Anisotropic Power Maps: A diffusion contrast to reveal low anisotropy tissues from HARDI data.

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Purpose: Quantification of water diffusion anisotropy is one of the key measures that is collected in almost every clinical and neuroscience applications using MR diffusion imaging. In tissues with a high structural organization, such as white matter, the measure of anisotropy provides useful information about microstructural changes that can occur in normal development or in neurological and psychiatric disorders [1]. Today, Fractional Anisotropy (FA) remains the most widely used anisotropy index. Other methods like Generalized Fractional Anisotropy (GFA)[2] and similar indices have been applied as an alternative to FA and to overcome some of the limitations of the diffusion tensor model. However, most of these methods remain strongly model based (the Orientation Distribution Function (ODF) profile used to compute the GFA index can change according to the imaging method chosen) or particularly sensitive to noise (the measure of variance across multiple directions is de facto also a way to quantify noise along different directions). The use of spherical harmonics (SH) of even order $l \geq 2$ to characterize anisotropy has been suggested since the first papers introducing the concept of High Angular Resolution Diffusion Imaging (HARDI). Frank and other authors have proposed using this approach to better quantify anisotropy of the apparent diffusion coefficient profile and classify white matter complexity [3-4-5-6]. In this study, building on this idea, we present a new index that, instead of quantifying diffusion anisotropy from a HARDI signal, measures the total power of the spherical harmonics coefficients encoding only the anisotropy information of the signal or, in short, it measures the anisotropic power (AP) of the signal. The aim of this index is to provide a simple, robust to noise and model independent measure that can be used to better characterize biological tissues and also potentially detect changes in low anisotropy regions that normally are not distinguishable from CSF regions or noise with standard anisotropy indices.

Theory If $a_{l,m}$ are the spherical harmonic coefficients of the HARDI signal normalized to the non-diffusion weighted signal ($S=S_{dwi}/S_{b0}$), the AP index can be defined as the sum of the angular power spectrum of each harmonic of even order $l \geq 2$ as:

$$AP = \sum_{l=2,4,6,\ldots} \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{l,m}|^2$$

Figure 1, shows as an example of the AP index evaluated for increasing harmonic orders on a HARDI signal defined by a diffusion tensor ranging from [2.1 0.0 0.0] to [0.7 0.7 0.7] x10^{-3} mm^2/s. Data was simulated with a value of b-value of 3000 s/mm^2 and 80 directions to fit SH orders up to l=10. The figure shows that most of the anisotropic power is captured by an AP evaluated up to order 6. Higher orders, even for the high b-value applied, don't contribute significantly to the final AP value.

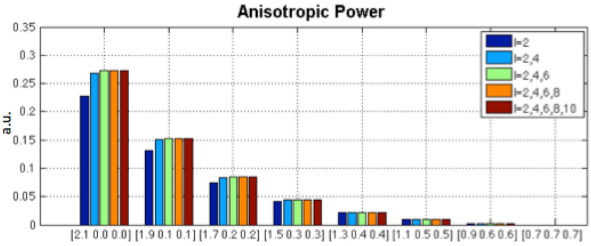

Figure 1

Due to the exponential relation between the MR signal and diffusivity, and since AP describes an un-normalised signal power, a convenient way to express this index is to use a neper scale:

$$AP_{np} = \ln(AP/AP_{ref})$$

where AP_{ref} can be a reference power (e.g. a fully anisotropic tensor [2.0 0.0 0.0] x10^{-3} mm^2/s).

In-vivo data. In order to compare AP measures with conventional anisotropy maps, 5 datasets from healthy subjects were acquired using a 3T GE MR750 system (General Electric, Milwaukee, WI, USA) with the following parameters: voxel size 2.0x2.0x2.0 mm, 128x128 matrix, 70 slices, TE 76.6 ms, b-value 3000 s/mm^2, 60 diffusion-weighted directions and 7 non-diffusion-weighted volumes using a spin-echo EPI sequence. Following correction for motion and eddy current distortion FA, GFA (based on qBall-ODF [7]), Generalized Anisotropy (GA)[4,5] and AP maps were estimated for each dataset.

