Optimal Acquisition Strategies for Transit Time Measurement with Continuous ASL

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Introduction: Arterial transit time (ATT) is a major confounding factor in ASL perfusion quantification. A good estimate of subject-based ATT is required to eliminate ATT effects without sacrificing the sensitivity of perfusion measurement. Estimation of perfusion and ATT with images acquired at multiple delays has been reported, but these methods tend to decrease the sensitivity of the perfusion measurement and require longer acquisitions. Though both a rapid, low resolution scan at multiple labeling delays (1) and more efficient encoding of multiple delay signals using Hadamard encoding (2,3) can reduce the time penalty, maximizing the sensitivity of ATT measurement and minimizing the number of acquisition delays is an important priority. Here, we seek for an optimization strategy: how to best allocate specific exam time to maximize the accuracy of ATT and perfusion measurement.

Methods: Assume that the specific exam time allows acquiring K of label-delay pairs (K=5 in the simulation). For a strategy with N ($2 \le N \le K$) label-delay pairs $[(\tau_1, w_1), \ldots, (\tau_N, w_N)]$ and the corresponding acquisition times $[s_1, \ldots, s_N]$, the total acquisition times need to be within the specific exam time, i.e. $s_1 + \ldots + s_N = K$, $0 < s_1, \ldots, s_N < K$, $s_1, \ldots, s_N$ are integers. The maximum possible number of $[s_1, \ldots, s_N]$ is denoted as I_N. We used a Monto carlo method to explore the range of possible label-delay pairs with 5000 randomized times for each N.

For each strategy, $\tau_1, \ldots, \tau_N$ were generated from uniform probability density over the interval [0, T] (T is the maximum allowed perfusion preparation time, T=5 s in the simulation), $w_1, \ldots, w_N$ were then generated from uniform probability density within the interval $[\delta_{min}, T-\tau_1], \ldots, [\delta_{min}, T-\tau_N]$ respectively. Acquisition times $[s_1, \ldots, s_N]$ were generated according to the acquisition index from uniform probability density within the interval $[0, I_N]$. In the strategy with $[(\tau_1, w_1), \ldots, (\tau_N, w_N)]$, ASL difference signals were generated for an ATT $\delta \in [\delta_{min}, \delta_{max}]$ (the target ATT range was assumed to be [0.7s, 3s] in the simulation) from the kinetic model (4,5) by assuming blood and tissue T1 of 1.66s (6) and 1.5 s. Noise was added to each of the signal values with each noise sample taken from a Gaussian probability density with a zero mean and a standard deviation of $[\sigma/\sqrt{s_1}, \ldots, \sigma/\sqrt{s_N}]$ (σ=0.06 in the simulation), and the set of N ASL signals was used to estimate ATT δ using nonlinear least square fitting to the kinetic model. The process was repeated M times (M=500) to calculate the average deviation of the calculated ATT from the theoretical ATT. The deviations of ATTs were calculated for all the $\delta \in [\delta_{min}, \delta_{max}]$ in step of δ_{step} (δ_{step} =0.3s in the simulation) and averaged to serve as a deviation measure of the strategy (σ_s). The minimal value of the ATT deviation measure was selected as the best acquisition strategy.

Simulation was also performed to test for the accuracy of ATT measurement using Hadamard encoding. Four-cycle Hadamard encoding with three label-delay pairs (Fig. 1) is shown in Table 1. For each cycle, either label or control is applied during time periods A, B and C according to the pattern in the Table 1. The post-labeling delays of A, B and C are defined as t3, t2, and t1. Times t1 and t4 were first fixed to δ_{min} and T (the minimum target ATT δ_{min} = 0.7s and T = 5s, the maximum allowed perfusion preparation time). Times t2 and t3 were generated from uniform probability density within the interval [0.7 s, 5s]. The 4-cyle theoretical signals can be calculated by Hadamard transformation of ASL signals of labeling during time A, B and C. Gaussian distributed noises with $\sigma/\sqrt{2}$ were added to the signals. The simulated signals from labeling during time A, B and C were calculated from the signals with noise added using the inverse Hadamard transformation. In an identical manner to the non-Hadamard simulations, the average deviation from the theoretical ATT for a range of ATTs $\delta \in [\delta_{min}, \delta_{max}]$ was calculated. The average deviation was also calculated with the start and end time of the Hadamard encoding, t1 and t4, allowed to vary according to a uniform distribution within the interval [0.7s, 5 s]. In addition a simulation with just 2 blocks, A and B, was performed. Since no 3 element Hadamard matrix exists, Four-cycle Hadamard encoding was used to generate two label-delay pairs by ignoring time duration C column in Table 1. The minimal value of the ATT deviation measure was selected as the best Hadamard acquisition strategy.

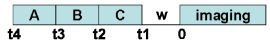

Fig 1. Illustration of hadmard encoding with three label-delay pairs. A, B, and C are three label duration with post-labeling delay of t3, t2, and t1 respectively.

Table 1. Four cycle labeling strategy using Hadamard encoding

cycle	A	B	C
1	1	1	1
2	-1	1	-1
3	1	-1	-1
4	-1	-1	1

Two label-delay pairs with Hadamard encoding, suggested as the best strategy from the simulations, was implemented to acquire in-vivo images to test the feasibility of ATT measurement using Hadamard encoding. The label/control was implemented as label/control in pulsed-continuous arterial spin labeling technique (PCASL) (7). Low resolution images were acquired with 3D stack of spirals RARE (FSE) sequence using 1 interleave and 1 NEX on a GE 3 Tesla scanner. The acquisition time of 4-cycle Hadamard encoding was just 30 s.

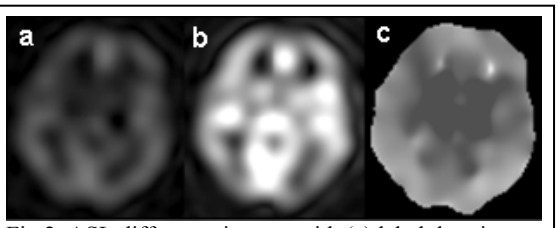

Fig 2. ASL difference images with (a) label duration of 2.2 s and post-labeling delay of 2.8 s and (b) label duration of 2.1 s and post-labeling delay of 0.7 s calculated from the Hadamard encoded acquisition and (c) the derived transit time map from (a) and (b).

Results & Discussions: The best acquisition strategy without Hadamard encoding was found to be two label-delay pairs (label durations of 2.1 s and 2.6s, with post-labeling delays of 0.7 s and 2.4s). Hadamard encoding with two label-delay pairs (label durations of 2.1 s and 2.2s, post-labeling delays of 0.7 s and 2.9 s) improved the accuracy of ATT measurement, as indicated by a 35% reduction in the deviation measure compared to the acquisition without Hadamard encoding. These results suggest that very few delays are required to estimate ATT over a typical clinical range and that Hadamard encoding can improve the measurement speed and sensitivity. In-vivo results demonstrate that a low resolution scan at two optimal delays and labeling durations using Hadamard encoding can measure ATT efficiently.

References: 1. Dai et al, 17th ISMRM 2009:625. 2. Wells et al, Magn Reson Med 2010;63(4):1111-1118. 3. Gunther M., 15th ISMRM 2007. 4. Buxton et al, Magn Reson Med 1998;40:383-396. 5. Alsop et al, Journal of Cerebral Blood Flow and Metabolism 1996;16:1236-1249. 6. Lu et al, Magn Reson Med 2004;52(3):679-682. 7. Dai et al, Magn Reson Med 2008;60(6):1488-1497.