Pseudo-Continuous Arterial Spin Labeling based Dynamic Angiographic Imaging with Decreased Number of Acquisitions
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Purpose: To obtain Pseudo-Continuous Arterial Spin Labeling (pCASL) based dynamic angiographic images with decreased number of acquisitions, replacing the conventional control-tag pair imaging with more efficient labeling based on Hadamard encoding.

Background: General Kinetic Model (GKM) [1] describes ASL measurements by the following equation:
\[ \Delta M(t) = 2M_0B \int_0^t c(t') r(t-t') m(t-t') dt' \]
where \( \Delta M(t) \) is the magnetization difference between control and tag measurements, \( M_0B \) is the equilibrium magnetization of blood, \( f \) is the flow, \( c(t) \) is the delivery function (normalized arterial concentration of magnetization arriving at time \( t \)), \( r(t-t') \) is the residue function (fraction of labeled spins that arrived at time \( t' \) and still in the voxel at time \( t \)) and \( m(t-t') \) is the magnetization function (fraction of original longitudinal magnetization that arrived at time \( t' \) that remains at time \( t \)).

Methods: In the measured ASL signal \( M(t) \), flow contribution \( M_f(t) \), and static tissue contribution \( S_0 \) can be separated:
\[ M(t) = S_0 + M_0B \int_0^t c(t') r(t-t') m(t-t') dt' \]
In continuous ASL (CASL) and pseudo-continuous ASL (pCASL) experiment, \( c(t) \) above can be written as \( e^{\delta t/T1B} w(t) \), where \( \delta t \) is transit time, \( w(t) \) is the arterial modulation function equals “+1” for control and “-1” for label images. Avoiding using an analytical expression for \( r(t) \) allows it to be redefined and include the transit time \( \delta t \) effect, such that \( r(t < \delta t)=0 \). Discretization of Eq-1 results:
\[ M(t_i) = S_0 + M_0B \sum_{j=1}^{\kappa} w(t_j) \int e^{(t_i-t_j)/T1B} \]

Fortunately, one can use arbitrary \( w(t_j) \) for arterial modulation. Forming \( w \) using Hadamard encoding is proposed as an efficient way of labeling [2-3]. Then, it becomes easy to obtain \( S_0 \) and \( r(t) \) by addition/subtraction of measured magnetizations:
\[ \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & -1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & 1 & 1 & -1 \end{pmatrix} \begin{pmatrix} M_1 \\ M_2 \\ M_3 \\ M_4 \end{pmatrix} = \begin{pmatrix} S_0 \\ \kappa R_3 e^{-3\Delta T/T1B} \\ \kappa R_2 e^{-2\Delta T/T1B} \\ \kappa R_1 e^{-\Delta T/T1B} \end{pmatrix} \]

Images are performed with a healthy volunteer (35 yo, male) in a 3T Siemens (Tim Trio) system. pCASL is used with 24° flip angle, 520 μs Hanning pulses, 1 ms pulse separation, 7.5 mT/m gradient amplitude, 1.0 mT/m mean gradient during tag and zero gradient during control pulses. 6 segment Turbo-Flash is used for readout, TR=10 ms, TE=3 ms, 10° flip angle, 192x152 matrix size with 1x1x50 mm voxel size. Dynamic angiographic images of the conventional (control-tag pairs) and the newly proposed sequences are obtained and compared. Former uses progressive durations of labeling (400 ms, 800 ms, 1200 ms) to obtain inflow effect [4, 5]. In the newly proposed (based on Hadamard encoding) sequence, 1200 ms bolus is split to three 400 ms sub-bolus, \([ 1 \ 1 \ 1 \ ], [-1 \ 1 \ -1 \ ], [ -1 \ -1 \ -1 \ ] \) bolus profiles for respective measurements. These acquired images \( [M_1, M_2, M_3, M_4] \) were put in Eq-4 to obtain \([S_0, R_1, R_2, R_3] \).

Results: Images obtained using control-tag pairs is shown in Figure-1a and demonstrates three different inflow phases. Images in Figure-1b are obtained by Hadamard method. R1, R1+R2 and R1+R2+R3 map are theoretically identical to \( \Delta M_1, \Delta M_2 \) and \( \Delta M_3 \) maps respectively.SNR measurements for six images were 27.3, 30.3, 38.5, 30.4, 30.1 and 34.4.

Discussion & Conclusion: Using Hadamard labeling scheme and performed analysis, inflow maps are obtained by reduced number of acquisitions. Three images of Fig1a are obtained by 6 measurements, on the other hand corresponding images of Fig 1b are obtained by only 4 measurements. SNR values were observed to be similar for both methods for the first two phases. A relative decrease of SNR in Hadamard method was measured for the longest phase, possibly because of adding more noisy \( R_3 \) map (response that is subject to longest T1 decay). Still, the SNR efficiency was better for all phases in Hadamard method. This scheme can also be extended such that 7 phases can be obtained with 8 acquisitions instead of 14. Previously, it is shown that longer bolus ASL signal curves can be reproduced by summation of short bolus signal curves [6]. To the best of our knowledge, it is first time that this scheme is applied in a dynamic angiographic study on human brain.