Angle Images using Gabor Filters in Cardiac Tagged MRI

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Abstract. Tagged Magnetic Resonance Imaging (MRI) is a non-invasive technique used to examine cardiac deformation *in vivo*. An Angle Image is a representation of a Tagged MRI which recovers the relative position of the tissue respect to the distorted tags. Thus cardiac deformation can be estimated. This paper describes a new approach to generate Angle Images using a bank of Gabor filters in short axis cardiac Tagged MRI. Our method improves the Angle Images obtained by global techniques, like HARP, with a local frequency analysis. We propose to use the phase response of a combination of a Gabor filters bank, and use it to find a more precise deformation of the left ventricle. We demonstrate the accuracy of our method over HARP by several experimental results.

Keywords. Tagged MRI, Gabor Filters, Angle Images, HARP

1. Introduction

Cardiovascular diseases have arisen as one of the main causes of mortality in recent years. A complete knowledge of the heart function, and how pathologies affect local and global myocardial contractility, would lead to a more accurate diagnosis. As the myocardium is a highly uniform tissue, when it is depicted in conventional Magnetic Resonance Images (MRI), only the displacement of myocardial wall boundaries is appreciated. Tagged MRI (figure 1) is a variant of this technique which generates a tag pattern within the tissue. It is represented by a grid of dark bands, which deform according to the heart during the cardiac cycle. This pattern is called SPAMM (Spatial Modularization of Magnetization) tag [3], [2].

Since the appearance of Tagged MRI ([1], [3]), several computational techniques have been developed in order to extract motion information from these images. Some of them treat tags as sparse features that have to be tracked, while others directly retrieve dense displacement maps. Regardless of the method, all of them share the same aim, which is to obtain automatically (or semiautomatically) these maps that cover the whole myocardium. These are the base for further quantitative data extraction for clinical use.

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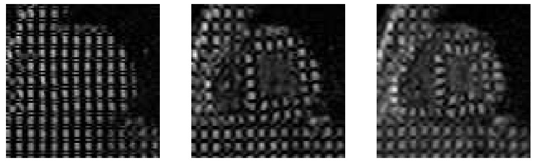


(a) (b) (c)

Figure 1. Examples of cardiac Tagged MRI. (a) Left ventricle at the starting of the systole. (b) Tagged MRI during the systole. (c) Left ventricle at the end of the systole.

In this paper we are focus on the Angle Images, a basic ingredient for tissue tracking, due to the fact that these images are strongly related to the movement of the myocardium in Tagged MRI. We explain this concept in section 2. Here, we also show some of the several techniques used to retrieve these kind of images. By one hand HARP (Harmonic Phase), is a method to obtain them by performing a global filtering in the frequency domain. Nevertheless, as the myocardium deforms locally due to heart fibers distribution, this technique is not well suited. By the other hand, we present a new method based on the use of Gabor filters to obtain Angle Images from a local analysis, which is strongly inspired in HARP. It can be said that our technique behaves as local HARP. In section 3, we describe Gabor filters fundamentals. In section 4, we explain how these are applied to Tagged MRI to obtain Angle Images. In section 5, we show some experimental results. Finally, in section 6, some conclusions are extracted.

2. Principle of Angle Images

According to Osman and Prince in [8], a Tagged MR image can be expressed as sum of multiple complex images:

$$\psi = \sum_{k=-K}^{K} \psi_k,$$

where ψ_k is a complex image whose phase is called Angle Image, and it is linearly related to the true motion of each point in the myocardium [9], [4]. By this fact, the phase of points becomes an intrinsic property of the tissue that remains constant during the cardiac cycle. Thus, tracking tissue points is equivalent to track their phases. Because of the image contrast variation due to fading, it is more robust to follow phase values than gray ones through the sequence. This fact is schematically depicted in figure 2, where the initial pattern changes by a deformation and fading. It can be observed how the estimated phase deforms in the same way and overcomes the fading.

