Optimization of pseudo continuous ASL tagging for robust inversion efficiency - A Bloch simulation and in vivo study at 3T

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Introduction

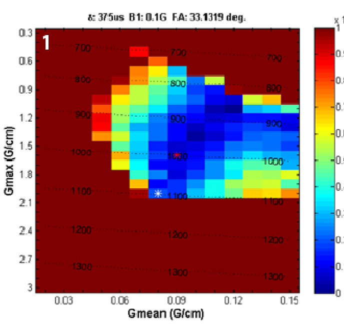
Pseudo continuous arterial spin labeling (PCASL) uses a long train of labeling pulses to induce adiabatic flow-driven inversion [1] as blood flows through the tagging plane. Each segment of the pulse train consists of a windowed RF pulse and gradient pulses that are characterized by the maximum B1 amplitude and maximum and mean gradient fields (G_{max} and G_{mean}), respectively. These parameters must be chosen carefully to satisfy the adiabatic conditions. The perfect inversion of flowing spins also requires that the phase between successive RF pulses follow the phase evolution of the spins. A mismatch between the two, defined as the phase tracking error, can lead to significant losses in inversion efficiency, corresponding decreases in perfusion SNR, and potentially large and unpredictable variations in quantification errors since the error can vary between subjects and scan sessions. Several techniques [2-5] have been proposed to correct for the off-resonance fields and gradient imperfections, which are the main sources of the phase tracking error. However, very little attention has been given to the fact that the phase tracking error, $\Theta_{error}=2\pi\Delta f\delta$, can be reduced fundamentally by minimizing the duration of the RF-to-RF spacing (δ) of the pulse train. Decreasing δ from 800ms to 400ms, for example, cuts the phase tracking error by half for a given resonance offset. Here we propose an optimized tagging scheme based on the balanced design [6] that strives to minimize RF-to-RF spacing while preserving high inversion efficiency over a wide range of flow velocities. The optimal tagging scheme is also relatively insensitive to B1 inhomogeneities and gradient errors, which were separately measured and accounted for in the Bloch simulations. In-vivo measurements are used to compare the effectiveness of the new optimized tagging parameters with those from a previous study [2].

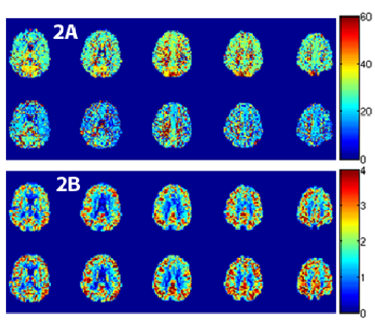
Methods

Bloch simulations were used to determine the inversion efficiency (α) as a function of flow velocity [10-60cm/s], G_{max} [0.3-3G/cm], G_{mean} [0.02-0.15G/cm], B1 [0.02-0.15G], and RF pulse width (τ) [300-500us]. An α map was generated over the 4D space spanned by G_{max}, G_{mean}, B1, and τ. Each point in this 4D map represents the average α over the velocity range of 10-60cm/s and nominal B1 ± 20% with increments of 10cm/s and 0.01B1. Since gradient errors can lead to G_{max}/G_{mean} deviations, it is preferable to select a region in the map with a high α_{ave}, but also where it is relatively insensitive along the G_{max} and G_{mean} directions. To quantify the degree of α_{ave} sensitivity, the standard deviation was calculated for each point in the map for the range of ±0.02G/cm. The standard deviation map was then multiplied with the (1-α) map to create an alpha index map. The minimum point from this map was identified, which corresponds to a tagging region with high α_{ave} and minimal dependence on gradient errors. To reduce the search space, regions corresponding to RF spacing (δ) greater than 1200us and relative SAR more than 70% of FDA limit were excluded from the search. For the in vivo perfusion study, a healthy male volunteer was imaged on a 3T GE MR750 scanner. Scan parameters were: 20 axial slices, 5mm thick with 1mm gap, TR=4200ms, TE=3.3ms, tag duration=2000ms, post labeling delay=1600ms, reps=60, and scan time=252s. The double angle method [7] was used to quantify B1 variations across the major arteries at the tagging plane. Similarly, an acquired field map was used to estimate the expected gradient errors along the major arteries. Finally, simulations were used to compare the inversion efficiency of the new tagging scheme and its dependence on phase tracking errors and flow velocities with another tagging scheme that utilizes short RF spacing [8].