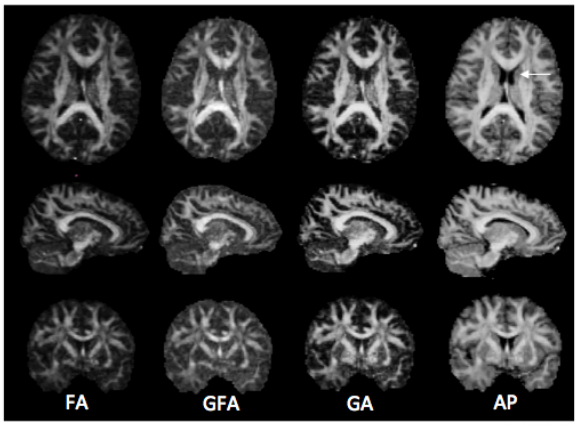

Figure 2

Results Figure 2 shows a comparison between different anisotropy maps and the $AP_{(np)}$ maps calculated up to order 6 for one of the subjects (similar results were obtained for all subjects).

While anisotropy maps reveal white matter and thalamic regions, AP maps are able to detect anisotropic power contributions also from grey matter regions in the cortex and in the caudate close to the ventricles (arrow). At the same time, AP maps are able to efficiently suppress any signal or noise from CSF regions (i.e. no signal power in even SH orders $l \geq 2$).

Figure 3 shows a comparison between the AP map and a T1 weighted structural image obtained from the same subject. Both images are able to separate white and grey matter structures similarly confirming that the AP index correctly discriminates between CSF and low anisotropic tissues.

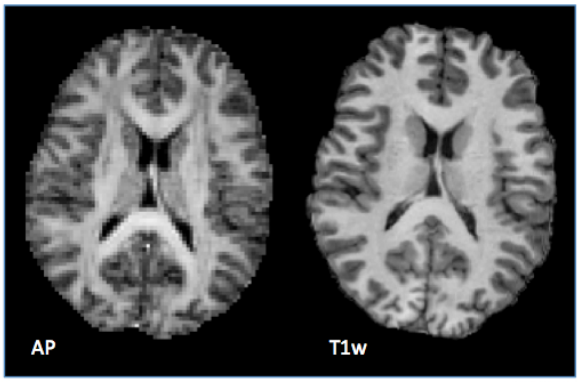

Figure 3

Discussion and Conclusions All the anisotropy information in a HARDI signal is captured by the spherical harmonic coefficients of even order $l \geq 2$. By measuring the total power of these coefficients it is possible to obtain an absolute measure of how much anisotropy information is contained in each HARDI signal and use this to better quantify and discriminate low anisotropy gray matter regions from CSF regions or noise. This measure is entirely model independent and particularly robust to noise as it can be obtained directly by the sum of the angular power spectrum of the first few SH coefficients of even order (i.e. l=2,4,6). These maps are relatively easy to extract from any existing HARDI dataset acquired with more than 30 directions (28 is the minimum required to fit SH of order 6). Since the AP map quantify how much anisotropy information is effectively available in each a voxel, this measure can be potentially useful to detect very small microstructural changes in low anisotropic regions beyond white matter. Also, these maps can be used to better calibrate or fine tune HARDI methods to extract fibre orientation distributions only in voxels with enough anisotropic signal power. Finally, the similar image contrast compared to structural images also makes the AP an ideal map to use when registering diffusion data to structural images.

References: [1] DK Jones, *Cortex*, 44: 936-952, 2008; [2] DS Tuch, *Magn Reson Med* 52:1358-1372, 2004; [3] LR Frank, *Magn Reson Med* 47:1083-1099, 2002; [4] E Ozarslan et al., *Magn Reson Med*, 53: 866-876, 2005; [5] M Descoteaux et al., *Magn Reson Med* 56: 395-410, 2006; [6] Chen Y et al. proc. 19th IPMI p246-257, Glenwood Springs, CO, USA, 2005; [7] M Descoteaux et al., *Magn Reson Med* 58: 497-510, 2007;