In order to obtain Angle Images, a ψ_k has to be isolated. Nevertheless, doing it is not an easy task, but there are different techniques that can approximate it. HARP is one of this. It is based on the extraction of the first harmonic peak from the Fourier spectrum of the image. However, the filter design to obtain this image is not trivial, and it does not support high level of local deformation, since it assumes a global frequency of the tags for all the images. Z. Qian *et. al.* [10] have proposed a variant to localize the tags by using Gabor filters based on the limitations of HARP [11]. They proved that Gabor filters are more reliable to recover the tags than HARP when there is a high level of

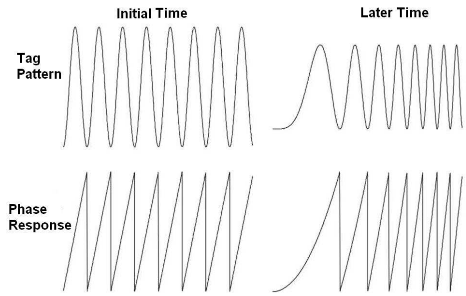


Figure 2. Principle of Angle Images. A sinusoidal tag pattern and its phase response at the initial time, and a short time later.

deformation locally. They suggest to deal with the parameters used in the filters and create maps from them [10]. However, this approach implies an exhaustive search for each pixel using many filters whose central frequencies are technically out of range. In the following sections, we describe a different approach by using Gabor filters. It is based on the principle of the Angle Image from HARP and, in order to improve it, we take advantage of the local analysis of Gabor filters.

3. Definitions

The Gabor filter was introduced by Daugman in [6] firstly. It is essentially a Gaussian g modulated by a complex sinusoid s. In 2 dimensions, a Gabor filter has the following form in the spatial domain:

$$h(x,y) = g(x',y') \cdot s(x,y),$$

where $g(x',y')$ and $s(x,y)$ are defined as:

$$g(x',y') = \frac{1}{2\pi\sigma_{x'}\sigma_{y'}} \exp\{-\tfrac{1}{2}[(\tfrac{x'}{\sigma_{x'}})^2 + (\tfrac{y'}{\sigma_{y'}})^2]\},$$

$$s(x,y) = \exp[-i2\pi(Ux + Vy)].$$

The rotation of the Gaussian is established by:

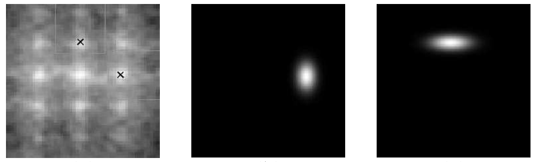
$$x' = x\cos\theta + y\sin\theta, \quad y' = -x\sin\theta + y\cos\theta.$$

x' and y' represent the spatial coordinates rotated by an angle θ. $\sigma_{x'}$ and $\sigma_{y'}$ are the standard deviations for the Gaussian envelope and they should not coincide necessarily. This allows us to deal with anisotropic envelopes. In fact, an aspect ratio λ and its orientation are defined as:

$$\lambda = \frac{\sigma_{x'}}{\sigma_{y'}}, \quad \phi = \arctan V/U$$

where U and V represent the 2D frequencies of the complex sinusoid.

It is well known that the Fourier transform $H(u,v)$ of $h(x,y)$ is a Gaussian centered on (U,V). Thus, the Gabor filter can be treated as a bandpass filter, and can achieve optimal resolutions in both, the spatial and frequency domains [11].



(a) (b) (c)

Figure 3. Power spectrum of the image of the figure 1(a). (b) Filter designed to analyze the horizontal peak. (c) Filter designed to analyze the vertical peak.

4. Gabor Filters in Tagged MRI

As we mentioned above, a Gabor filter is a bandpass filter with a Gaussian envelope. So, by extracting the central frequency of the first harmonic peak ψ_1, we can isolate this peak and take advantage of the Gabor resolution achievement. In order to localize it, we design a region of interest, which depends if we are analyzing the vertical tags or the horizontal ones, and we look for the maximum value in this area. Figure 3(a) shows the localization of these frequencies for the image of figure 1(a).

The bandwidth of the filter is established through $\sigma_{x'}$ and λ. Thus, the value of $\sigma_{x'}$ is fixed by:

$$\sigma_x = \frac{1}{\sqrt{U^2+V^2}},$$

where (U, V) are the frequencies of ψ_1 of the input image [11]. The orientation of the Gaussian has been designated to be equal to the orientation of the complex sinusoid, $\theta = \phi$ [5].

