ANISOTROPIC ANOMALOUS FILTER AS A TOOL FOR DECREASING PATIENT EXAM TIME IN DIFFUSION WEIGHTED MRI PROTOCOLS

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Abstract: Diffusion weighted imaging (DWI) and diffusion tensor imaging (DTI) are noisy submodalities images in magnetic resonance imaging (MRI) and usually have long acquisition time due to repetitions needed to improve the signal noise ratio (SNR). Here we propose and evaluate anisotropic anomalous diffusion (AAD) filter on DTI and DWI to enhance SNR and reduce the need for repetitions. Anisotropic anomalous diffusion filter is an iterative parametric diffusion filter based on anomalous diffusion. Fractional anisotropy (FA) and mean diffusivity (MD) maps were acquired with different repetitions times and processed using AAD filter to investigate optimum *q* parameter. SNR, RMSE and Full Width at Half Maximum (FWHM) measures were evaluated as image quality metrics. The results show that filtering based on AAD approach can improve DWI and DTI image quality and preserving relevant aspects in images. We conclude that when the AAD is applied on DWI and DTI images maps we can use images with lower acquisition repetitions time and maintain the image quality comparable to higher acquisition images.

Keywords: Spatial filtering, Anomalous diffusion, Magnetic resonance imaging, DWI, DTI.

Introduction

In recent decades there has been a remarkable improvement in several imaging techniques for clinical diagnosis and therapy and one of these advances has been the improvement of brain imaging techniques such as diffusion-weighted magnetic resonance imaging (DWI and DTI). Many studies in neuroscience has been made with this promising diffusion techniques, which makes it possible to improve the diagnosis of various neuropathologies such as Alzheimer disease, Parkinson disease, Multiple Sclerosis and others [1]–[4]. However, these imaging techniques are still noisy and data processing is needed in order to have a precise diagnosis.

Usually spatial filters are used in digital image processing to attenuate noise. One of the most applied and well know spatial filter is the classical anisotropic diffusion filtering [5]. The use of spatial filters has been widely studied for the improvement of quality in MRI images, obtaining promising results for these non-invasive imaging techniques [6]–[8]. However, this classical filter comes from the idea of solving the problem of distortion caused by Gaussian filter kernel convolution. However, its application is restricted to image models that follow low complexity geometry. The classical anisotropic filter is not robust enough to images that reflect complex geometry structure such as fractals features and non-homogeneous medium, which are found in various regions of the human body [9].

From anisotropic anomalous diffusion approach, specifically a filter based on porous media diffusion [10], we derived an iterative filter that can be used to study objects with complex geometries [10], [11]. Several studies have been made with the non-extensive statistical approach [10], as an example of knowledge areas as Biology, Physics, Economics and others [12]–[15]. The anisotropic anomalous diffusion paradigm could be a useful tool for image processing on DTI and DWI maps, such as the fractional anisotropy (FA) and mean diffusivity (MD) measurements, in order to attenuate the noise present in each of these image techniques [8], [14], [16], [17].

In order to improve the image quality, directly from the MRI tomography, usually is used repeated N successive image averaging. One possible solution is the investment in hardware upgrade of the tomography, which improves the external magnetic field and the gradient magnetic field intensity. Although, these approaches are expensive and other solutions must be studied. Our proposal here is to use anisotropic anomalous diffusion filter (AAD) as an image enhancement method for DTI and DWI images with small N. Here we investigated if AAD filter applied on DTI and DWI quantitative maps can improves image quality and reduce the time necessary for patient exam.

Materials and methods

Imaging protocol

The DTI and DWI images were acquired with a 3T magnetic resonance imaging equipment at Clinical Hospital of Ribeirão Preto, Brazil. The imaging parameters used for the DTI imaging protocols were: Echo Planar Imaging (EPI) acquisition technique, voxel resolution 2.0 x 2.0 mm, image matrix size 128 x 128, 2 mm of gap between slices, 15 diffusion gradients and b-factor = 1000. We selected 20 healthy volunteers aware to the committee of ethics previously approved to this research. The age range for the volunteers was 25 to 35 years old to avoid different brain mature stages.