Results & Conclusion

The tagging parameters that corresponded to the minimum alpha index value were: G_{max}: 1.6G/cm, G_{mean}: 0.09G/cm, B1: 0.1G, τ: 375us. This tagging scheme yielded δ of 998us at a slew rate of 200mTm^{-1}ms^{-1} as used on the GE MR750 scanner. As a comparison, our previous parameters were G_{max}: 0.8G/cm, G_{mean}: 0.06G/cm, B1: 0.05G, τ: 800us with δ of 1644us at a slew rate of 140 mTm^{-1}ms^{-1}. Note a 61% reduction in δ. The alpha index of the new scheme was also lower (5.24e-4 vs. 6.16e-3). Fig. 1 is the 2D alpha index map corresponding to B1 and τ equal to 0.1G and 375us, respectively. The point indicated by a white star showed the highest α, but didn't yield the lowest value in the alpha index map due to a high sensitivity to gradient errors.





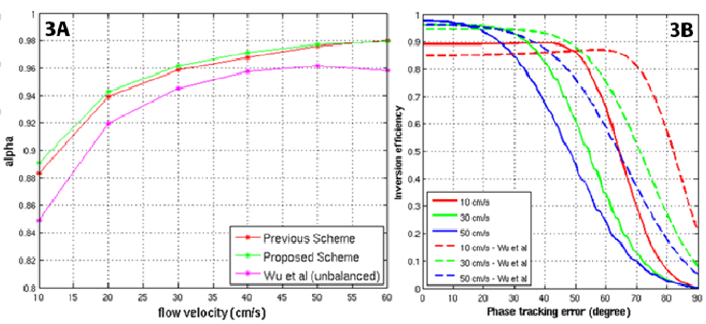


Fig. 1. *Alpha index map with the lowest index value denoted by the red star.* **Fig. 2.** *Phase error map (A) and Temporal SNR map (B) acquired with the previous (upper row) and new tagging (bottom row) schemes.* **Fig. 3.** A: Inversion efficiency vs. flow velocity for three simulated tagging schemes when the phase tracking error is zero. B: Inversion efficiency vs. phase tracking error for two tagging schemes with sub-millisecond RF-to-RF spacing.

The point marked with the red star represents the optimized tagging region. The outer region in red was excluded from the search. The range of B1 variations along the main arteries were -17.5 to 5%. The measured gradient errors ranged from 0.014-0.027 G/cm. Note that the B1 and Gmin/Gmax ranges of ±20% and ±0.02G/cm used in the simulation were selected based on these empirical results. Fig 2A shows the phase tracking error maps acquired with the previous (top) and new (bottom) tagging schemes. The mean gray matter phase errors corresponding to the previous and new tagging schemes were 30.14° and 20.31°, respectively. Similarly, the temporal SNR was also higher (2.16 vs. 1.93) with the new tagging scheme (Fig. 2B). The new scheme produced higher inversion efficiency than that proposed by Wu et al. across all range of simulated flow velocities when the phase tracking error was less than 18° (Fig. 3A and 3B). However, our scheme was more susceptible to efficiency loss when the phase tracking was larger, particularly for a higher flow. This underscores the trade-offs between these two approaches. In our site the ASL data is routinely acquired with the OptPCASL technique [2], which reduces the phase tracking error to less than 15°. Under this condition, our new proposed tagging scheme is preferred over the one by Wu et al. as it yields higher inversion efficiency.

References

1. Garcia DM et al. 13th ISMRM (Abstract 37). **2.** Jung Y et al. MRM 64:799-810. **3.** Shin D et al. 18th ISMRM (Abstract 1744). **4.** Luh W-M et al. 18th ISMRM (Abstract 520). **5.** Jahanian H et al. 18th ISMRM (Abstract 519). **6.** Wong E et al. MRM 58:1086-1091.**7.** Stollberger R et al. MRM 35:246-251. **8.** Wu W-C et al. MRM 58:1020-1027.