IMPACT OF EDDY CURRENTS ON QUANTIFICATION OF PERFUSION USING VELOCITY SELECTIVE ARTERIAL SPIN LABELING

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Introduction: Velocity Selective Arterial Spin Labeling (VSASL) is a pulsed ASL technique that is insensitive to bolus arrival time, since arterial spins are tagged based on their velocity rather than their spatial location [1]. However, inaccurate measurement of perfusion using VSASL can arise due to sensitivity of the velocity selective preparation to B_0/B_1 inhomogeneities [2]. In this study, we evaluate the additional static tissue artifacts generated by eddy currents during the VS preparation. Three VS preparations are compared – a Double Refocused Hyperbolic Secant (DRHS) [1], BIR-4 [3] and a novel BIR-8 preparation, which reduces the eddy current effects whilst maintaining the B_0/B_1 insensitivity of BIR-4.

Theory: For a system with eddy current amplitudes A_n with time constants τ_n, the additional gradient due to eddy currents ($g(t)$) is modeled as

$$g(t) = -\frac{\partial G(t)}{\partial t} \otimes \sum_n H(t) A_n \exp(-t/\tau_n)$$

where $\otimes$ represents convolution with the desired gradient waveform ($G(t)$) and $H(t)$ is the unit step function [4]. At the end of a trapezoidal gradient ramp ($t=r$), g is given by

$$g(t=r) = -G_{MAX} \cdot \sum_n \frac{A_n \tau_n}{r}\left(1 - \exp\left[-r/\tau_n\right]\right)$$

where G_{MAX} is the maximum amplitude of the desired trapezoidal gradient. We can therefore linearly modulate the eddy current gradient amplitude by applying the VS preparations with different G_{MAX}, keeping rise time r constant.

Methods: **BIR-8 Preparation Design**: To overcome the B_1 sensitivity of the DRHS (fig. 1a) an adiabatic BIR-4 pulse with monopolar gradients for velocity selection was proposed (fig. 1b) [3]. In order to add the bipolar gradient scheme to the BIR-4 to reduce eddy current effects we doubled the number of segments from four to eight, to give a BIR-8 (fig. 1c). This maintains pulse symmetry about the mid point of the RF, and thus the B_0 insensitivity of the pulse [5]. We then inserted four gradient lobes of equal duration at the last three zero points of the RF amplitude function. The BIR-4 and BIR-8 were designed with identical RF segments to be insensitive over $\Delta B_0 = \pm 250$ Hz, with $\zeta = 15$, $\tan(\kappa) = 60$, $\omega_{MAX} = 250$ kHz, and segment length = 2 ms. **Bloch Simulations**: As adiabatic pulses are used the decay of the tag magnetization during each preparation is not pure T_2 [6]. The tagging efficiency (α) was simulated for each preparation using $T_1^{BLOOD} = 1664$ ms [7] and $T_2^{BLOOD} = 150$ ms [8]. The response of static tissue to the VS preparations in the presence of eddy currents was simulated at different positions from isocenter by varying A_n from 0.01% to 1% and τ_n from 10^{-4} to 1 s with $G_{MAX} = 40$ mT/m. **Data Acquisition**: Five healthy subjects were scanned on a Verio 3T system (Siemens Healthcare) with a 32 channel coil. Data were acquired using a SE-EPI sequence with flow crushers and a global pre-saturation $T_{SAT} = 3.2$ s before the VS preparation. For each VS preparation we varied G_{MAX} from 10 to 40 mT/m in five steps whilst keeping $V_C = 2$ cm/s and $r = 500$ µs. The acquisition order was randomized. Since reducing G_{MAX} will increase the tagging gradient duration we assumed pure T_2^{BLOOD} decay during this extra time. Acquisition parameters were TR = 5.1 s, TE = 32 ms, TI = 0.7 s, 256 mm FOV, 64x64 matrix, thk = 5 mm, 18 slices, tagging applied on the x axis and 16 tag-control pairs for each VS preparation and G_{MAX}. A body coil image was acquired for coil sensitivity correction and M_0^{CSF} calibration. A double inversion recovery acquisition was used as a grey matter mask. Total scan time = 50 minutes. **Post Processing**: Data were motion corrected and registered to the M_0 acquisition using FLIRT. Perfusion (f) was quantified on a voxelwise basis using a modified single compartment model:

$$\Delta M = M_0^{BLOOD} \cdot \alpha \cdot f \cdot TI \cdot q_p \cdot (1 - \exp[-T_{SAT}/T_1^{BLOOD}]) \cdot \exp(-TI/T_1^{BLOOD})$$ where q_p is as defined in [9] and $T_1^{GM} = 1.3$ s.

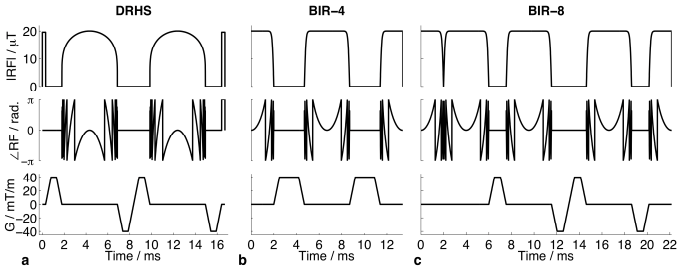

Figure 1: VS preparations used: DRHS (a), BIR-4 (b) and BIR-8 (c) for G_{MAX} = 40 mT/m, r = 500 µs, V_C = 2 cm/s.