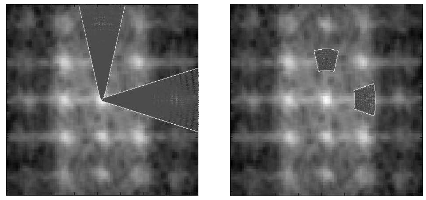
We take special care of the bandwidth of the Gaussian in the y' direction, because of the presence of a harmonic peak at the addition of the vertical and horizontal peaks in the frequency domain in 2D tagging. This peak is produced by both tag sequences, and represents the frequency created by the intersection of the orthogonal tags. Thus, we have designed $\lambda = 2$. Figure 3(b) shows the Gabor filter for the horizontal peak, while the figure 3(c) displays the filter for the vertical one. The logarithmic spectrum is shown to a better understanding.

Based on this analysis, we can verify that applying a Gabor filter centered on the first harmonic peak is a variant of HARP. The only difference is the shape of the filter. Therefore, we can deal with the phase response of the filtered image as an Angle Image, and estimate a displacement field by tracking points with the same estimated phase. However, applying only one filter does not improve HARP at all. It is because it roughly assumes one frequency for all the image, and it generates a level of error especially when large local deformations are present.

By designing a set of Gabor filters, the most relevant information for an specific frequency can be recovered. In [10] an approach using Gabor filters is described. However, they suggest to vary the central frequency of the first harmonic peak by the equations:

$$U' = \Re\{(U + i \cdot V) \cdot m \cdot \exp(i \cdot \Delta\phi + \omega),$$
$$V' = \Im\{(U + i \cdot V) \cdot m \cdot \exp(i \cdot \Delta\phi + \omega)$$

where m, $\Delta\phi$ and ω, are parameters to vary, and deal with the ω map as a phase image which is recovered from the maximum response of the filters tested for each pixel. U and



(a) (b)

Figure 4. Scanned space of frequencies for the horizontal and vertical first harmonic peak. (a) Scanned space suggested in [10]. (b) Mapped space we test to look for local variations of the central frequency.

V are the central frequency of the first harmonic peak. The ranges of the parameters are established as:

$$m \in [0.85, 1.3], \quad \Delta\phi \in [-\pi/12, \pi/12], \quad \omega \in [-\pi, \pi]$$

Although the advantages of the Gabor filters are used, the variations in the frequency space is out of range, because it tests Gabor filters with frequencies that are out of a possible deformation in the tags, as it is shown in the figure 4(a). In addition, it has a high computational cost besides HARP and our method, and it suggest to estimate a displacement map based on the parameters of the filters that maximize the response.

On the other hand, we deal with the phase response obtained from the use of a set of Gabor filters, which were generated by varying the central frequencies according to the following equations:

$$U' = \Re\{(U + i \cdot V) \cdot m \cdot \exp(i \cdot \Delta\phi)\},$$
$$V' = \Im\{(U + i \cdot V) \cdot m \cdot \exp(i \cdot \Delta\phi)\},$$

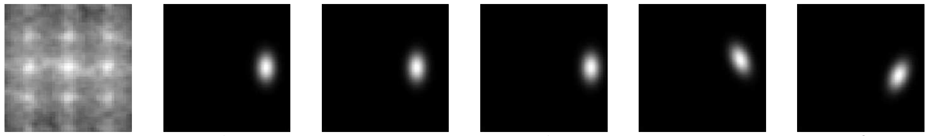
where m represents a linear variation on the frequency, and $\Delta\phi$ represents a angle orientations of the frequency.

Because the Gaussian envelope of the Gabor filters is adaptable to the orientation of the 2D frequency, and the bandwidth is a function of the frequency, we can modulate m and $\Delta\phi$ to map the possible frequencies that could be present in the cardiac motion. Thus, we can build a more precise Angle Image by creating a Gabor filter bank, and taking the highest response for each pixel. The parameters used to modulated are in the following ranges:

$$m \in [0.8, 1.2], \quad \Delta\phi \in [-\pi/12, \pi/12].$$

These ranges map to frequencies that are around the center of the first harmonic peak. It is expected to match the local patterns mostly in this space. The scanned space is shown in the figure 4(b).