The quantitative maps were acquired with different N (N = 1, 2, 4, 6, 8 and 16) to study different noise levels and the filtering performance. Image set with N = 16 was adopt as a noise free image and it was used as reference image to calculate all the quality metrics cited in the section *Image quality metrics*. For all these images it was performed the same pre processing pipeline, such as: register, gradient magnetic field artifacts correction and diffusion processing algorithms. All these pre processing steps were made with the free computational software FSL [18], that is a common image processing tool to reconstruct FA and MD quantitative maps.

Filter implementation

The anisotropic anomalous filter is based on the partial differential anomalous diffusion equation, known as porous media equation [10]. Equation (1) describes the continuous form of the anomalous equation [10]. A detailed explanation could be provided in others studies applied with the non-linear Fokker Planck like equations [10], [19], and in this studied we avoid deep explanation to not extend this study scope. Here we use the porous media equation to define the AAD and the numeric form of the anisotropic anomalous equation. For more details about the AAD method implementation see [16].

$$\frac{\partial I(r,t)}{\partial t} = \nabla[D_q(r).\nabla I(r,t)^{2-q}] \qquad (1)$$

The power law behavior, present in anomalous diffusion process, differ from classical approach only when q ≠ 1 and this generalization can be denoted as $<x^2> = D_q.t^{(2-q)}$, i.e. the generalized Einstein relationship with the non-linear random motion. The main parameter that is investigated here is the anomalous parameters, *q*, due the anomalous probability distribution that is iteratively generated, i.e. the *q-Gaussian* probabilities distributions [19]. The others filter parameters were set up with optimum values for MRI denoising method [16].

Image quality metrics

Here, it were used two quality index based on statistical information (SNR and RMSE) and one quality index that could provide a visual quality information (full width at half maximum, FWHM). Our research approach was defined to compare the smoothing effectiveness obtained with the AAD filter and the classical anisotropic diffusion filter [5]. Note that when *q* = 1 our algorithm recover the classical anisotropic approach, i.e. the Perona and Malik filter [5]. When *q* ≠ 1 we obtain the called *q-Gaussian* filters that has different smoothing behavior depending the *q* value. [16]

Results

The first result show here will be the statistical indexes, SNR and RMSE (Figure 1). The RMSE index results had a similar effect compared with SNR curves, but with the inverse behavior, i.e. optimum value for RMSE is the lowest found value. For this reason we decided to not show the RMSE results. In general, it could be seem that the smoothing effect maintain the same behavior with q value, for both metrics. In addition, an interesting result appeared when $q \neq 1$. The second result is show with the FWHM experiment were it could be seen the visual quality enhancement when it is applied the AAD filter (Figure 2).

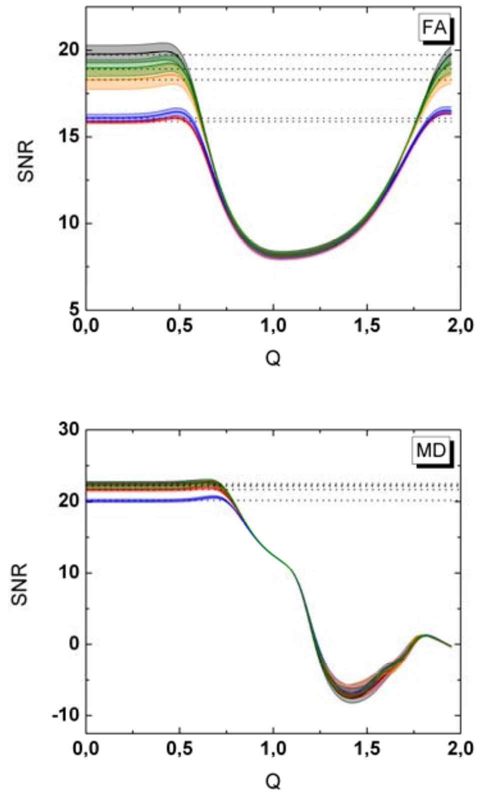

Figure 1: SNR graphics with the FA and MD quantitative maps. The dotted lines in all graphs represent the SNR baseline values for image for each N. It is important to see that are found SNR peaks values for q ≠ 1, and more often to *q*<1. The SNR values found with AAD filter are often higher than the values found with classic anisotropic filter and the SNR baseline level (N defined image).

