Is it possible to achieve sufficient inversion efficiencies in CASL experiments at high B_0 and low B_1 field strengths?

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Introduction

Perfusion imaging using magnetically labeled water as an endogenous tracer is capable of measuring cerebral blood flow (1). Several studies at different main magnetic field strengths $\mathbf{B}_0$ were performed over the last decade (2-4). Perfusion measurements at 7 T are expected to be more sensitive because of the increased signal-to-noise ratio (SNR) at higher field strengths. For quantification of perfusion in continuous arterial spin labeling (CASL) experiments, however, an exact estimation of the inversion efficiency α is required. As CASL experiments are based on the adiabatic inversion of the flowing spins several simulation studies were performed focusing on different experimental and physiological parameters of the adiabatic fast passage, such as the $\mathbf{B}_1$ field amplitude, the strength of the applied gradient and the blood flow velocity (5-7). The presented work, however, centers on issues arising with higher field strengths. At such field strengths (e.g., 7 T) the specific absorption rate (SAR) limits the application of radio-frequency pulses so the $\mathbf{B}_1$ field should be as low as possible. Therefore, we investigated whether it is possible to achieve sufficient inversion efficiencies in CASL experiments at high $\mathbf{B}_0$ and low $\mathbf{B}_1$ field strengths.

Method

The determination of the inversion efficiency was based on a solution of the Bloch equations using the hard-pulse approximation (8,9). Spin relaxation was included in the simulation. The magnetization was calculated recursively while the actual values of the frequency offset (determined by the applied gradient) and the $\mathbf{B}_1$ field were inserted into the solution at every integration step. The simulation of the time dependent magnetization was started far below resonance and ended above resonance at a distance of 3 cm. The step size for the simulation was decreased until the results were stable. The simulation was performed in dependence on the gradient strength and the amplitude of the $\mathbf{B}_1$ field assuming a main magnetic field strength $\mathbf{B}_0$ of 7 T. For comparison, the inversion efficiencies were also calculated at $\mathbf{B}_0$ field strengths of 3 T and 1.5 T. As an estimate, T_1 and T_2 relaxation times of 2000 ms and 250 ms for arterial blood at 7 T, of 1700 ms and 275 ms at 3 T and of 1200 ms and 300 ms at 1.5 T were assumed. It should be noted that slightly different values for T_1 and T_2 do not affect the results of the simulations substantially. As the inversion efficiency is relatively insensitive to the blood flow velocity within the physiological range (5) and as the influence of the cardiac cycle can be neglected as long as the labeling pulse comprises at least one cardiac cycle (7), a constant blood flow velocity of 20 cm/s was assumed. For better comparison the inversion efficiencies were also plotted against the adiabaticity factor β which is described elsewhere (7). As for high field strengths the SAR limits the application of RF pulses a low $\mathbf{B}_1$ field is desirable. Therefore, gradient strengths producing maximum inversion efficiencies at low $\mathbf{B}_1$ field amplitudes were calculated.

Results

Inversion efficiencies α in dependence on the amplitude of the $\mathbf{B}_1$ field and on the gradient strength are summarized in Tab. 1. The dependence of α on the adiabaticity factor β is shown in Fig. 1. Whereas the absolute values of the inversion efficiencies vary slightly with field strength $\mathbf{B}_0$ a very similar relationship between α and β was found for the different field strengths. An optimum adiabaticity of 3…4 was obtained (Fig. 1). Fig. 2 depicts the dependence of α on the amplitude of applied gradient strength at 7 T. As dictated by the SAR limit low $\mathbf{B}_1$ field amplitudes of 1.2 and 0.6 µT were assumed for the simulation. Maximum inversion efficiencies of about 88% (B_1 = 1.2 µT) and 85% (B_1 = 0.6 µT) were found at gradient strengths of 0.8 and 0.25 mT/m, respectively.

Tab. 1: Inversion efficiencies at a mean velocity of 20 cm/s.

