Simulating the tagging process in Velocity-Selective ASL

D. Gallichan[1], and P. Jezzard[1]

[1]FMRIB Centre, University of Oxford, Oxford, Oxfordshire, United Kingdom

INTRODUCTION

Velocity-Selective Arterial Spin Labelling (VS-ASL) is a recent development to perfusion imaging using MRI which seeks to measure cerebral blood flow (CBF) without being affected by variations in the transit time of blood from the tagged region to the target tissue [1]. The principle of VS-ASL is that two velocity-sensitive preparations are applied a time TI apart, and an image is collected after the second. Both of these preparations aim to saturate spins in vessels flowing above a chosen velocity, V_c. Consequently, only blood which has slowed from $>V_c$ at the first preparation to $<V_c$ at the second preparation will be 'tagged'. Acquiring a second image using only the second preparation serves as a control, and subtracting the tagged image from the control provides the perfusion-weighted image.

This study presents a simplified model of the velocity-sensitive preparations used in VS-ASL and investigates under what circumstances the assumption that full saturation at velocities $>V_c$ will be met.

METHODS

A Monte Carlo simulation was constructed using MATLAB (The Mathworks, Inc.) where 50,000 isochromats flow through an idealised, straight, cylindrical blood vessel with non-pulsatile parabolic flow (*see figure 1(a)*) with peak velocity V_{max}. Each isochromat is originally assigned a longitudinal magnetisation, M_z, equal to 1. This is subsequently modulated by the VS-module (90_x-grad-180_y-grad-90_{-x}) which it is assumed results in $M_z(v) = \cos(\pi v/V_c)$ where v is the velocity of each isochromat and V_c is the chosen cut-off velocity. The mean of all M_z across the vessel corresponds to the expected signal from the vessel. After one VS-module, this yields the sinc-shaped dependence on V_{max} as predicted by Duhamel *et al* [2].

The M_z distribution after the first VS-module was then used as the starting distribution for a second, identical VS-module. To evaluate the expected control-tag difference signal, the mean M_z following a single VS-module was used as the control signal. To simulate the effects of lateral water diffusion within the vessel each isochromat was displaced by a random vector drawn from a 2D Gaussian distribution with standard deviation corresponding to the simulated diffusivity.

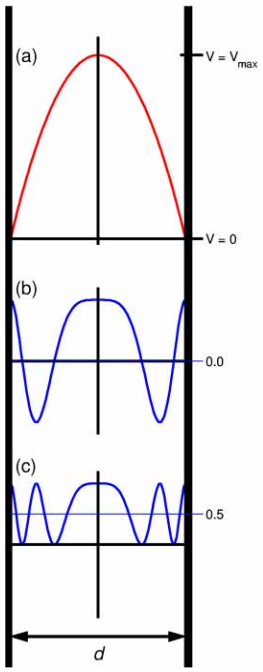

Figure 1: *Cross-section through blood vessel showing* ***(a)*** *velocity;* ***(b)*** *M_z following one VS-module;* ***(c)*** *M_z following two VS-modules. V_{max} set to induce one complete phase roll during VS-module ($V_{max}=2V_c$).*

RESULTS AND DISCUSSION

When T_1 relaxation and diffusion effects are neglected entirely, as might be the valid for a large vessel and a very short TI, the second VS-module will induce in M_z the cosine-dependence on v on top of the existing cosine-dependence from the first VS-module. The result is a cosine-squared dependence of M_z on v, as shown in figure 1(c). Figure 1(a) shows the radial M_z profile within a vessel where $V_{max} = 2V_c$. As V_{max} is greater than the cut-off velocity, the vessel should be completely saturated. Indeed, the cosine profile in figure 1(b), after the increasing area with radius is accounted for, averages to zero. However, the cosine-squared profile in figure 1(c) is entirely positive, and averages to 0.5. This means that when the tag image (2 VS-modules – fig. 1(c)) is subtracted from the control image (1 VS-module – fig. 1(b)) there will be signal arising from vessels flowing faster than V_c. There will be signal arising even in vessels with constant flow, contrary to the assumptions of VS-ASL. We refer here to this artefactual signal as the double-tagging effect.

