Diffusion weighted imaging with a hole-burning sequence

D. L. Weber[1], P. M. Jakob[1]

[1]Dept. of Experimental Physics 5, University of Würzburg, Würzburg, Germany

Introduction

We describe a method of acquiring diffusion weighted images that is based on a hole burning technique [1-2] instead of using the common bipolar gradients. The stripes burned into the magnetization are on subvoxel level, so that they are not resolved in the image. A b-value can be defined analogously to conventional diffusion experiments which does not exclusively depend on the parameters of the sequence, but also on the diffusion and the T_1 value. Because only the longitudinal magnetization is affected, the results are independent of T_2-effects.

Methods

The sequence used is made up of a pre-experiment that creates a diffusion and T_1-weighted z-magnetization which is read out with a subsequent snapshot-FLASH-experiment [3] (fig. 1). The pre-experiment is essentially composed of $N = 25$ short hard pulses (duration $\tau = 3$ µs, pulse separation $\Delta = 1$ ms) applied under a gradient $G = 0.45$ T/m. This pulse train burns a “hole-comb” with a spatial distance of $\Delta x = 2\pi / (\gamma G \Delta) =$ 52 µm into the longitudinal magnetization (hole width approx. 5 µm), each stripe modulated with a sinc-shaped function: $\mathrm{sinc}(N/2\ \Delta\ \gamma\ G\ x)$. The maxima are also modulated with a sinc-shaped function with the form $\mathrm{sinc}(N/2\ \Delta\ \gamma\ G\ x)$. After each pulse train, the generated transversal magnetization is spoiled. The system is allowed to evolve for a time $T_{ev} = 25$ ms. During this time, the longitudinal magnetization is rebuilt due to T_1 relaxation; in addition, the burned profile is blurred due to diffusion (z-magnetization is conserved). After the time T_{ev}, the entire procedure is repeated L times, with the hole-comb remaining at its original position. A steady state is achieved after $L \approx 20$ loops (fig. 2); this steady state depends on the diffusion coefficient and on T_1 and is read out with a FLASH-experiment (TE = 2.5 ms, TR = 4.3 ms, centric reordered). NMR imaging was performed on a Bruker AMX-500 system at 11.75 T with a spatial resolution of 156 µm in-plane (three stripes per pixel). For simulations, it is sufficient to model the longitudinal magnetization of a repeated unit cell with periodic boundary conditions, only taking the influence of T_1, the diffusion, and the applied pulses into account [4].

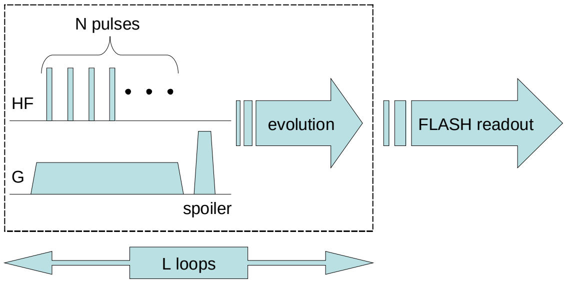

Fig. 1: Hole-combs are burned repeatedly on subvoxel level, with a subsequent FLASH readout. The longitudinal magnetization is then a function of the diffusion in the gradient direction and of T_1.

Results

Experiments were performed on a phantom filled with three different relevant solutions: normal water, doped water (with Gadolinium), and oil. The first two solutions have equal diffusion coefficients and different T_1 values, whereas the last two have equal T_1 values but different diffusion coefficients, thereby showing both diffusion (fig. 2) and T_1-weighting (fig. 3). The acquired signal progression corresponds well to the simulations. In fig. 4 images are shown for different values of the loop counter L. One can see the signal loss due to the saturation of spins diffusing into the hole-comb. The b-value is dependent not only on the sequence parameters, but also on the diffusion coefficient and T_1 (in case that it is defined as usual as $b = 1/D \ln(M_0/M)$). Here we obtain b = 932 s/mm² for normal water, b = 324 s/mm² for doped water, and b = 5693 s/mm² for oil.

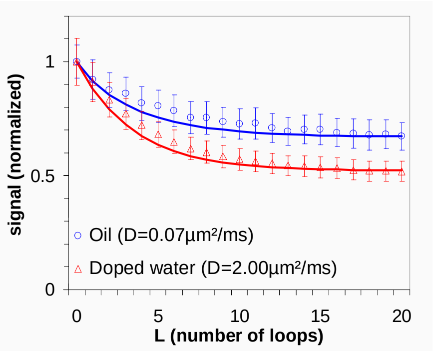

Fig. 2: Diffusion weighting depending on the number of loops L. Two compartments with equal $T_1 = 360$ ms but unequal diffusion coefficient are shown (experiment and simulations).

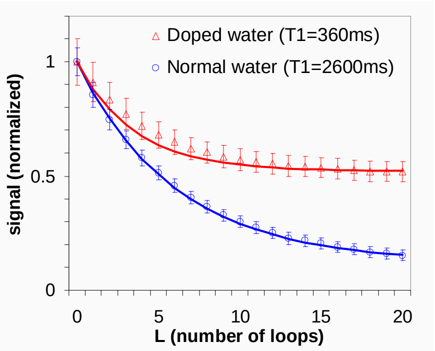

Fig. 3: Diffusion weighting depending on the number of loops L. Two compartments with equal D = 2.00 µm²/ms but unequal T_1 values are shown (experiment and simulations).

Discussion & Conclusion

We have shown that the presented sequence is able to acquire diffusion weighted images without T_2-effects with a diffusion weighting (b-value) dependent on diffusion itself and on T_1, which may in certain cases provide a good contrast. Furthermore, it is relatively easy to simulate the sequence in order to make predictions and optimize parameters. After further calculations, it might be possible to quantify the T_1 and diffusion coefficient, as well as use these diffusion coefficients to measure diffusion tensors by varying the gradient strength and direction.

Acknowledgement

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Reference

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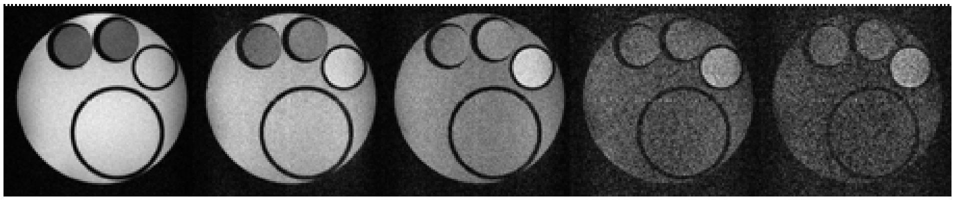

Fig. 4: Phantom measured with L = 0, 5, 10, 15 und 20 loops. The big tube contains water, while the smaller tubes on the top left contains oil and that on the top right contains doped water.