Improved Inversion Efficiency in Arterial Spin Labeling Using Adiabatic Null Pulses

E. T. Petersen[1,2], and X. Golay[1,3]

[1]Neuroradiology, National Neuroscience Institute, Singapore, Singapore, [2]CFIN, Department of Neuroradiology, Aarhus University Hospital, Aarhus, Denmark,
[3]Laboratory of Molecular Imaging, Singapore Bioimaging Consortium, Singapore, Singapore

INTRODUCTION: The generation of perfusion maps from an arterial spin labeling (ASL) experiment relies on the subtraction of two images. During labeling, the arterial blood spins are inverted outside the imaged volume and flow into the imaging region, whereas in the control experiment they are left unperturbed. Ideally, the subtracted images would include information about perfusion only. However, the RF pulse applied during labeling saturates the stationary brain tissue within the volume of interest via off-resonance magnetization transfer (MT) effects, in a way very similar to an MT-weighted technique [1]. The resulting saturation effect of the macromolecular pool will lead to a reduced signal of the free water pool in the tissue [1], resulting in overestimation of perfusion. Additional factors that can alter the signal intensity between the two experiments include differences in slice profile, water/fat-shift, eddy currents and thereby potential differences in stimulated echoes between control and labeling pulse sequences. Furthermore, it is often interesting to reduce the distance between the labeling plane and the imaging slices as much as possible, in order to minimize the effects of blood T_1 relaxation prior to its arrival in the tissue. If the control experiment uses different RF power or is non selective, this can lead to artifacts especially in the slices closest to the labeling slab. Various implementations and different labeling schemes have been proposed in order to correct for these effects [2] and generally, the aim is to get as symmetrical an acquisition as possible with regards to both RF and gradient design. Here, we propose a practical implementation of an adiabatic null pulse, which is based on the principles of time reversal as earlier proposed for conventional [3] and adiabatic pulses [4,5].

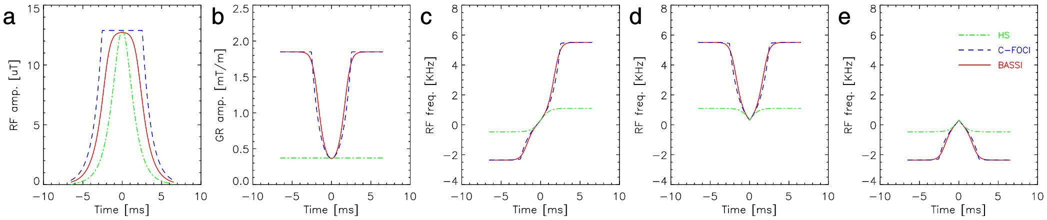

*Figure 1. The RF and gradient scheme for Hyperbolic Secant, C-FOCI and BASSI adiabatic pulses. **a)** RF amplitude modulation, **b)** Gradient modulation, **c)** Frequency modulation for inversion pulse (notice that it is for an off-centered slab), **d-e)** Frequency modulation for null pulse for even and odd control acquisitions respectively.*

THEORY: Adiabatic RF pulses differ from conventional pulses in the way that the magnetization precesses in a tight cone around the effective magnetic field, and as such is "parallel" to the field, contrary to conventional pulses, where the magnetization is perpendicular to the applied RF field. Inversion can be achieved by appropriate modulation of the RF amplitude and frequency as well as the selection gradient (Fig. 1 a-c), causing the effective field to be slowly tilted from the positive z-axis via the transverse plan to finally point towards the negative z-axis [5]. Throughout this "sweep", the magnetization will follow the effective field, as long as this modulation is slow enough, and the adiabatic condition is maintained. The basic idea for 0 degree adiabatic pulses is to reverse this motion at the magnetic center of the pulse, where the effective magnetization is ideally in the transversal plane. This can be achieved by simply mirroring the RF amplitude and frequency modulation for the second part of the pulse (Fig. 1 a, b, d and e) [4,5]. It will bring the effective RF field back to the positive z-axis resulting in a net 0 degree pulse with the same RF amplitude and power as in the inversion case. Now, in case of asymmetrical pulses such as C-FOCI and BASSI pulses [6], two potential mirroring strategies can be chosen (Fig. 1d and e). In order to fully compensate for MT in ASL, the two versions of the null pulse are interleaved at odd and even control experiments resulting in a 4 step sequence of labeling (Fig. 1c), control 1 (Fig. 1d), labeling (Fig. 1c) and control 2 (Fig.1e). After subtraction (control-label) and subsequent averaging, the MT effects, RF power and applied gradients are all fully symmetrical for both label and control experiments.

