Optimised encoding scheme for vessel-encoded pseudo-continuous arterial spin labelling

Eleanor S K Berry[1], Peter Jezzard[1], and Thomas W Okell[1]
[1]*FMRIB Centre, University of Oxford, Oxford, Oxfordshire, United Kingdom*

Introduction: Vessel-encoded pseudo-continuous arterial spin labelling (VEPCASL) can trace the blood from individual arteries in the brain. VEPCASL produces an approximately sinusoidal variation in inversion efficiency across space; specific combinations of arteries can be tagged, or encoded. Combining information from a number of different encodings allows perfusion territories[1] or the brain vasculature[2] to be mapped. Currently methods for choosing encodings are only suitable for a small number of arteries, require manual intervention, and may not optimise the signal-to-noise ratio (SNR) of the resulting images. We present an automated method that calculates optimal encodings for arbitrary sets of vessels.

Theory: The key to this method is defining an ideal encoding scheme, where arteries are perfectly tagged (-1) or controlled (+1), and finding the real encodings that best match this by:

1. Constructing an "image" of the ideally encoded vessels (static tissue = 0) (e.g. Fig. 1a)
2. Taking the Fourier transform of this "image", masking, and up-weighting lower frequencies (Fig. 1b)
3. Finding the maximum intensity in this Fourier space.

This maximum point provides the frequency and phase of the encoding function that encodes closest to the ideal scheme (Fig. 1c). Preventing high frequencies from being chosen makes this method more robust to gross subject motion.

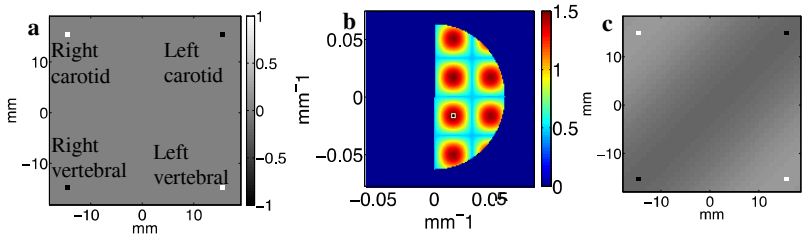

Fig. 1. ***a:*** *Idealised neck vessels with the desired encoding.* ***b:*** *Weighted and masked Fourier space, maximum intensity point = (0.017,-0.016)mm^{-1}.* ***c:*** *Neck vessels superimposed on the optimised encoding function; the maxima and minima line up well with the desired encoding.*

Methods: As a demonstration, the optimised method was compared to the standard and random methods[3] currently used for encoding the four main brain-feeding arteries: the right and left internal carotids and right and left vertebrals. The encodings used were: non-selective tag and control, two left-right, two anterior-posterior, and two diagonal. In the standard method, left-right encodings are chosen to perfectly encode the carotids and anterior-posterior to encode at the average carotid/vertebral positions. Diagonal encoding attempts to tag the right carotid and left vertebral, whilst controlling the other two vessels, and vice versa. To test the robustness of the proposed method to variations in subject positioning and vascular anatomy, the encodings produced by the new and standard methods were simulated in Matlab for four vessels (in a square) in two scenarios: 1) rotation by a range of angles and 2) perturbation of each vessel by a random direction and distance drawn from the normal distribution (mean = 0 ± 10mm). The resulting encodings were used to construct "encoding matrices", from which the SNR efficiency (ideally = 1) was derived[1]. In addition, three healthy volunteers were scanned at 3T in both straight and rotated (~15-30°) orientations to compare the SNR of the perfusion territory images following the proposed, standard and random encoding methods. Simulations of the proposed method and the effect on SNR efficiency of perturbing the vessels by random distances (mean = 0 ± 10mm) were also performed on nine vessels above the circle of Willis, for which there is currently no optimised encoding scheme. Here the ideal encodings were columns of a Hadamard matrix, ensuring optimal SNR[1].

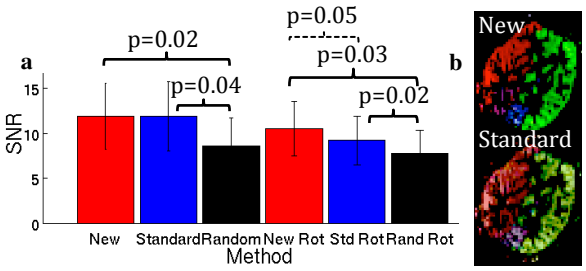

Fig. 2: ***a:*** *Mean SNR ± standard deviation of the perfusion territories of the main brain-feeding arteries for all encoding methods in the straight and rotated cases.* ***b:*** *An example rotated subject, the perfusion territories have been poorly assigned in the standard case. Red=right carotid, green=left carotid, blue=right vertebral, magenta=left vertebral.*

Results: In the rotation simulation of four vessels, once the angle increased above 30° the SNR efficiency of the standard scheme deviated considerably from the ideal of 1 (mean = 0.575 ± 0.289). However, the proposed method maintained near-ideal performance (mean = 0.998 ± 0.001). When the four vessels were randomly perturbed the mean SNR efficiency of the proposed method was closer to the ideal (0.992 ± 0.005) than the standard method (0.727 ± 0.223). Fig. 2 compares the SNR of the vascular territories for the different encoding methods with the subjects straight and rotated. When rotated the proposed method maintains a higher mean SNR than the standard method and, in both scenarios, a higher mean SNR than the random method. Four results are significantly different following a paired t test. The mean simulated SNR efficiency of the proposed method encodings for shifted vessels above the circle of Willis was 0.756 ± 0.058, versus 0.638 ± 0.047 for random encoding ($p=2\times10^{-13}$).

Discussion: The proposed method produces near-optimum vessel encodings in simulations of the simple four-vessel case, irrespective of rotation or shifting of the vessels. Our preliminary healthy volunteer experiments confirmed that the proposed method is robust to subject rotation and appears to produce images with higher SNR than the standard and random encoding methods. Random encoding requires less planning but theoretically has lower SNR efficiency and requires a greater number of encoding cycles than the new method. This becomes more important when the scan following each encoding takes time to acquire, as for vessel-encoded dynamic angiography[2]. Further experimental data are required to validate the proposed method, determine whether deviations from the assumed sinusoidal encoding function have a significant impact and to test it on a greater number of vessels above the circle of Willis. Achieving the ideal SNR efficiency of 1 is not generally possible on more complex vessel configurations but this new method provides optimised encodings for any number and geometry of vessels.

References: 1. Wong 2007, *Magn Reson Med* **58**:1086; 2. Okell 2010, *Magn Reson Med* **64**:698; 3. Wong 2012, *Magn Reson Mater Phy* **25**:95. **Acknowledgements:** Financial support provided by the EPSRC