In a real VS-ASL experiment there will be significant diffusion of water within the vessel during the TI between the first and the second VS-module. The simulated effect of diffusion on the double-tagging effect is shown in figure 2. The magnitude of the double-tagging artefact for a particular vessel is dependent on the ratio of V_{max}/V_c and the ratio of the diffusivity to the vessel diameter. If the relationship between vessel diameter and vessel velocity were well-known, a quantitative estimate of the observable effect could be made. Due to a paucity of such data, however, we make assumptions to form a qualitative estimate:

Typically in VS-ASL we are interested in choosing a V_c which will induce saturation of blood vessels close to the capillary level, and Wong *et al* suggest choosing a value of 1-2 cm/s in order to target arterioles 30-50μm in diameter [1]. If V_c=2 cm/s is used, then from figure 2 it can be seen that a vessel with $V_{max} = 2V_c = 4$ cm/s will have no detectable double-tagging effect provided the TI is long enough to allow the diffusion to be on the order of 20% of the vessel diameter. A flow of 4 cm/s corresponds to a vessel of diameter ~120μm [3]. Assuming water diffusivity in a blood vessel to be similar to that of free water ($2.3\text{x}10^{-3}$ mm^2/s [4]) we can then estimate that TI needs to be at least ~125 ms to avoid the double-tagging effect in this vessel. Typical TIs in VS-ASL are in the range of 600-1800 ms [5], meaning that for V_c = 2 cm/s, there is unlikely to be any effect in vessels of this size. Major vessels such as the ICA, however, have a diameter of ~4.5 mm and average velocity of ~20 cm/s [6]. By the same types of calculation, in the ICA the diffusion would need to be on the order of 110μm for the double-tagging effect to diminish. This corresponds to a TI of 2.75s, meaning the effect could persist for much longer than typical experimental TIs.

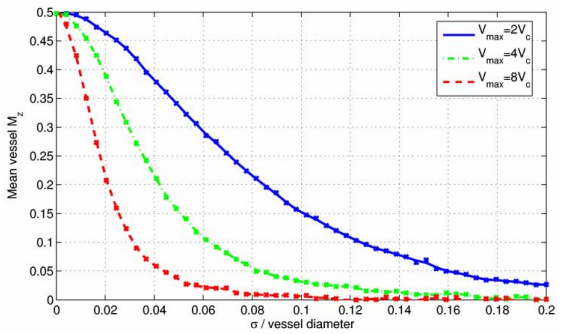

Figure 2: *Simulated decay of double-tagging artefact with increasing diffusion. Curves are shown for $V_{max}=2V_c$, $4V_c$ and $8V_c$.*

T_1 relaxation was included in the simulation, but was found to have little direct influence on the double-tagging effect (which is a proportion of the inherently T_1-dependent VS-ASL signal).

This model does not include the important effects of flow pulsatility and vessel tortuosity which are likely to further dampen the double-tagging effect. At longer TIs the blood will also have had time to make significant progress through the vascular tree before the second VS-module, thus largely reducing the effect. However, it is expected that there will be vessels where this effect can be observed, most likely in large vessels with lower flow-rates (such as veins). Because the double-tagging effect decays with diffusion, it is especially likely to affect short TI measurements.

CONCLUSION

The nature of the tagging process in VS-ASL is such that if the cross-sectional vessel M_z induced by the first VS-module persists at the time of the second module, there will be artefactual contrast in the perfusion-weighted image. Special care should be taken when performing quantitative VS-ASL using short TIs.

[1] Wong *et al.* Proc. ISMRM 2002, p621; [2] Duhamel *et al.* MRM 50:145 (2003);
[3] Kobari *et al.* JCBFM 4:110 (1984); [4] Thomas *et al.* Phys. Med. Biol. 45:R97 (2000);
[5] Wu and Wong, Neuroimage 32:122 (2006); [6] Schebesch *et al.* Acta Neurochir. 146:983 (2004)