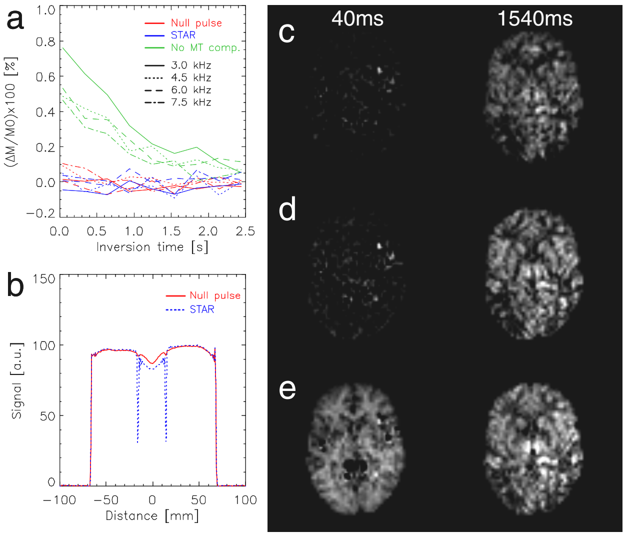

*Figure 2. **a)** MT effects from 6% agar phantom as a function of inversion time (Look-Locker readout) for the three control schemes. **b)** The slice profile using STAR and null pulse in a doped water phantom. The control slab was applied in a 30mm slice centered in the middle of the phantom. **c)** ΔM image at 40&1540ms using STAR, **d)** using null pulses, **e)** without MT compensation.*

METHODS: The null pulses above were implemented in the QUASAR ASL-sequence [7], and the efficiency of the MT compensation was tested in agarose phantoms with increasing agar concentration (2, 4 and 6%). The new null pulse method was compared to the original signal targeting by alternating radio-frequency pulses (STAR) approach [8] as well as to the situation where no MT compensation is used. In a second experiment, the profile of the zero inversion pulse was acquired in order to verify the expected improvement of the inversion efficiency. The inversion efficiency itself shall remain the same whether the null pulse or the STAR scheme is used. Finally, 8 healthy volunteers were scanned, all giving written informed consent before participation. All subjects had total perfusion map done, aiming at ensuring complete MT compensation of the sequence *in vivo*. One subject had acquired perfusion images using the new null pulse, STAR and no MT compensation schemes. The protocol was approved by the local ethics committee and performed on a 3T Philips Achieva whole body system. General scan parameters were: TR/TE/ΔTI/TI1=4000/23/300/40 ms, 64x64 matrix, 7 slices, FOV=240x240, flip-angle=35°, SENSE=2.5. $V_{enc}=[\infty,4\ cm/s]$, 60 averages [6].

RESULTS and DISCUSSION: Fig. 2a shows full compensation of the MT effects using both STAR and the null pulses, whereas the acquisition without MT compensation as expected shows clear MT effects that gradually disappears with the number of applied Look-Locker readouts. In Fig. 2b, the improvement of the control experiment is seen in the slice profiles. Because the STAR sequence uses two full inversion pulses, complete "re-inversion" will never be achieved due to non-perfect inversion in both pulses. It is also seen that at the edges, this re-inversion is compromised, resulting in an overall reduced inversion efficiency when used for ASL. Fig. 2c-e shows the difference images (ΔM) at an early time point as well as later when the labeled blood has arrived in the tissue for the STAR scheme, the null pulse approach as well as without MT compensation. Fig. 2d clearly shows the increased signal intensity at 1540 ms due to the gain in inversion efficiency and possible reduction of other asymmetry artifacts. Fig. 2e, demonstrates severe MT artifacts due to lack of compensation at early inversion times, which at later times misleadingly shows up as perfusion signal, especially pronounced in the white matter.

CONCLUSION: In the present work, a robust adiabatic null pulse has been developed and tested. It was found to be superior to the existing STAR implementation, due to improved overall inversion efficiency which is essential for enhanced SNR as well as quantification of blood flow.

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