Model of Blood Transport Couples Delay and Dispersion and Predicts ASL Bolus Measurements

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Introduction

The properties of the blood transport through the brain vasculature is of fundamental interest for the diagnosis of cerebral diseases such as stroke or cancer and therefore of particular interest for the associated imaging modalities in MRI such as DSC perfusion and ASL. Where in DSC perfusion this information is crucial to profoundly understand the tracer kinetic model [1], in ASL the detailed knowledge of the bolus shape is necessary for the description of the inflow of labelled blood [2, 3]. In this work a model for a vascular tree together with laws of laminar flow are used to describe the blood transport. This description is in excellent agreement with data measured using ASL for early branches of the vascular tree.

Methods

Laminar Flow. The blood flow in the brain vasculature can be assumed to be laminar. The vessel segments between bifurcations are assumed to be cylindrical pipes, a situation in which the radial velocity distribution is well known. From this, the transport function, which is the distribution of the transport time trough the pipe, takes the form $h(t) = t_0/t^2$ for $t>t_0$, where t_0 is the minimal transition time of blood in the central streamline. The transport trough a network of connected pipes is then given by a chain of convolutions of h(t) for each segment yielding the total transport function.

Scaling Rule. According to the ideas described in [4], the arterial tree is self-similar and obeys Murray's Law.. Assuming the splitting in two equal vessels, their size is reduced by the factor $2^{1/3}$ at each bifurcation. So do the segment lengths, l, and the central velocity, v_0, which results in an invariant $t_0=l/v_0$.

Vascular Tree. The vascular tree was modeled to consist of vessels between r_{max} = 1.5 mm (at v0 = 70 cm/s) and r_{min} = 0.05 mm (14 levels of the vascular tree). Vessels of smaller radii are excluded from the consideration, as only the transport of the blood to the input of the individual voxels has to be taken into account. The proportionality constant between the vessel radius and its length was estimated to be 50.

Measurement. A single-shot 3D-GRASE sequence [5] was used for image readout (26 slices, resolution 5×5×4mm3, acquisition time 340ms, TE 18 ms, centric reordered, TR 3300ms) at a 3T scanner (Magnetom Trio, Siemens, Erlangen). A time series was acquired with 28 time steps starting at TI=300ms with an increment of 100 ms. No repetitions were used, thus, a total scan time of less than 3 minutes was achieved. A constant bolus length of 500ms was used.

Theoretical prediction. The bolus was computed by convolution of the transport function with a rectangular bolus of 500ms. For the comparison with the data a T1 decay with T1=1500ms was applied to the result. The model was fit to the data using a normalisation factor and t_0 as global adjustable parameters and selecting the number of generations between the tagging site and the bolus acquisition site.

Results

In figure 1, the bolus shapes at different positions in the vascular tree are shown together with the theoretical prediction. Figure 2 illustrates the sensitivity to the generation number. The curves for voxel 3 in figure 1 are reproduced together with the theoretical prediction for the bolus for one generation before and after the chosen one. In figure 3, the generation determined from the fitting is shown on a voxel by voxel basis. The large arteries (low generation number,) can clearly be distinguished in the image.

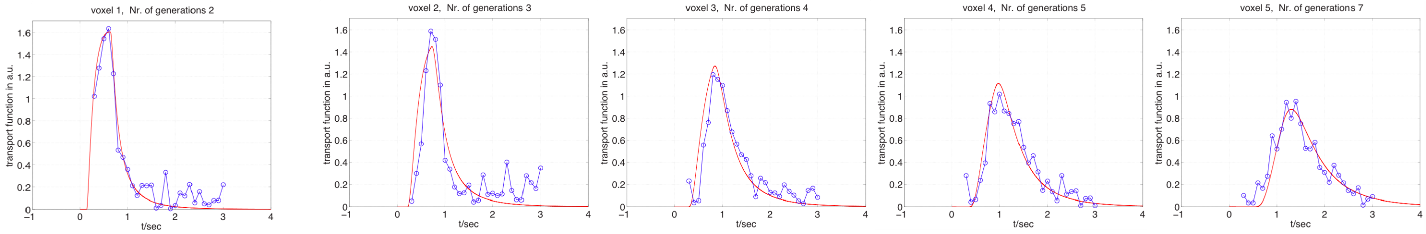

Figure 1: Bolus shapes at different levels of the arterial tree. Blue: measurement, red: theoretical prediction. The left curve was acquired in the ICA right before entering the circle of Willis. The three curves in the middle were acquired at different positions within the ACA and the right curve represents tissue curve close to the ACA.

Discussion

The laws of laminar flow in cylindrical vessels arranged to form a dichotomic tree allow a theoretical prediction of the ASL bolus that is in strikingly good coincidence with the experiment. This forms the basis for a more elaborate understanding of the blood transport in the brain. Specific applications, which will be reported elsewhere, are models of the residue function in brain tissue as well as for the effects introduced by choosing a global arterial input in DSC perfusion. Furthermore the present theory enables an improved model for the inflow in ASL, as the experiment clearly shows a deviation from plug flow or a Gaussian distribution.

References

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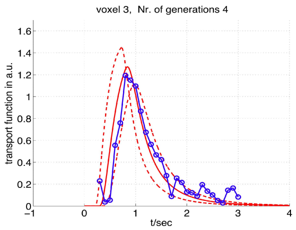

Figure 2: Measured curve (blue) together with theoretical prediction for estimated generation number (red, solid line) and ± 1 generation (red, dashed line)

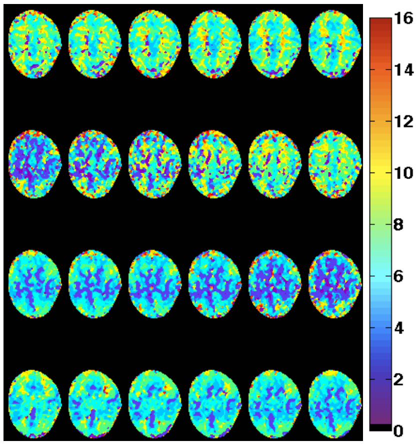

Figure 3: Color coded generation number.