

Biexponential Analysis of Diffusion Related Signal Decay in Human Cortical Grey Matter

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Synopsis:

ADC values of gray (GM) and white (WM) matter obtained with conventional diffusion imaging exhibit no difference. This study explored differences in GM and WM water diffusion in normal human brain with CSF signal attenuated, high b-factor line scan imaging. Biexponential analysis of the diffusion data resulted in two diffusion coefficients ADC1 and ADC2 and their respective volume fractions. While ADC1 and volume fractions for GM and WM appeared to be similar, ADC2 in GM was found to be up to three times higher than in WM. Fundamental differences in tissue architecture may explain the different ADC2 values.

Introduction:

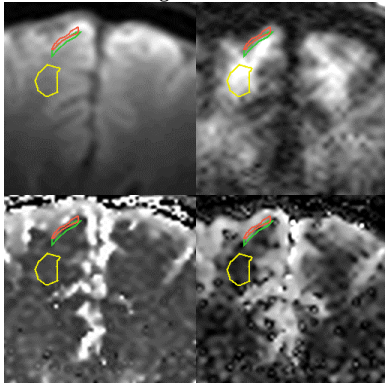
It is well known that ADC values of gray (GM) and white (WM) matter obtained with diffusion imaging at a normal range of b-factors exhibit very little or no difference. For a b-factor range larger than typically used, it has been demonstrated that the brain water signal attenuation is better described with a biexponential rather than a monoexponential model [1-3]. To date reliable biexponential diffusion data of in vivo human brain have only been published for white matter. Limited spatial resolution of high-b diffusion imaging sequences and contamination by strong CSF signal make assessment of biexponential diffusion coefficients in cortical GM a challenging endeavor. The study presented here used line scan diffusion imaging (LSDI) integrated with an inversion pulse for CSF signal suppression (FLAIR). LSDI [4] is a method distinguished by remarkably low distortions in areas of susceptibility variations, and thus suitable for imaging cortical GM in the vicinity of the skull.

Materials and Methods:

A FLAIR-LSDI sequence was implemented on a 1.5 T scanner (LX, release CNV3, General Electric, Milwaukee, WI) with a maximum gradient strength of 40 mT/m. With FLAIR-LSDI, a selective inversion pulse precedes the sequential column excitation by several excitation time intervals according to the desired inversion time TI. Four healthy volunteers, mean age of 38 years, were scanned with a 3 inch surface coil placed on their forehead. The image acquisition parameters were as follows: 3 mm slice thickness, 220x220 mm FOV, 128x128 column scan matrix, +/-2.2 kHz bandwidth, 10 s TR, 2400 ms TI, 86 ms TE. Images of an axial slice, at the level of the lateral ventricles, were obtained with constant δ and Δ at 16 b-factors ranging from 5 to 5000 s/mm². The scan time for three orthogonal diffusion directions (trace configuration: (0.5,1.0,1.0), (-1.0,1.0,-0.5), (1.0,0.5,-1.0), 60 mT/m maximum combined amplitude) was 24 minutes. Spatial resolution and bandwidth had been optimized to yield sufficient signal, i.e., at least 3 times above baseline noise, in cortical GM at the highest b-factor used. The data was processed off-line. For each pixel the geometric mean $(s_1 s_2 s_3)^{1/3}$ of the three directional signal values was formed and biexponential fits with the Levenberg-Marquardt method yielded two diffusion constants ADC1 and ADC2 and their respective volume fractions f1 and f2. Regions of interest (ROI) were drawn manually with a program that permits simultaneous visualization of the contour drawing process on different image backgrounds. The border between cortical GM and CSF was determined with the aid of a diffusion-weighted image, whereas the area of transition between GM and WM was determined on the T2-weighted image with the lowest diffusion-weighting (5 s/mm²). Two neighboring regions of interest were defined within the cortical GM: one adjacent to CSF (GM_{CSF}) and one proximal to WM (GM_{WM}). Moreover, a region of interest was defined within the frontal WM. Finally, data sets acquired previously, with the head coil at a lower resolution and without FLAIR CSF suppression, were used to obtain biexponential values within deep gray matter areas (frontal caudate nucleus and thalamus) and white matter areas (internal capsule).

Results:

The FLAIR-LSDI sequence allowed for excellent 91% suppression of the CSF signal, reducing the CSF/WM signal ratio at b=5 s/mm² from 3.7 to 0.34. Figure 1 shows an example of the ROI analysis performed. Average biexponential diffusion coefficients and their standard deviations are presented in the table shown below. Biexponential values in frontal WM and internal capsule WM were very similar and in excellent agreement with data published previously [2, 3]. Deep GM structures and cortical GM adjacent to WM (GM_{WM}) revealed a fast diffusing component with a similar ADC, whereas in the cortical GM bordering to CSF (GM_{CSF}) the ADC of the fast diffusing component appeared to be considerably higher. The ADC of the slow diffusing component, however, for all GM areas investigated was significantly higher than in the WM areas (p<0.001, Student's paired t-test). The ADC2 volume fraction f2 among all ROIs except GM_{CSF} (f2=51%) exhibited no significant difference and ranged between 30 and 38%.



n=4	GM _{CSF}	GM _{WM}	Frontal CN	Thalamus	Frontal WM	IC WM
ADC1 [$\mu\text{s}/\text{mm}^2$]	1.48	1.14	1.11	1.15	1.16	1.21
Stddev	0.17	0.11	0.06	0.05	0.05	0.05
ADC2 [$\mu\text{s}/\text{mm}^2$]	0.47	0.34	0.30	0.23	0.13	0.17
Stddev	0.02	0.03	0.01	0.01	0.01	0.01

GM, Gray Matter; WM, White Matter; CN, Caudate Nucleus; IC, Internal Capsule

Fig. 1: T2W (top left), 5000 s/mm² DWI (top right), ADC1 map (bottom left), and ADC2 map (bottom right) of the frontal lobe of a normal subject. Overlaid are the ROIs for GM_{CSF} (red), GM_{WM} (green) and frontal WM (yellow). The rim of elevated values next to the central sulcus appears slightly wider on the ADC2 map than on the ADC1 map.

Discussion:

Biexponential analysis of high-b diffusion data reveals a profound difference in water diffusion between GM and WM. Evidently the results need to be interpreted with great care, since the ADC1 value appears to increase in the layer closest to the cortical surface. One possible interpretation of the elevated ADC1 is the incomplete suppression of the CSF signal. It has been proposed that cellular architecture may contribute to the observed deviation from a pure monoexponential diffusion signal decay [5]. Cellular architecture in GM and WM are fundamentally different and may explain the two to threefold higher ADC2 value in GM. The presence of nerve fibers, corroborated by the slightly elevated anisotropy on conventional diffusion tensor scans, may explain the somewhat lower ADC2 values in the deep GM structures. This observation furthers our understanding of non-monoexponential diffusion signal decay and may ultimately hold the key to a correct interpretation.

References:

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