Gradient [mT/m]	$\mathbf{B}_1$ field [µT]	β	α @ 7 T	α @ 3 T	α @ 1.5 T
1.25	1.2	1.5	84%	83%	80%
1.25	2.4	6.1	89%	88%	85%
1.25	3.6	13.8	86%	86%	84%
2.5	1.2	0.8	65%	64%	61%
2.5	2.4	3.1	91%	90%	86%
2.5	3.6	6.9	90%	89%	86%
5.0	1.2	0.4	42%	42%	40%
5.0	2.4	1.5	84%	83%	80%
5.0	3.6	3.4	91%	90%	87%

Discussion and Conclusion

Inversion efficiencies of CASL experiments were calculated numerically under realistic experimental and physiological assumptions. It was shown that the main magnetic field strength and the resulting T_1 and T_2 relaxation times have an influence of the adiabatic inversion of flowing spins. Hence, for an exact estimation of the inversion efficiency in CASL experiments the field strength $\mathbf{B}_0$ has to be considered. However, for all $\mathbf{B}_0$ field strengths a $\mathbf{B}_1$ field amplitude and a gradient strength resulting in an adiabaticity factor β of about 3…4 can be considered as an optimum. Low $\mathbf{B}_1$ field amplitudes as desired at high main magnetic field strengths such as 7 T are still able to produce a sufficient efficiency of the adiabatic spin inversion. This is achievable if a corresponding low gradient strength is applied. However, it has to be mentioned that the simulations were performed assuming a perfectly homogeneous main magnetic field $\mathbf{B}_0$. A realistic, more inhomogeneous main magnetic field could markedly influence the shape and the strength of the applied gradient which would be especially problematic for low gradient strengths. For the adiabatic inversion it would become even more of an issue if the range of gradient strengths ensuring a sufficient inversion efficiency is very small as it is the case for B_1 = 0.6 µT (see Fig. 2). For B_1 = 1.2 µT, however, the range of optimum gradient strengths is substantially larger. Therefore, a strategy for obtaining optimum parameters at high field strengths is to use the highest possible $\mathbf{B}_1$ field amplitude which is still below the SAR limit. The gradient which has to be applied is then determined by this $\mathbf{B}_1$ field amplitude using the presented simulation.

References

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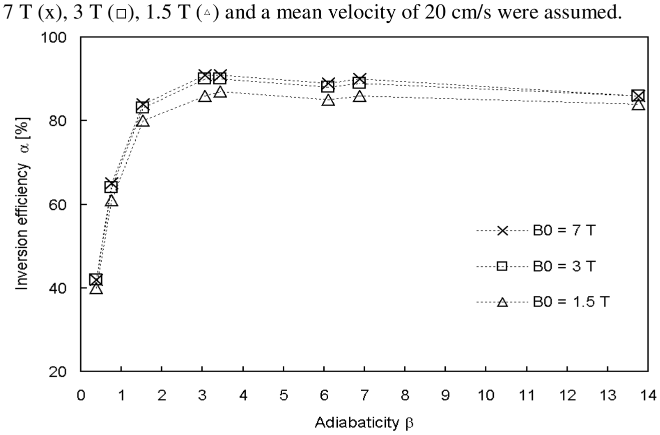
Fig. 1: Dependence of the inversion efficiency α on the adiabaticity β. Field strengths of 7 T (x), 3 T (□), 1.5 T (△) and a mean velocity of 20 cm/s were assumed.



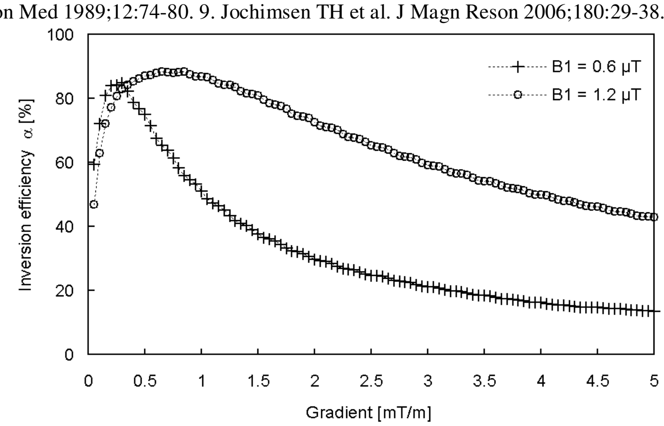


Fig. 2: Dependence of α on the gradient strength. A $\mathbf{B}_0$ field strength of 7 T, a mean velocity of 20 cm/s and $\mathbf{B}_1$ fields of 1.2 (○) and 0.6 (+) µT were assumed.