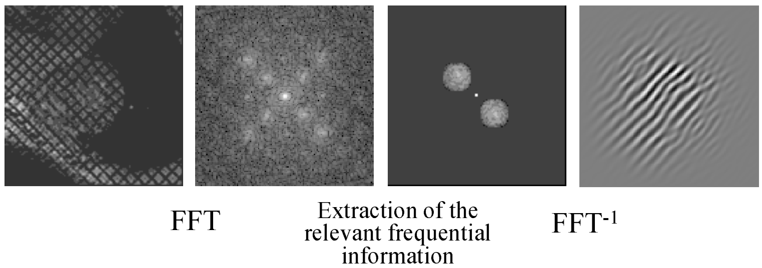

Fig. 4. Extraction of the tag information in the Fourier's representation.

This approach allows a denoising of the tag information which leads us to a more precise estimation of **A** and allows to take into account the deformations of the grid due to the contraction of the LV. Moreover, in order to compute a precise estimation of θ, we propose a method for its calculation based on the work of Rao [16] and Terebes [17] using the analysis of the eigen vectors of a particular neighborhood of the studied pixel.

3 Results

The result presented in Figure (5.a), shows the restoration of the 45°-oriented tag on the first image of a tagged cardiac sequence by the diffusion approach.

As we can see in Figure 5.a, the diffusion process makes possible the fading of noisy artifacts, and non-45°-oriented lines.

Moreover, because the orientation of **A** is locally calculated taking into account a particular neighborhood, the diffusion process remains efficient even if the tag is locally deformed due to myocardial contraction (Figure 5.b).

The different preserved images (45° and 135° ones) are then integrated as a new external energy in our active contour model for the detection and the following of the grid of tags as follows :

Each intersection point of the initial grid represents a node for which the global energy E is computed on a $N \times N$ neighborhood. A research for the minimum of E on the considered neighborhood allows to displace the studied node to a new position in accordance with the tag information. The resulting grid

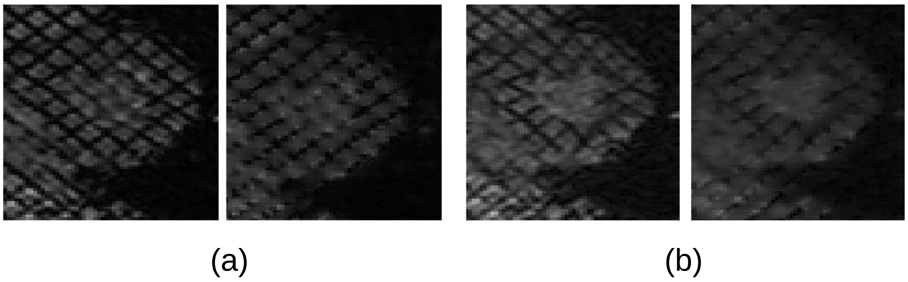

Fig. 5. Preservation of the 45°-oriented tag on (a) the initial image of a tagged sequence and (b) for $t \neq t_0$.

obtained for a particular instant t is used for the initialisation of the detection at the successive instant $t+1$ time. The $N \times N$ neighborhood has been empirically fixed to 5. For $N = 3$ the research window does not contain enough information. The value $N = 7$ gives the same results as those obtained for $N = 5$, but increase the calculation time. The same minimization of energy presented in [9] being implemented, the results presented Figure (6) are then obtained.

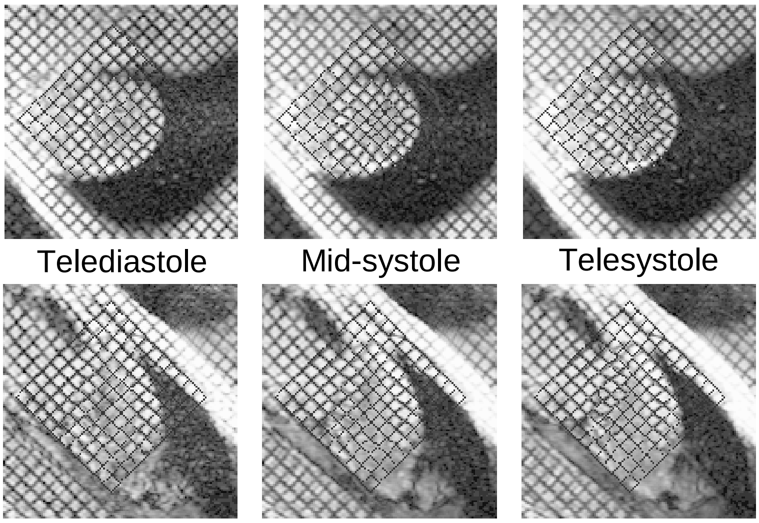

Fig. 6. Detection and following of the grid of tags on both SA and LA sequences.

