Off-resonant Artifact Correction of RF Pulse Concatenation for Blood Flow Imaging Applications

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Introduction: To obtain accurate quantitative perfusion data, continuous arterial spin labeling (CASL) requires balancing magnetization transfer (MT) effects in the control and tag experiments. Traditionally, this is done by applying RF pulses in control experiments that are placed at equal distance as the tag pulse to the imaging slice, but distal to the imaging slice of interest and far enough to prevent tagging of venous flow. More recent methods including RF modulation [1], they require that the tagging plane to be at some distance from the imaging slice in order to equilibrate MT effects between tag and control. However, in order to reduce transit time effects, it may be desirable to have the saturation or inversion plane very close to the imaging slice. Additionally, in newly developed flow imaging techniques such as flow enhancement of signal intensity (FENSI) [2], in which the tagging plane has to be within the imaging slice, the requirement for close or coincident tagging planes makes control of MT effects difficult.

In this study, we investigate the use of concatenated RF pulses for labeling at the imaging slice. These pulses have been used in ASL to control magnetization transfer, in the method called magnetization transfer insensitive labeling technique (TILT) [3,4]. Tag composite RF pulses are obtained by applying the RF pulses in phase with each other, resulting in a net flip angle, and control composite RF pulses are obtained by applying the RF pulses with opposite phase, resulting in no net flip angle (Fig.1). However, the time delay between the centers of the RF pulses will lead to sensitivity to magnetic field inhomogeneity and off-resonance effects. In this abstract, we provide a framework for analyzing and compensating for the off-resonance effects in concatenated RF pulses.

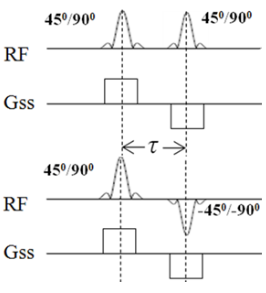

Fig. 1 RF pulse concatenation. Above: tag is achieved by two selective $45^0/90^0$ pulses with opposite polarity of the 2nd gradient. Bottom: control has the 2nd pulse with π phase shift.

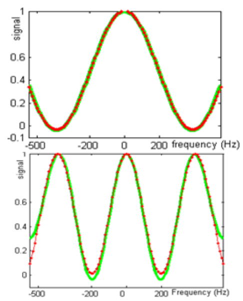

Fig. 2: Simulated signal profiles as a function of off-resonant frequency (green). Red dot lines stand for fitting. Above: τ =1280 μs; Bottom: τ =2560 μs.

Theory: Although the target is blood flow imaging, in this work, the present work focuses only on the efficiency of tag and control pulses. Future work will involve adapting the pulses and the analysis for perfusion and flow quantification. MT equivalence by RF pulse concatenation could be achieved by applying two successive slice-selective (45^0,45^0) RF pulses for saturation in tag, and (45^0,-45^0) for 0^0 slice selective labeling in control (Note that similarly a (90^0,90^0) could be used for inversion).The net MT effect on macromolecular spin magnetization is the same for both the $+45^0/+45^0$ and $+45^0/-45^0$ cases, ensuring that MT-related signal in static tissue is cancelled out by the subtraction procedure. The pulse scheme is arranged in a particular fashion in which the second selection gradient has the opposite sign compared with the first one and the second RF shape is inverted in time if it's not symmetric as shown in Fig.1, and following the recommendations in [4].

With difference in time between the centers of the RF pulses, τ, sensitivity to off-resonance artifacts (main field inhomogeneity and chemical shift) can cause significant signal loss, variability in the effective flip angle for tag and control pulses, and induce blood flow quantification error[4,5]. To correct this artifact, we first validate that the signal profile in the function of off-resonant frequency Δf is similar to that of binomial pulses, which follows the equation [6], $S(\Delta f)=\cos^2(\pi\Delta f\tau)$, where S is normalized signal and τ is RF spacing (Fig.1). Then, we recover the signal $S_0(x,y)$ from $S(x,y)$ based on the model and measured field map $\Delta f(x,y)$: $S(x,y) = S_0(x,y)\cos^2(\pi\Delta f(x,y)\tau) + \varepsilon$ (1), where ε stands for measurement noise. We assume no noise in the field map.