Table 1: Full width at half maximum (FWHM) values found with N averages images obtained with no filtering application. Note that the FWHM tend to decrease when N increase. This effect happens because the overall SNR enhancement.

MRI DTI Imaging					
	N=1	**N=2**	**N=4**	**N=6**	**N=8**
FA_{FWHM}	0.134	0.131	0.124	0.123	0.122
σ_{FA} (x10^{-4})	11.66	9.91	9.82	9.95	10.07
MD_{FWHM}	4.30	4.16	4.06	4.05	3.99
σ_{MD} (x10^{-6})	4.9	5.3	4.8	4.8	4.6

*MD values x10^{-4}

Table 2: Full width at half-maximum (FWHM) values found with the both filters, AAD and the Perona and Malik filter. In some occasions we can found a FWHM decrease for FA and MD maps. These measurements could be useful to determine a better tissue segmentation threshold, i.e. with a lower FWHM value imply in a more defined gray level intensity.

	Filtered Images									
	N=1		**N=2**		**N=4**		**N=6**		**N=8**	
	AAD	**AC**	**AAD**	**AC**	**AAD**	**AC**	**AAD**	**AC**	**AAD**	**AC**
FA_{FWHM}	0.129	0.134	0.125	0.116	0.120	0.113	0.118	0.111	0.116	0.110
σ_{FA} ($x10^{-4}$)	9.64	11.14	8.88	11.65	10.82	10.97	7.90	8.87	8.21	10.50
MD_{FWHM}	4.17	5.09	4.06	3.83	3.93	3.74	3.87	3.75	3.87	3.72
σ_{MD} ($x10^{-6}$)	0.6	0.6	0.6	0.7	0.7	0.6	0.6	0.6	0.5	0.6

