Paradoxical diffusion effect in opposed-phase MR images of the spine

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Introduction

SSFP sequences with an additional diffusion-sensitizing gradient have been successfully used for non-quantitative diffusion-weighted imaging, e.g., in the brain and in the spine [1, 2]. Since the acquired echoes in SSFP sequences are gradient-shifted, in-phase and opposed-phase effects can be observed depending on the sequence timing. In the presence of fat and water, this can paradoxically increase the signal intensity with increasing diffusion gradient strength as is demonstrated in this study.

Materials & Methods

An SSFP diffusion sequence was used to acquire diffusion-weighted images of an oil-water emulsion (2/3 vegetable oil, 1/3 water) and of the lumbar and sacral spine of a 27-year old healthy volunteer on 1.5 T whole-body scanners (emulsion: Siemens Magnetom Symphony; volunteer: Siemens Magnetom Sonata). In the emulsion, an approximate opposed-phase condition was found with a flip angle α of 50°, TR = 25 ms, and an interval ΔT of 18.3 ms between RF pulse and read-out gradient (center-to-center). Signal attenuation was measured in the emulsion and in a reference water phantom as a function of the diffusion gradient (0 – 28 mT/m, duration δ = 12 ms). In the vertebral bone marrow of the volunteer, an approximate opposed-phase condition was found with α = 50°, TR = 27 ms, and ΔT = 15.5 ms; navigator echo correction was used to reduce motion artifacts. Signal attenuation was measured in the vertebral bodies, in the CSF, and in subcutaneous fat as a function of the diffusion gradient (0.2 – 5 mT/m, δ = 8 ms). The data was fitted to a vector model based on [3] with 3 additional parameters (signal ratio *R* oil/water or fat/water, phase angle ϕ between signals, diffusivity of water).

Results

Figure 1 shows the diffusion attenuation of the oil-water emulsion and of the reference fluid (scaled by 0.05). The signal of the emulsion has a minimum at a diffusion gradient amplitude of 13 mT/m and increases for stronger diffusion gradients whereas the water signal decreases monotonically. The data agrees well with our mathematical model. The results of the fitting procedure are: phase angle ϕ of 170°, signal ratio *R* oil/water of 0.48. Figure 2 shows results of the measurements *in vivo*. The signal curves in the vertebral bodies (S1, L5) show different dependencies on the gradient strength: in S1, the signal increases and in L5 a minimum is observable at about 3 mT/m. We observed a monotonically decreasing CSF signal with increasing diffusion gradient and an approximately constant fat signal corresponding to comparably high and very low diffusivity, respectively.

Discussion

The observed paradoxical diffusion effect can be explained by two signal components with opposed phase and different diffusivities. The water signal with high diffusivity is increasingly suppressed by the diffusion gradient whereas the signal of the oil or fat component (with negligibly low diffusivity) remains approximately constant. At higher amplitudes, only the oil or fat signal remains. *In vivo*, this effect can be observed in tissues that contain fat and water like the vertebral bone marrow. Due to motion artifacts and low signal intensities the statistical errors of the measurements *in vivo* are relatively high. The different signal curves in the vertebrae can be explained by different signal ratios of water and fat components (fit results: signal ratio fat/water *R* = 11 in S1, *R* = 0.9 in L1; the phase angle was set to ϕ = 160°). Generally, diffusion-weighted images, e.g., of the spine, will be more simply interpretable by avoiding opposed-phase conditions or by additionally applying fat signal suppression. A similar effect has been described for contrast agents in opposed-phase images [4, 5].

References

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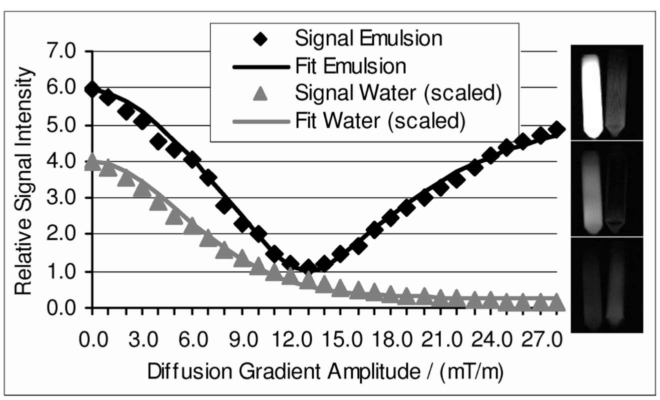

Figure 1: Signal intensities in oil-water emulsion and in reference fluid (scaled by .05) as a function of the diffusion

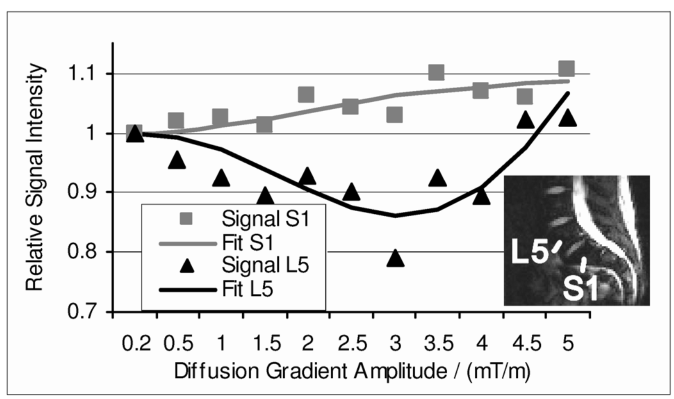

Figure 2: Normalized signal intensities in vertebral bodies S1 and L5 as a function of the diffusion gradient amplitude