Methods: ***Pulse Examination*** All investigations were performed using a 3 T Siemens Allegra head scanner. We tested the off-resonance effects of the pulses and the proposed correction by collecting EPI slice preceded by the proposed labeling pulses applied to the same imaging slice, as follows. Two concatenated windowed sinc RF pulses (45^0,$+45^0$/-45^0) are incorporated into a EPI sequence just before the excitation pulse for tag/control sessions respectively. In an *in vivo* experiment on a healthy subject (SE-EPI, $\alpha=90^0$, TR 2s, TE 40ms,64×64, FOV 22cm, slice 1cm, τ 2560μs), the images obtained are shown in Fig.3: (a) is the reference image without concatenated pulse but only the EPI excitation pulse, (b) is the normalized difference image between the control image obtained by composite (45^0,-45^0) pulses and the reference image (a), and (c) is the field map. ***Off-Resonant Artifact Correction*** Numerical Bloch simulation is used to explore the signal profile of concatenated pulses (windowed sinc pulse with TBW =4, τ =1280/2560μs, sampling step 5μs, Δf range [-500,500] Hz). Then we curve-fit the simulated signal profiles with $\cos^2(\pi\Delta f\tau)$ as in Eq.(1) by minimum least squares algorithm in MATLAB 7.4.0. The fitting results are in Fig.2 with residual errors smaller than 0.2. After validation, we use the signal model in Eq.(1) and correct the contaminated control image. To estimate $S_0(x,y)$, we applied the quadratic penalty weighted least square algorithm [7] to solve the inverse problem in Eq.(1).

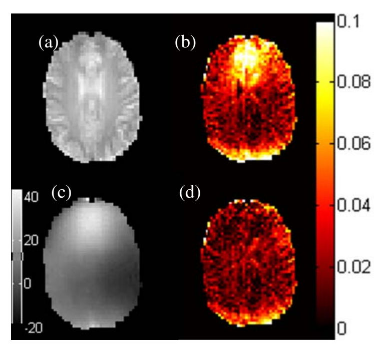

Fig.3:(a) reference image w/o prelabeling. (b) uncorrected error map for control image with (45^0,-45^0) prelabeling. (c) field map in Hz. (d) corrected error map for control image.

Results: For the tag image with presaturation by (45^0,45^0) pulses, the signal is almost gone as expected. For control image with 0^0 presaturation by (45^0,-45^0) pulses, the difference in performance from the reference image (a) is small overall as shown in Fig.3(b), implying that it would be a good approximation for control image. However, in the frontal sinus and posterior areas with high field inhomogeneities as shown in the field map of Fig.3(c), the errors are as large as to 10% in Fig3(b), which would bring significant error to flow quantification results. Image (d) illustrates the error map of the corrected image with errors reduced to less than 2%, which may be caused by noise or the slice profile property of composite pulses.Fig.4 is the statistical analysis of error map (b) and (d) as a function of off-resonant frequency Δf, as it's shown, for the uncorrected image (solid line), the error increases with Δf within the period [$-1/2\tau$,$1/2\tau$,], in agreement with simulation results, while for the corrected image (dash line), the error keeps much smaller and uniform. We could easily see that, after our correction, the error due to off-resonant artifacts has decreased significantly in the frontal sinus and posterior areas of the brain.

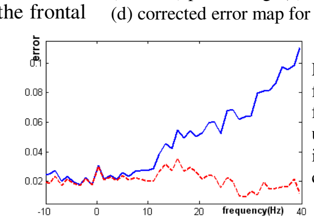

Fig. 4: image error in function of off-resonant frequency. Solid line: uncorrected error in image (b); Dash line: corrected error in (d).

Conclusion: The correction of the off-resonant artifacts in concatenated RF pulses is crucial for quantification of perfusion from ASL techniques that use labeling pulses coincident with the imaging slice, as in FENSI [8]. Using the proposed approach, MT balanced tagging and control pulses can be robustly applied very close to or coincident with imaging slices, without off-resonance effects. Incorporating this pulse scheme into ASL and FENSI techniques will enable us to significantly reduce transit time effects in arterial spin labeling.

References: **1.**Alsop et al, Radiology 1998, (208)410-6; **2.**Sutton et al, MRM 2007,(58):396-401; **3.**Golay et al, JMRI 1999, (9) 454-61; **4.**Pruessmann et al, JMR 2000, (146)58-65; **5.**Norris, ISMRM 1998, p1211; **6.** Hore, JMR 1983,(54) 539-42; **7.** Fessler TMI 1994, (13)290-300; **8**. Ciobanua, et al, ISMRM09,submitted.