*MD values $x10^{-4}$

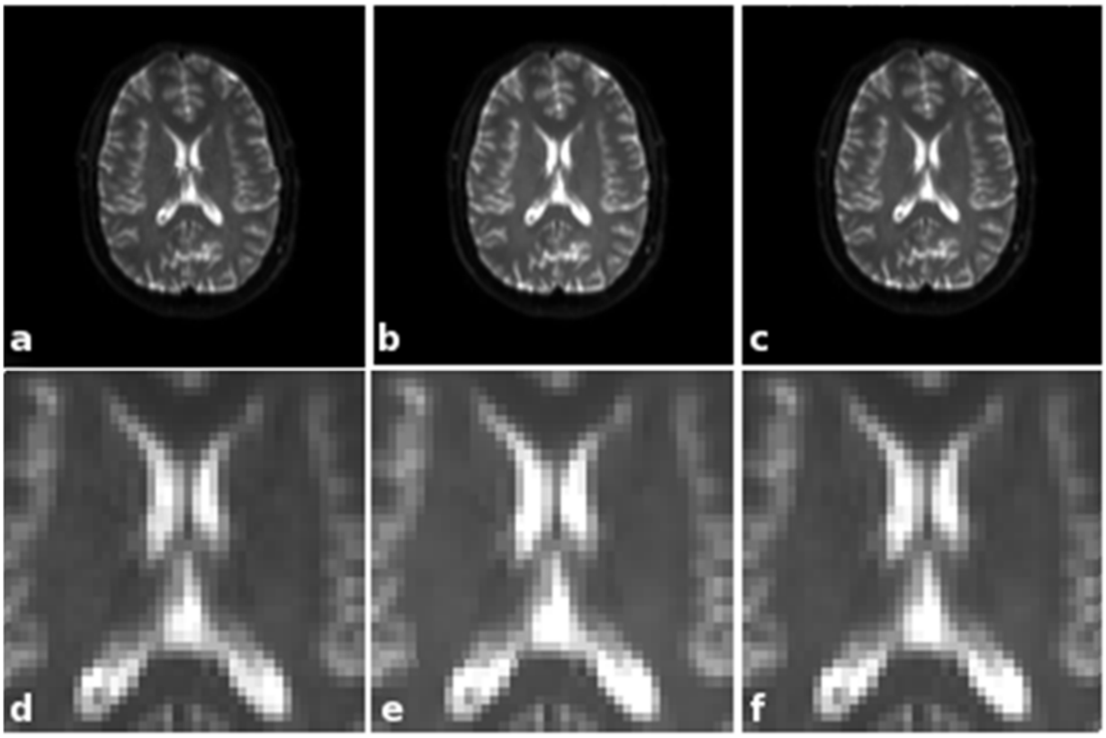

Figure 2: Filtered images with the anisotropic anomalous filter on the quantitative MD map. **a)** The original image from mesial position of the brain with N=2 acquisitions. **b)** The same image in a) filtered image with t=10, D_q = 0.2 and q=0.5 anisotropic anomalous filter parameters. **c)** The original image with same position, but with N=4 acquisitions. The anomalous filtering preserves the edge contrast and has an effective noise attenuation. The images **d)**, **e)** and **f)** are magnification of the same images above just to better edge preservation visualization

Discussion

We found comparable SNR and RMSE values for testing and reference images sets, i.e. filtered and higher N averages. These results show that the enhancement behavior with $q\neq1$ values could obtain, for each N, a specific optimum filtering region. See Figure 1 and compare the dot lines with the continuous lines.

The FWHM quality index analysis represents the capability of tissue segmentation based on gray intensity levels. The Table 1 shows the results for FWHM only for the N mean images. It is expected that the noise are reduced and image edges are preserved when the AAD are applied and these carry a thin histogram peak effect. Our anomalous filtering approach presents a superior enhancement, see Table 2.

In order to visualize the AAD filtering effect see Figure 2. Basically, it can see that the AAD filter preserve efficiently the inner structures edges (brain tissues conformation) and also attenuate the noise present in all image space. Figure 2 illustrate with more details the *corpus callosum* region, but this highlighted effect can be generalized for different brain structures into image. Furthermore, the interface between white and gray matter remains with contrast similar that obtained with the usual multiple acquisition method.

The optimum q values found for RMSE are the same q values found for SNR. In addition, the measures with FWHM also suggest that the visual quality improves in all images with the same q value set for the statistical measures. The general quality observed for filtered N_i image is similar to N_{i+1} image, e.g. N=1 images has SNR, RMSE and FWHM values equivalents to N = 2 images. This enhancement behavior is seen with other N values (N = 2, 4, 6 and 8). When the AAD filter is applied on each FA and MD maps, it is possible to reduce the number of acquisition necessary to obtain an image with reasonable quality. This possibility for reduction in exam time could offer a better comfort to patient and decrease the artifacts caused by patient movement.

Conclusion

The main limitations in the DTI imaging modality are the time necessary for acquisition repetitions and the low spatial resolution. In addition, the investment in gradient fields and a more accurate instrumentation is an expensive alternative that not always can be adopted. The AAD filter shows as an effective, robust and available alternative for DTI spatial filter in order to attenuate the noise present in FA and MD quantitative maps. Furthermore, we can note that the AAD filter also preserves the biological structures edges, which is essential for a clinical diagnosis and future image processing steps such as tissue segmentation. The results from this study suggest that there is an enhancement in image quality when AAD is applied and it should be sufficient for low SNR image acquisition. The proposed anisotropic anomalous filtering method suggest a balanced use of MRI image acquisition DTI protocol and the AAD filter application. It seems that AAD filter is a suitable solution to reduce total exam time while it improves the general image quality. In general, AAD filter has a potential application in quantitative DTI images in FA and MD maps, providing a cheap alternative to reach images with high quality without expensive investments.

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