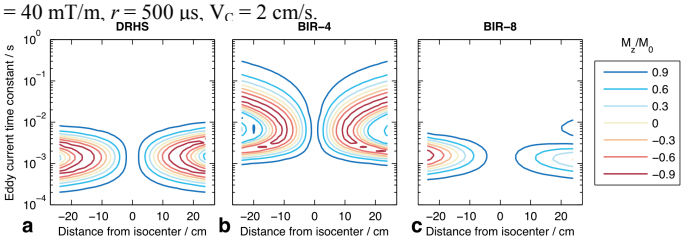

Figure 2: Simulated static spin response to DRHS (a), BIR-4 (b) and BIR-8 (c)

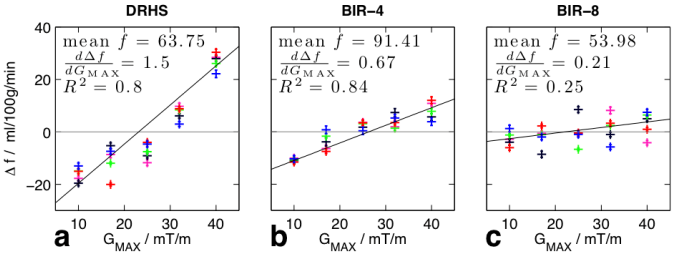

Figure 3: Variation of mean grey matter perfusion with G_{MAX} in five subjects (colours) for the DRHS (a), BIR-4 (b) and BIR-8 (c).

Results: For $G_{MAX} = 40$ mT/m and $V_C = 2$ cm/s the tagging efficiencies were found as: $\alpha_{DRHS} = 0.92$, $\alpha_{BIR\text{-}4} = 0.93$, $\alpha_{BIR\text{-}8} = 0.89$. Simulations of the static tissue response are shown in fig. 2 for A_n=0.5%. At isocenter static spins are returned to $+M_Z$, as expected for a VS preparation. For all preparations static spins can become inverted with increased distance from isocenter, which will appear as a spatially dependent hyper-perfusion in the ΔM images. Simulations show that the DRHS is sensitive to short τ_n (10^{-4} to 10^{-2} s) and the BIR-4 to longer τ_n (10^{-3} to 1 s), whilst the BIR-8 preparation has the least sensitivity to eddy currents. This is supported by the mean grey matter perfusion values (table 1), where both the DRHS and BIR-4 measured significantly higher perfusion than the BIR-8 ($P < 0.01$). The change in apparent perfusion with G_{MAX} is shown in fig. 3. Perfusion measured by the DRHS and BIR-4 significantly correlated with G_{MAX} ($P < 0.0001$). This is further supported by the representative perfusion maps shown in fig. 4 for two G_{MAX}, indicating that the subtractions show artifacts with the expected spatial variation of perfusion. The perfusion as measured by the BIR-8 pulse correlated with G_{MAX} ($P = 0.011$), however, the R^2 and artifacts are reduced.

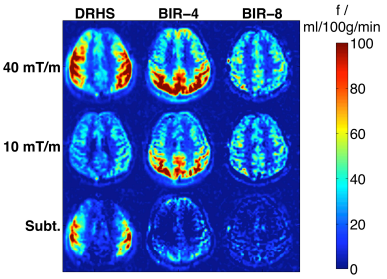

Figure 4: Representative perfusion maps from subject C for the DRHS (left), BIR-4 (middle) and BIR-8 (right) pulses. Maps are obtained with G_{MAX} = 40 mT/m (top), 10 mT/m (middle) and the subtraction of the two (bottom) demonstrating the artifacts generated with increasing eddy current.

Discussion: The data show that all VS preparations may overestimate perfusion due to static spin contamination in the ΔM image, caused by eddy currents. The BIR-4 measured the highest perfusion, but exhibits hyper-perfusion in the brain posterior that persists for G_{MAX} = 10 mT/m, whilst artifacts at this G_{MAX} are absent from the DRHS and BIR-8. The artifact in the BIR-4 is on an orthogonal axis to the applied gradient but we attribute this to a long τ eddy current cross term as perfusion correlated with G_{MAX}.

	Mean perfusion over all G_{MAX} / ml/100g/min		
Subject	**DRHS**	**BIR-4**	**BIR-8**
A	52.30	86.25	45.94
B	65.04	88.46	50.03
C	70.33	90.37	59.68
D	71.75	93.46	58.51
E	59.34	98.51	55.75
Mean	63.75 ± 3.60	91.41 ± 2.13	53.98 ± 2.61

Table 1: Mean f in a grey matter mask for all volunteers.

Conclusions: Eddy currents during the VS preparation cause unwanted tagging of static tissue and an overestimation of perfusion in VSASL. The BIR-8 preparation is the most robust VS preparation to both eddy currents and B_1 with comparable efficiency to BIR-4.

Acknowledgements: Funding from Cancer Research UK and EPSRC **References**: [1] Wong et al. MRM 55:1334 2006 [2] Duhamel et al. MRM 50:145 2003 [3] Wong & Guo Proc. ISMRM, p.2853 2010 [4] Vaals & Bergman JMR 90:52 1990 [5] Garwood & Ke JMR 94:511 1991 [6] Conolly et al. MRM 18:28 1991 [7] Lu et al. MRM 52:679 2004 [8] Zhao et al. MRM 58:592 2007 [9] Buxton et al. MRM 40:383 1998