Based on this analysis, we propose to modulate the bank of Gabor filters to recover a more accurate local deformation. We take the phase of the complex image generated by the extraction of the maximum response of the filtered images at each pixel. It is done in order to create the Angle Images locally. Figure 5 displays some examples of a Gabor power spectrum we use. The filters shown were generated to analyze the first horizontal harmonic peak. The effects of modifying the parameters m and $\Delta\phi$ can be observed. The m parameter moves the center of filter horizontally, while $\Delta\phi$ rotates the central frequency and the orientation of the filter.



(a) (b) (c) (d) (e) (f)

Figure 5. Examples of power spectrums of Gabor filters (a) Power spectrum of a Tagged MRI at the starting of the systole. (b) First chosen filter (c) Shifted filter, $m = 0.8$, $\Delta\phi = 0$. (d) Shifted away filter: $m = 1.2$, $\Delta\phi = 0$. (e) Positive rotated filter: $m = 0$, $\Delta\phi = -\pi/12$. (f) Negative rotated filter: $m = 0$, $\Delta\phi = -\pi/12$

5. Results

Figure 6 shows an example of our method to obtain the Angle Image versus HARP based method. As it is illustrated, in the first image the both techniques report practically the same results (low deformation). In the second image, some differences are shown. These are essentially that Gabor filters follow better the tags deformation. However, the deformation in the myocardium is not much, and the result generated by HARP is still efficient. In the third image a greater difference between HARP and our method is observed. For this image, HARP has lost one tag completely in the upper center of the myocardium (squared area). Here the frequency has increased because of the approximation of vertical tags, while the frequency in other sections of the myocardium has decreased, and HARP is not prepared to deal with this issue. So, HARP tends to blur the frequencies of the myocardium, and it generates an Angle Image with smoothed deformations. In fact, it is possible to lose tags, as in this example, when the frequency of the tags changes a lot locally due to motion, and in several regions increases while in others decreases. On the other hand, our method creates a more precise Angle Image. In this example, despite of the fading of the tags, all the tags are recovered, and deformations are well generated.

The images discussed in the last paragraph are of low quality, especially because of the tag fading. So, even when our method generates better results than HARP, there are some errors due to the quality of the images. In figure 7 another example is shown with a higher quality images. From this example, we can see that our method describes better the behavior of the tags deformation than HARP. This image, from the end systole, shows a contraction to the center of the left ventricle. The results shown by HARP have some problems in the tag recovery, in fact there are some regions where some of them are lost. In addition, the deformations reported by HARP are not as accurate as our results. The deformation is smoothed by HARP again, while using our method it is better described. The differences between methods are shown in figure 7(d) and (h). The squared areas highlights the regions where the variations are the greatest.

In order to generate relevant information for clinical usage, the measurement of the myocardial deformation using our method is shown in figure 8. Displacement maps are obtained using phase tracking as described in [7]. It can be observed that the estimated field describes the rotation of the myocardium despite of the quality of the images. From the magnitude of the displacement, it can be noted the distribution of the deformation over the myocardium. From this parameter, it can be determined when the heart is rotating under the baseline, and elaborate the appropriable diagnostic.