These results are characterized by a good precision compared with usual methods, but also by a good robustness regarding the necessary weighting of $E_{external}$ and $E_{internal}$. Indeed, a quantitative study of the variation of the committed error (expressed in number of false detected pixel) in terms of the ratio $\frac{w_{external}}{w_{internal}}$ shows that a 20% variation of it does not alter significantly the precision of the detected grid.

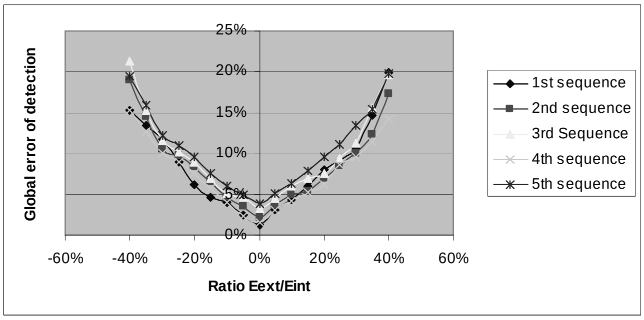

Fig. 7. Variation of the made error (expressed in number of false detected pixels) in terms of the ratio $\frac{w_{external}}{w_{internal}}$.

In addition, the detection has been tested on 10 different sequences without changing any parameters and the obtained results have been judged satisfying by medical experts on all images.

4 Quantification

In order to make a first validation of the method, we have also quantified classical cardiac parameters on the 10 studied sequences as radial, circumferential, longitudinal displacements, torsion or deformations. We present in Tab.1 a comparison between our obtained results for the quantification of the radial displacements and two studied of the medical literature.

	Base	Mdian	Apex
[20] (12 patients)	5.9 ± 0.4	6 ± 0.3	4.65 ± 0.2
[12] (31 patients)	5.0 ± 1.3	4.3 ± 1.1	4.2 ± 1.6
Our estimation (10 patients)	5.7 ± 0.5	4.9 ± 0.7	4.3 ± 0.9

Table 1. Comparison between our quantification and two studies of the medical literature concerning the estimation of the radial displacements (expressed in millimeters) for healthy volunteers.

5 Conclusion

The method presented in this article, based on both active contours and diffusion process, finally allows to (i) smooth the image with a preservation of the tag patterns, (ii) to ensure the robustness and the precision of the grid detection and (iii) to completely automate the detection and follow-up process.

Moreover, by associating the detection method with an original automatic detection of the myocardial boundaries (epical and endocardial ones) [8], it is possible to realize a two-dimensional temporal map (according the recommandations of the American Hospital Association) characterizing the local displacements and local deformations of the myocardium (Figure 8).

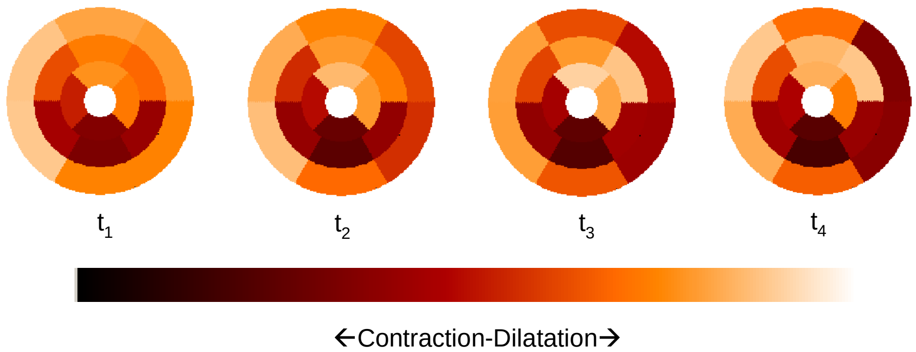

Fig. 8. Radial contraction of the heart.

The results presented are very interesting for radiologists to evaluate torsion, shearing, longitudinal and radial displacements of the LV and then to draw early diagnoses of particular cardiopathies.

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