An off-resonance correction method for vessel-encoded pseudo-continuous arterial spin labeling using the optimized encoding scheme

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Introduction: Vessel-encoded pseudo-continuous arterial spin labeling (VEPCASL)[1] induces a periodic variation in inversion efficiency across space, allowing combinations of arteries to be tagged, or encoded. Combining information from different encodings allows perfusion territories[1] or the brain vasculature[2] to be mapped. Unipolar VEPCASL[3] produces a sinusoidal-like variation in inversion efficiency (i.e. an encoding function) across the plane where blood is labeled. In the presence of a B_0-induced frequency offset the inversion efficiency remains constant but the encoding function is shifted locally. If unaccounted for this can lead to reduced SNR and errors in the separation of signals from different arteries. Here we present a method incorporating a correction for off-resonance at the vessels into a method for optimizing the encoding schemes for multiple vessels[4].

Theory: When no off-resonance is present the VEPCASL transverse gradients induce a phase offset between the desired control (π phase shift between pulses) and label (0 phase shift) locations. For a non-uniform B_0 field the unipolar VEPCASL label and control locations will be shifted unevenly within the labeling plane. We previously described an automated method for choosing optimal encoding functions[4] based on defining the ideal encoding scheme (with each vessel in a label or control condition) and then finding the real encodings that best match this. Here, we define the ideal encodings as the desired phase at each vessel. In this way the phase offset due to off-resonance at each vessel can be included and corrected for. The modified optimized encoding scheme including a correction for off-resonance is as follows:

a: An "image" of the ideal encoding scheme is constructed. Each vessel is represented by $e^{i\theta}$. θ is the desired phase including subtraction of phase offset due to B_0 inhomogeneity at that vessel. Zeros represent static tissue

b: The lower spatial frequencies of the "image" in the Fourier domain are up-weighted and the highest spatial frequencies masked to ensure low spatial frequencies are preferred, improving robustness to motion

c: The maximum intensity point in the weighted Fourier space is found, providing the spatial frequency and phase of the encoding function that best matches the ideal encoding, including an off-resonance correction.

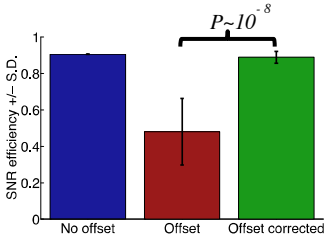

Fig. 1. The mean SNR efficiency of the encodings for three scenarios across 20 different shim offsets.

Methods: ***Simulations:*** Encodings for a set of four vessels were simulated in Matlab and their SNR efficiency compared across three scenarios: 1. No phase offset present; 2. Phase offset present, encodings un-corrected; 3. Phase offset present, encodings corrected. Phase offsets were taken from two field maps of a phantom in which linear and quadratic shim offsets had been applied. The phase offsets were gradually increased to test the method across twenty offsets ranging from -300 to 372 Hz. ***Phantom scan:*** A Eurospin test object 3 phantom, containing plastic rods used to represent the main brain feeding arteries in the neck, was scanned on a Siemens 3T TIM Verio system with a 12-channel head coil. The labeling parameters of Okell et al[2] were used, with a labeling duration of 400 ms and a single imaging slice (spoiled-gradient echo readout, flip angle=10°, voxel size=0.9x0.9x5 mm, TR=118.4 ms, TE=2.95 ms) placed across the labeling plane to image the encodings for the three scenarios tested in simulations (Fig. 2). A large linear shim term was applied in the *x* direction (right to left) to generate a phase offset in the labeling plane. ***Subject scan:*** A healthy subject was scanned on the same system with a 32-channel head coil. Labeling and imaging parameters as in Berry et al[4] were used to acquire perfusion data for the four main brain feeding arteries for the scenarios above (Fig. 3). Image analysis was performed using a Bayesian maximum a posteriori method[5] to separate out vessel-specific information. The phase offsets at the vessels needed to calculate the corrected encodings in the phantom and subject were taken from field maps of the labeling plane (voxel size=4.1x4.1x5 mm, TR=400ms, TE1=5.19 ms, TE2=7.65 ms, acquisition time <1 min). A correction for 1D phase wrapping was applied to the phase values at the vessels to get the true offsets.

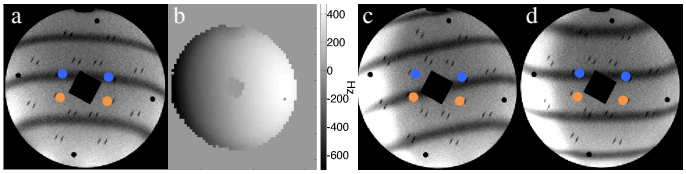

*Fig. 2. Blue dots = right/left internal carotid 'arteries', orange = right/left vertebrals. Dark stripes = labeled regions, pale = control. **a:** Anterior-posterior (AP) encoding without any offset. Anterior arteries are labeled, posterior controlled. **b:** Field map showing a linear shim offset. **c:** AP encoding in the presence of the offset. The encoding has shifted from the desired vessels. **d:** AP encoding corrected for the applied phase offset, desired vessels are labeled/controlled.*

Results: The simulations demonstrate that corrected encodings result in a SNR efficiency similar to encodings when there is no offset and significantly more than when there is an offset present (Fig. 1). The encodings imaged in the phantom scan shift away from the vessel locations when an offset is present whilst the corrected encodings label the desired vessels (Fig. 2c & 2d). The subject scan shows that if encodings do not take phase offsets at the vessels into account then it is difficult to correctly identify vascular territories and there is a loss in signal as a result of poor encoding of the vessels. These problems are mitigated by the corrected encodings (Fig. 3c & 3d).

Discussion: Simulations, phantom and subject scans demonstrate the efficacy of including a phase offset correction in the calculation of optimized encodings for VEPCASL. Although it is necessary to acquire a field map to perform this correction during a subject scan, and any phase wrapping at the vessels of interest must be accounted for, the time needed to complete these processes is short (<1 min for a field map) and could be incorporated into a scan protocol. The next step is to apply this correction when labeling vessels above the circle of Willis where B_0 inhomogeneities are greater than in the neck. Also, this method could be used to correct for inhomogeneities in conventional PCASL scans, akin to previous studies[6,7].

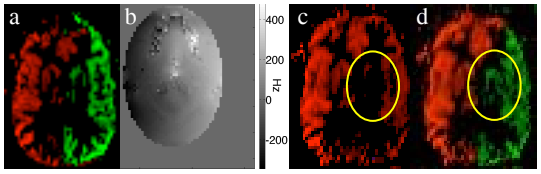

*Fig. 3. **a:** Vascular territory map (VTM) of the main brain feeding arteries (red/green=right/left internal carotids) with no added phase offset in the labeling plane. **b:** Field map of the labeling plane in the neck with a linear shim offset **c:** VTM following acquisition with a shim offset. Yellow circle highlights signal dropout. **d:** VTM following acquisition with corrected encodings. Yellow circle shows signal recovery.*

References: 1. Wong 2007, *Magn Reson Med* **58**:1086; 2. Okell 2010, *Magn Reson Med* **64**:698; 3. Guo 2012, *Magn Reson Mater Phy* **25**:95; 4. Berry 2014, *Magn Reson Med,* online early view (DOI: 10.1002/mrm.25508); 5. Chappell 2012, *Med Image Anal* **16**:831; 6. Jahanian 2010, *NMR in Biomed* **24**:1202; 7. Luh 2013, *Magn Reson Med* **69**:402.