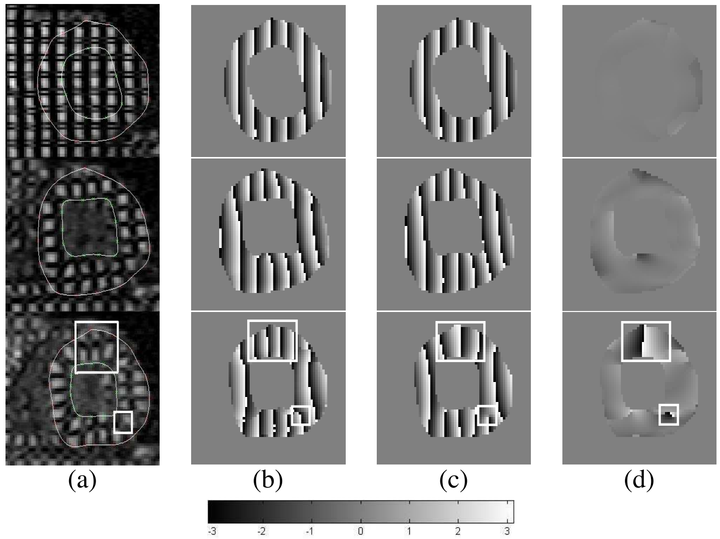


Figure 6. Example of Angle Images obtained of the horizontal harmonic peak using Gabor filters and HARP. (a) Original Tagged MRI in short axis during systole. (b) Angle Images generated by our method. (c) Angle Images produced by HARP. (d) Difference between methods. The left ventricle has been delineated for a better understanding. Tags can be identified in the Angle Images through the discontinuities from $-\pi$ to $+\pi$.

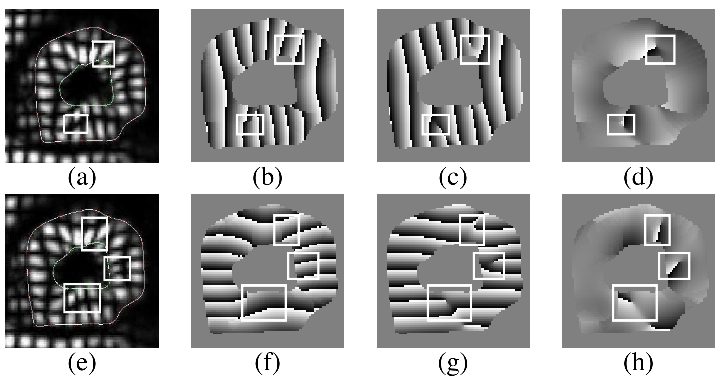


Figure 7. Example of Angle Images obtained using Gabor filters and HARP. (a) Original Tagged MRI at the end systole. (b) Angle Image of the horizontal harmonic peak using our method. (c) Angle Image of the same peak using HARP. (d) Difference of (b) and (c). (e) Original image. (f) Angle Image of the vertical harmonic peak using our method. (g) Angle Image of the same peak using HARP. (h) Difference of (f) and (g).

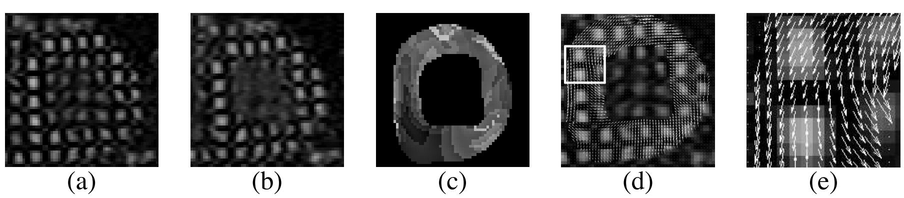


Figure 8. Measured deformation. (a) A systole image. (b) Next image in the sequence. (c) Calculated magnitude of the displacement. (d) Measured displacement. (e) Highlighted region.

6. Conclusion and Discussion

In this paper we have described a new approach to obtain the Angle Images from cardiac Tagged MRI, through the use of a Gabor filters. We suggest an alternative method besides HARP and the proposed in [10]. It has been demonstrated that our method is more accurate than HARP, and is less expensive in the meaning of computational cost than the proposed by Qian *et al*. in [10]. Essentially, our method recovers the best of these techniques to generate a new approach in this issue.

We have tested our method with a set of 14 patients, 10 of them are normal, while 4 have suffer some type of infarct. We have observed the same differences expose here in the Angle Images. However, in order to determine an analytical parameter of accuracy, we are now in process of developing a technique to perform this task.

The method exposed here is potentially an improved way to obtain more precise 3D reconstruction and fully cardiac motion. It is due to the ability to recover more accurate Angle Images. Other parameters like strain and torsional deformation could be calculated too. The application of this method to long axis Tagged MRI can be also considered. However, depending of the characteristics of the tags, the parameters ranges could remain equal or experiment some changes.

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