Analysis of Flow Dispersion as a Source of Systematic Error in Quantitative Arterial Spin Labeling

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INTRODUCTION: Arterial spin labeling (ASL) techniques provide a direct noninvasive measure of local cerebral blood flow. Furthermore, due to proximity of signal enhancement to the capillary exchange bed, perfusion imaging may be more closely related to neuronal activity as compared to BOLD. The kinetics of signal enhancement of tagged arterial blood presented by Buxton, *et al*. [1] requires knowledge of the velocity flow profile. In most ASL studies, a constant velocity flow profile (plug flow) is assumed. Here we investigate flow dispersion as a source of systematic error in quantitative blood perfusion, and as a meaningful physiological parameter. Shown in Figure 1 is a schematic diagram of velocity flow distribution *f*(*v*), for (a) plug flow, (b) laminar flow, and (c) an intermediate case, referred to as flow dispersion. Plug flow is an idealized case. The flow profile across the vessel is assumed constant, and the velocity distribution is a delta function, with $v = \bar{v}$ (see Fig. 1a). In pure laminar flow, a parabolic flow profile is assumed across the vessel. The velocity distribution is constant from 0 to $v_{max} = 2\bar{v}$, and $f(v) = 1/v_{max}$ (see Fig. 1b). An intermediate case between pure plug and pure laminar flow occurs if: 1) there are several vessels within a voxel, each with a unique plug flow profile, 2) there are mixing within the cylindrical shells of a laminar flow profile, 3) the flow is turbulent which often occurs at higher flow rates [2]. As shown in Fig. 1c, the width of the velocity flow distribution, *w*, measures the degree of flow dispersion. The flow velocity distribution for this model is assumed to be a linear combination of discrete flow velocities. Whereas modeling laminar flow in the arterial kinetic model requires fitting no additional parameters as compared to plug flow, for flow dispersion the width of the velocity distribution *w*, were also fitted to the model. Estimated values of *w* can be interpreted as a measure of path length distributions in brain microvasculature.

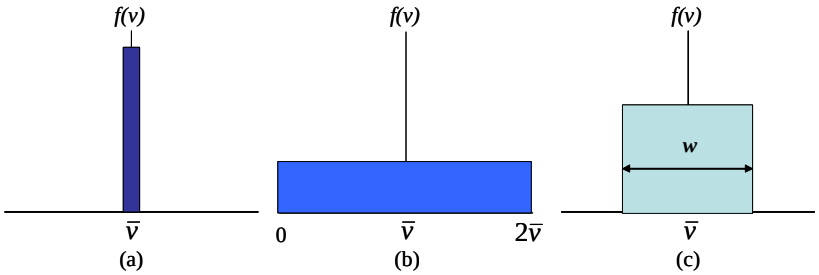

Figure 1: Flow velocity distribution f(v), for (a) plug flow, (b) laminar flow, and (c) flow dispersion.

METHODS: Five adults (ages 20-30, 3 female) were scanned after receiving written informed consent. All imaging was performed on a 3T Varian System (Palo Alto, CA), equipped with a volume head transmit coil and a single channel surface receive coil (Nova Medical, Wakefield, MA). Perfusion images were obtained with the PICORE [3] sequence with a single-shot gradient-echo EPI readout. The imaging parameters were: $\theta = 90°$, FOV = 24.0×24.0 cm^2, TR/TE = 2000/27.3 ms, 3 slices, slice thickness = 8.0 mm. The inversion slab was 100 mm thick, and the distance from the edge of the inversion slab to the proximal edge of the fist slice was 10.0 mm. 160 time frames were acquired during functional paradigm with inversion delay times, TI, set to 300, 600, 900, 1200, 1400, and 1600 ms for each scan. The task consisted of a block design visual paradigm, 4 cycles, with 40 s on/off colored radial checkerboard flashing at 8 Hz. Reconstructed data were motion corrected using the image registration program in AFNI [4]. Perfusion time-series were calculated for all TI values and functional maps were generated from the averaged time-series of TI = 1400 ms and 1600 ms. Voxels were assumed to be activated if the correlation coefficient with a boxcar waveform after detrending was above 0.4. The first 4 points of each epoch were ignored in the transit curve analysis due to signal fluctuations. Selected data were fitted to a theoretical ASL kinetic model [1], with a plug flow profile, laminar flow profile, and flow dispersion. Only voxels that exceeded correlation coefficients of 0.7 for the goodness-of-fit criteria of the fitted curves were included in the mean analysis.

RESULTS AND DISCUSSION: In Figure 2, the arterial transit curve during visual task for a single selected activated voxel is shown. The fitted models correspond to plug, laminar, and flow dispersion, with *w* = 5.3 mm/s providing the best fit. For any given voxel, flow velocity is inversely related to arterial transit delay Δt, and bolus width T_A. Hence, broadening of the flow velocity distribution which occurs in both laminar flow and flow dispersion results in the spreading of the arterial transit delay and bolus widths. An additional motivation for this analysis was the fact that neglecting distribution of flow velocities can result in systematic errors in the QUIPSS II [3] sequence for quantitative perfusion imaging. The requirements of this sequence are that first, the delay in applying saturation pulse to the region be less than the arterial bolus width T_A, and secondly, that the pulsed tag be applied after a delay that is greater than $TI_1 + T_A$. If the values of Δt and T_A are selected based on a plug flow velocity profile, spins moving with slower velocities with not satisfy the first requirement, and faster moving spins might not satisfy the second requirement.

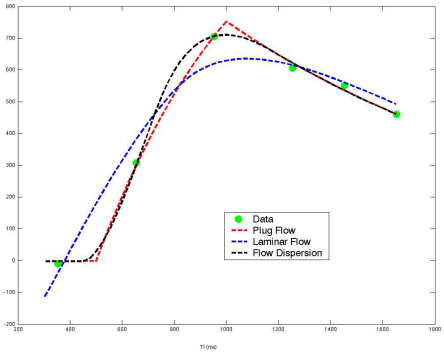

Figure 2: Arterial transit curve fitted to three flow velocity distributions.

REFERENCES: [1] Buxton R. B., *et al*., *MRM* 40, 383-396, 1998. [2] White F. M. *Fluid Mechanics*. New York: McGraw-Hill; 1994. [3] Wong E. C., *et al*., *NMR in Biomed* 10, 237-249, 1997. [4] Cox, R.W., *Computers in Biomedical Research* 29, 162-184, 1996.