Does changes in gradient duration influence q-space-based determinations of displacement in vivo?

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Introduction

The aim of this study was to evaluate the effect when violating the Short Gradient Pulse (SGP) approximation and its effect on FWHM. The evaluation was done on a clinical 3T MRI scanner, using a specially developed diffusion weighted SE-EPI pulse sequence. We hypothesised that it is possible to visualise the effect of violating the SGP, and thereby indirect visualize structural sizes and permeability of the cell membranes that constitute the confining diffusion geometry *in vivo*.

Theory

In q-space imaging a short diffusion encoding gradient pulse duration δ is assumed [1]. Violation of the condition $\delta \ll \Delta$ leads to an under estimation of measured structural size. With a clinical scanner, this condition it is rarely possible to fulfil since δ needs to be relatively long to achieve sufficiently high q-values. When δ increases the water molecules will get a phase shift correlated to the Centre of Mass (COM) of the path they have travelled during the time δ. For large δ, the water molecules are reflected by the barriers of the confining geometry and the COM will approach the centre of the geometry and it will hence be less likely for the water molecules to have its COM close to the pore walls [2]. This assumption of COM is only valid when the structure walls are perfectly reflecting.

Materials and Methods

This study was preformed *in-vivo* at a 3T Philips Achieva system with a maximum effective gradient strength of 89 mT/m using a SE-EPI sequence. Three healthy volunteers were scanned after their informed consent was obtained. q-Space data was sampled in sex directions with q varying from 0 to 889 cm^{-1} in 12 steps. To gradually increase the violation of the SGP, measurements were made with δ = 24, 30, 36 and 42 ms and a diffusion time T_D = 80 ms. The repetition time (TR) was 2000 ms and the echo time (TE) was varied from 124 ms to 148 ms as δ varied. Pixelwise calculations were performed and for each pixel the S(q) curve was re-sampled to 24 data points to yield equidistant steps in q and then mirrored so that S(-q) = S(q), giving a nominal resolution of 5.6 µm [2]. After calculation of the Full Width at Half Maximum (FWHM) of the displacement probability in each direction, a tensor analysis was performed [4]. The largest eigenvalue λ_1 and the smallest eigenvalue λ_3 of the tensor then provided the FWHM in the most restricted and most unrestricted direction, respectively. In the parametric maps of λ_1 and λ_3 regions of interest (ROI) were positioned in the splenium of corpus calosum (scc, red), genu of corpus callosum (gcc, blue), and in gray matter (GM, green), see figure 1. In order to verify the obtained result a simulation of a random walk was performed. Perfectly reflecting planes were assuming, separated a distance = 5, 10, 15, 20 and 50 µm. The diffusion encoding parameters were the same as in the *in vivo* protocol. The simulation was performed without noise.

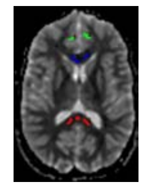


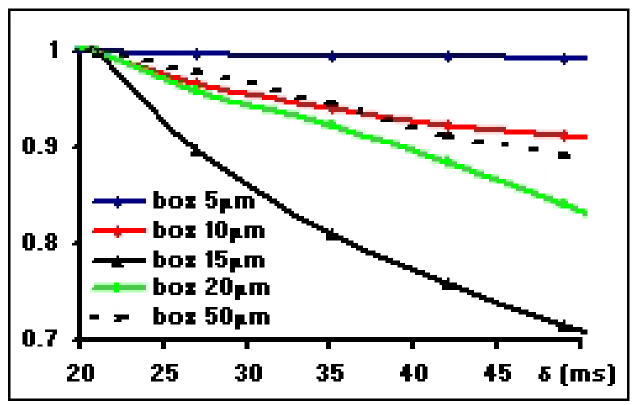
Figure 1: The used ROIs (λ_3)

Results

Table 1 shows the obtained FWHM values, with a slight declining trend both in sccand gcc for both eigenvalue one (λ_1) and three (λ_3). Figure 2 shows the result from the simulation.

δ	Scc		Gcc		GM	
(ms)	λ_1	λ_3	λ_1	λ_3	λ_1	λ_3
24	35.8±3.4	7.4±0.6	35.6±2.6	7.0±0.5	24.1±1.3	21.4±1.4
30	34.6±2.6	7.1±0.5	34.9±1.2	6.6±0.5	24.6±1.4	21.2±1.6
36	33.2±0.9	7.1±0.5	33.0±0.9	6.6±0.6	25.8±0.6	21.7±1.3
42	33.5±12	7.0±0.5	31.8±1.8	6.4±0.6	25.6±1.3	21.9±2.1
k / R	-0.14 / 0.9	-0.02 / 0.9	-0.22 / 1.0	-0.03 / 0.9	0.10 / 0.9	0.03 / 0.8

Table 1: The obtained FWHM from the ROIs in WM and GM. The given standard deviation correspond to the deviation between results from experiment. The data for δ is given in mean ± Standard Deviation, k=slope and R=correlation coefficient for the linear approximation fitted to the measured values.



Figur 2: Obtained FWHM values, normalised for δ=21 ms. It can be seen that the smallest decline is obtained with the smallest box size, due to the asymptotic behaviour when violating the SGP to a different degree.

Discussion

A slight decrease of FWHM for increasing δ, was found for both λ_1 and λ_3. In the most restricted direction, λ_3, this result is expected from the COM theory as well as from the simulations. Assuming a confined geometry of 5 µm and δ=[22-42] ms, the violation of SGP is so severe that only a slight decrease in FWHM is expected. This result is also in agreement with the NMR spectrometer results of Nossin-Manor [6] who found a small decrease in the mean displacement (proportional to FWHM) orthogonal to the fibres with δ = 2 and 20 ms. However, in our results we see a decrease also in the largest eigenvalue λ_1. This possibly indicates effects of a restriction in the diffusion also parallel with the fibres. The simulations might suggest such an interpretation, since the effects of the violation of the SGP would be more pronounced for a larger confining geometry than for a smaller. In conclusion, small but observable changes in FWHM are seen, indicating that the "severity of violation" of the SGP condition has a minor influence on the measured parameter FWHM when changing δ in the range studied in this work.

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Reference

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