Delay and Dispersion in DSC Perfusion Derived from a Vascular Tree Model Predicts ASL Measurements

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Introduction

Dynamic susceptibility contrast MRI is a widely used technique for the quantification of cerebral perfusion. An accurate estimation of cerebral blood flow (CBF) is particularly important in acute ischemic stroke for identification of ischemic, yet salvageable tissue. Technically, CBF is determined using the tracer kinetic model [1]. In terms of this model, the concentration measured in a tissue is described as the convolution of the input at the voxel of interest (VOI), the arterial input function (AIF), with a residue function R(t). The obtained value is the product CBF×R(t) which yields the blood flow within the voxel using the condition R(t=0)=1. In practice, the AIF is determined at a site distant to the VOI. This leads to additional delay and dispersion of the AIF from it's location to the input of the VOI [2]. It has been shown [2] that the definition of local AIFs improves the CBF estimation, although such AIFs are likely to be masked by partial volume effects. In this work we present a framework for the estimation of the effects acting on the AIF during the blood transport through the vascular system and show an ASL in vivo measurement that is in good correspondence with the theoretical finding. In order to obtain the theoretical vascular transfer function (VTF) we shall imply scaling rules applicable to the cerebral vasculature as reviewed in [3] and the model for laminar flow.

Methods

Laminar Flow. The blood flow in the brain vasculature is known 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 $h(t) = l/(v_0 \times t^2)$ for $t > l/v_0$, where l is he segment length and v_0 is the velocity 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 VTF.

Scaling Rule. According to the ideas described in [3], 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. The latter is referred to as the velocity scaling rule specified by the dependence of the central velocity as a function of the vessel radius, v(r).

Simulation. The vascular system 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 VOI has to be taken in to account. The proportionality constant between the vessel radius and its length was estimated to be 50.

Measurement. The VTF was be acquired in vivo using the recently proposed QUASAR arterial spin labeling method [4], which is capable of measuring local arterial input functions (AIF). Because lower slices often include major feeding vessels like the right or left internal carotid artery or the basilar artery for example, a so called "global AIF" can be extracted in such large vessels and the vascular transfer function can be found by deconvolution of a given local AIF with this global AIF. Voxels with more than 2.0% arterial blood volume were considered allowing a reasonable SNR of the acquired AIFs. The protocol was approved by the local ethics committee and performed on a 3T Philips Achieva whole body system. General scan parameters were: TR/TE/ΔTI/TI1=4000/23/300/40 ms, 64x64 matrix, 7 slices, FOV=240x240, flip-angle=35/10°, SENSE=2.5 V_{enc}=[∞,4 cm/s], 84 averages. QUIPSSII bolus cut-off time = 640 ms.

Results

The VTF derived from the above vascular tree model after 3, 6 and 9 levels is shown in Fig. 1. The effect of the VTF on R after 9 generations is shown in Fig. 2. Fig. 3 shows the boli measured by ASL before and after the trespass trough approximately 15 cm of the vascular tree starting from the circle of Willis. The radius of the starting vessel for the theoretical model was determined from the ASL dataset using MeVisLab (MeVis, Germany). The total length of the vascular path suggests the passage trough 2 generations according to the above scaling rules. By deconvolution of the curves in Fig. 3 the measured VFT was determined and compared to the theoretically predicted curve (Fig. 4).

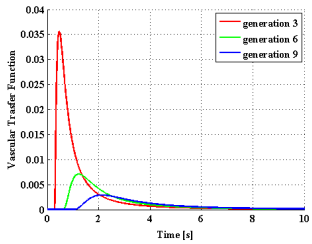

Fig. 1: Evolution of the VTF due to laminar flow trough 3, 6 and 9 generations.

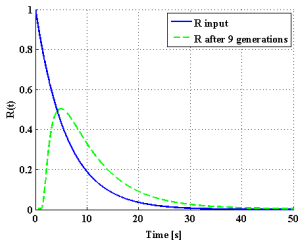

Fig. 2: Effect of the VTF on R after 9 generations.

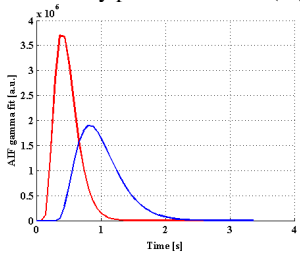

Fig. 3: Bolus before (red) and after (blue) passage trough a vascular path measured by ASL.

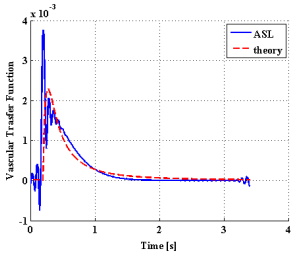

Fig. 4: Measured & theoretically predicted (normalized) VTF for the curves in Fig. 3.

Discussion

The laws of laminar flow couple delay and dispersion of the AIF due to the blood transport along a vascular path governed by a scaling rule. During it's evolution the VTF accumulates the delay and the squared dispersion from each level additively. The theoretical and measured VTFs are in good agreement for large vessels. A verification for higher generations within the vascular tree still remains a challenge, although the results presented here encourage to face it. Using such models a dependence between the delay of the maximum of R and the underestimation can be established in order to correct the flow values. An application to perfusion measurements is too early, as the model needs further improvement and verification.

References

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