Vessel Encoded Arterial Spin Labeling using Fourier Encoding

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INTRODUCTION Pseudo-continuous ASL (PCASL) tagging can be used for vessel encoded ASL (VE-ASL) utilizing gradients applied during the tagging period to spatially encode multiple feeding arteries [1]. A random encoding strategy was introduced for the detection of arteries without *a priori* knowledge of vessel locations [2]. However, PCASL-based VE-ASL methods often require a long scan time and complicated clustering algorithms to classify multiple vascular territories. In addition, resolving mixed signals from multiple arteries can be an issue. Particularly in clinical situations a reasonable scan time (<5min) is required and minimum intervention is desired for both acquisition and post-processing. We introduce a novel method by which vessel territory maps can be generated without operator intervention or complicated algorithm. This method is also capable of resolving multiple sources feeding blood to a single voxel.

METHOD The tagging efficiency, a signal difference of tag/control pair, can roughly be represented as a sinusoidal function [3] and is modulated by the offset phase of the tagging RF pulses [4]. Gradient pulses between tagging RF pulses define the periodicity (or wave length) of the sinusoidal modulation based on the location of a feeding artery. When multiple gradient steps are applied, like phase encoding steps in imaging, the location of the source artery can be detected after applying the inverse Fourier transform. For better localization, the sinusoidal modulation should be complex and the imaginary component of the modulated signal can be formulated with 90° phase offset. The phase offsets and the amount of gradients applied for the Fourier encoding (shown in Fig. 1) can be expressed by:

Phase offsets ($\Delta\theta$): 0°/180° pair (for real part) and 90°/ 270° pair (for imaginary part)

Gradient steps: $n/(\gamma\ FOV_{det})$ n: $-(N-1)/2, .., 0,.., (N-1)/2$

where γ is the gyromagnetic ratio, FOV_{det} is the predefined detection FOV set at the tagging plane, and N is the number of encoding steps in a direction. The number of steps (N) defines the resolution of the vessel localization. The 1D inverse Fourier transform converts the modulated complex signal into the projected ASL signals onto the encoding direction. Note that taking the absolute value of the Fourier transformed signal removes the phase errors due to off-resonance effects at the location of the artery. When the acquisition and processing are performed in two orthogonal directions, such as physical x and y axes, the vessel location in 2D space can be estimated. In addition, an analysis of multiple peaks in x and/or y directional encoding allows detection of multiple sources since arterial mixing, if presents, can be expressed as the superposition of each sinusoid. To reduce the gradient steps while preserving the detection resolution, positive or negative gradient steps are skipped and synthesized by taking the complex conjugate of the other mirrored steps based on Hermitian symmetry.

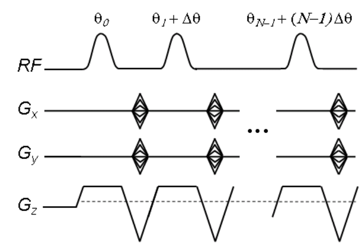

Fig. 1. The four phase offsets ($\Delta\theta$) form the real and imaginary parts of the complex modulation and same gradients in x or y are applied across the entire tagging period. Multiple gradient steps allow the Fourier encoding to resolve vessel locations in x or y direction.

The example shown had a tagging plane where all carotid and vertebral arteries overlapped each other in x or y to demonstrate that two 1D encoding procedure is capable of localizing the feeding arteries in 2D tagging plane. The detection FOV was set at the gradient center and localization parameters in x and y directions include: 9cm & 6.6cm FOV_{det}, 15 & 11 encoding steps (7 & 5 skipped steps), 6mm & 6mm resolution. A total of 56 repetitions (4sec TR) were acquired (2(tag/control pair) x 2(real/imaginary) x (8 steps in x + 6 steps in y)). Scan time for the Fourier encoding was 3min 42sec.

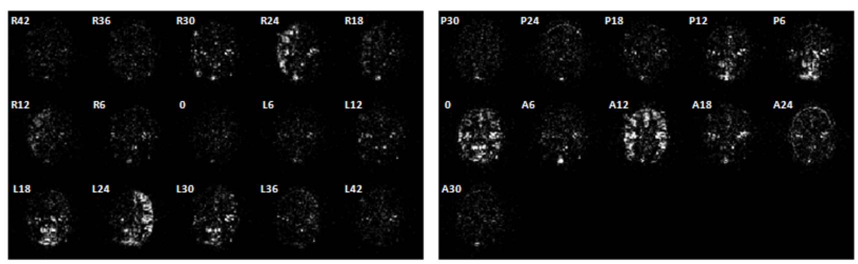

Fig. 2. The inverse Fourier transformed images representing the location of feeding arteries in x (left) and y (right) directions. Labels at the upper left corners indicate the estimated locations of the source arteries.

RESULTS Fig. 2 shows single-slice vessel encoded images across x and y directions. The peak locations of an individual voxel in two orthogonal directions allowed estimating the 2D location of the source artery. The magnitude and source location of ASL signal from the primary peak are shown in the upper left panel of Fig. 3. The vascular territories were well defined without the use of complicated clustering algorithms. The color of each voxel represents the source of artery (shown in the right panel of Fig. 3). Second peak information forming secondary component is shown in the lower left panel of Fig. 3. The second component appears to be mostly vascular pulsations and no distinct secondary components due to mixing were presented in this subject.

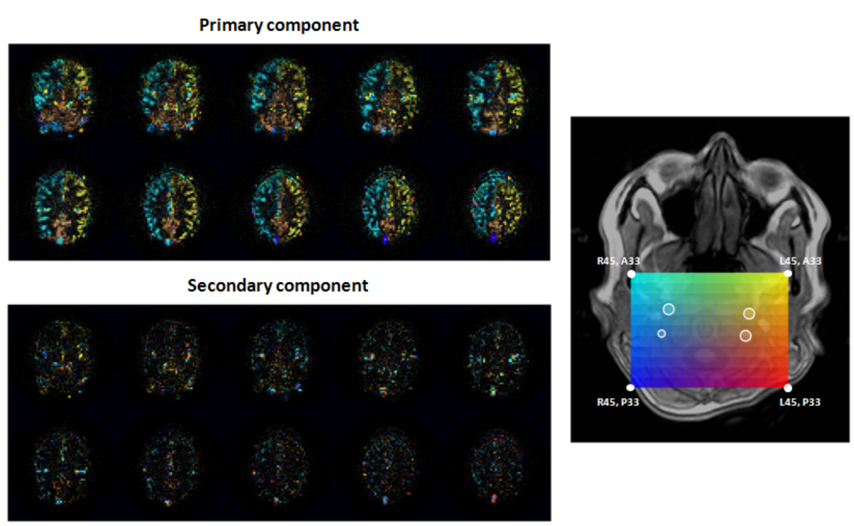

Fig. 3. The primary (upper left) and secondary (lower left) contributions from feeding arteries and a 2D color map representing the estimated locations of feeding arteries (right). The color map was overlaid on a time-of-flight image and white circles indicate the main arteries at the tagging plane.

DISCUSSION VE-ASL using Fourier encoding offers quantitative vascular territory mapping without the knowledge of accurate locations of feeding arteries or complicated post processing algorithm. In addition, the method is immune to phase errors due to resonance offsets, which may cause severe tagging efficiency loss in patients with carotid stents or aneurysm clips. While the experiment required minimum planning, the size of the detection FOV should be larger than any distance of two main arteries to prevent aliasing and there is a trade-off between the size of the detection FOV and the detection resolution.

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