Multiple wave vector diffusion experiments on restricted diffusion

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INTRODUCTION

Most diffusion weighted imaging experiments use gradient pulses of a single direction between excitation and data acquisition, sometimes split into several gradient pulses to suppress eddy current effects. P. P. Mitra [1] developed a theoretical description of the MR signal when two successive gradient pulse pairs of different direction are used between excitation and acquisition (multiple wave vector diffusion weighting, MWV). In that description, the signal depends sinusoidally on the angle between the gradient directions if diffusion in the sample is restricted. The effect might be used to estimate the mean cell size in vivo in the human brain. The present study attempts to measure the described effect in a biological sample, as a first step towards in vivo application.

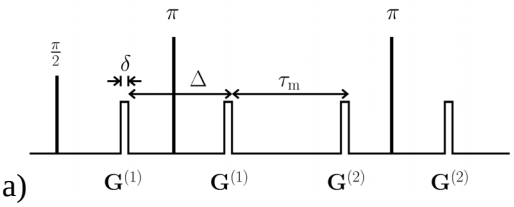
MATERIALS AND METHODS

If the mean time required for diffusion across a pore, τ_D, and the duration, δ, and separation, Δ, of the diffusion gradient pulses (see Fig. 1a) obey $\delta << \tau_D << \Delta$ then the MWV weighted signal from randomly oriented pores should depend on the angle θ between the diffusion gradients as $S(\theta) \propto 1 - (k^2/3) \langle r^2 \rangle (2+\cos\theta)+O(k^4)$, for small $k = \gamma\delta G$ and $\tau_m = 0$ [1]. $\langle r^2 \rangle$ denotes the mean squared radius of gyration, i.e. the ensemble average over I/M (I moment of inertia of a pore with respect to an axis through the centre of gravity, M pore mass). Hence, the diffusion-induced signal loss should vary with θ by a factor of 3.

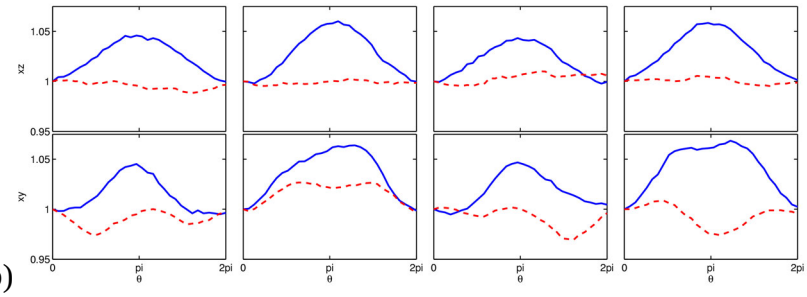
We acquired images of tap water and a sample of radish (*Raphanus sativus L.*) using single-shot echo planar imaging (EPI) with double-spin echo diffusion preparation (see Fig. 1a): for each of 6 different directions of the second gradient 64 directions of the first diffusion gradient were used, and an image without diffusion weighting was acquired (1 axial slice, resolution $3.5 \times 3.5 \times 5$ mm^3, TR = 6800 ms, TE = 180 ms, δ = 4 ms, Δ = 74 ms, diffusion weighting per gradient pulse pair b = 0, 100 s/mm^2 [2], phase encoding along y, slice gradient along z). $\tau_m = \delta$ was chosen to suppress cross terms between the two preparation parts. Signal variations due to varying spoiler gradient direction with respect to the diffusion gradients were avoided by using a fixed spoiler gradient perpendicular to both $\mathbf{G}^{(1)}$ and $\mathbf{G}^{(2)}$. The spoiler amplitudes for the second refocusing rf pulse were chosen to be twice that for the first refocusing pulse to suppress unwanted coherence pathways.

RESULTS AND DISCUSSION

Fig. 1b shows the observed EPI signal variation upon varying the angle, θ, between the diffusion gradients. The relative signal variation in radish is approximately 5% (peak-to-peak), whereas in water it is below 3.5%. Regardless of the absolute gradient direction, the signal modulation in radish has the expected sinusoidal shape with a maximum around $\theta = \pi$, in contrast to water. With increasing delay τ_m the variation amplitude decreased. We estimated the cell diameter in the radish sample by light microscopy to approximately 50 µm. Assuming a diffusion coefficient of $2 \cdot 10^{-9}$ m^2/s this means that the condition $\tau_D << \Delta$ is violated. This might explain the relatively small signal variation with θ. The signal variation in water is most likely related to eddy currents. The effect in question aside, there are a number of possible reasons that could explain the observed difference in amplitude variation between radish and water. The two samples may differ not only in terms of restrictions to diffusion but also in terms of background gradients, diffusion coefficient, and relaxation times. However, if the observed effect is caused by macroscopic background gradients, it should depend on the absolute orientation of the gradients, as it does in water but only little in radish. Eddy current effects should also be present in water. Hence, it is possible that the observed signal variation with the angle between the two diffusion gradients reflects the restriction of diffusion as described by Mitra [1]. This method could provide a new tool to estimate cell sizes in vivo.



a)



b)

Fig. 1a: Multiple wave vector diffusion preparation used for EPI ($\tau_m = \delta$ in these experiments, $|\mathbf{G}^{(1)}| = |\mathbf{G}^{(2)}| = G$).

Fig. 1b: Signal amplitude versus angle θ between diffusion gradients, averaged over a region of interest in radish (solid line) and in water (dashed line). $\mathbf{G}^{(1)}$ was rotated in the xz plane (top row) and in the xy plane (bottom row). The signal was normalized to the first value in each subplot. The gradient $\mathbf{G}^{(2)}$ was aligned along +x, +z, -x, -z (top row from left to right), and along +x, +y, -x, -y (bottom row from left to right), respectively. Spoiler gradients were constant in each subplot. The water signal exceeded that in radish by a factor of approximately 7.

REFERENCES

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