MRI-Based Modeling of Vascular Territories and Collateral Circulation of the Brain

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Introduction: A key aspect for the management of stroke patients is the differential diagnosis of hemodynamic border zone infarction and thromboembolic ischemia, which is largely based on the location of the visualized infarct relative to the arterial territories and border zone regions [1]. However, it has been shown (using unfixed human brain specimens) that the variability of the major cerebral arterial territories can vary quite significantly [2]. Since individual arterial territories are difficult to identify *in vivo*, interpretation of acute stroke subtype and underlying pathogenesis, based on the topographic patterns alone, is often inaccurate [1]. The leptomeningeal anastomoses (LMA), a connecting branch between two major arterial territories, is believed to be important in the understanding of stroke mechanisms. However, there is no consensus in the literature regarding the role of LMA in the outcome of the penumbra [3]. Therefore, there is a need for the development of new techniques for the *in vivo* mapping of arterial territories, as well as for the assessment of the changes to the border zone regions under compromised situations, such as carotid stenosis or occlusion. Furthermore, the development of models to investigate the effect of LMA on the arterial territories and the border zone regions could prove very beneficial; they could be used to further our understanding of the potential effect of LMA on cerebral circulation, as well as shed some light on their functional significance in stroke mechanisms. The currently limited understanding of the collateral circulation in the human brain can be greatly enhanced through the development of vascular models, providing the basis for future therapeutic and prognostic applications. This study presents a novel method to create a subject-specific vascular model, which is based on combining MRI and MRA data with computer generated 3D arterial tree structures.

Methods: A 3D model of the circle of Willis (CoW) was constructed from MRA data using an iso-surface deformable model approach [4], and the main efferent vessels were truncated after one or two generations. For each of these vessels, an arterial tree model was generated using an image-based constrained constructive optimization method [4,5]. In this well-established approach, a location inside a perfusion volume (specified from MR images) is randomly selected and a new arterial branch is created connecting this point with the closest branch of the current tree, subject to a set of physiological boundary conditions and geometric constraints (e.g. the radii of the segments must obey a power law at bifurcations, the new branch must not intersect any other branch, and the total intravascular volume must be minimized [4,5]). This algorithm was modified so that multiple arterial trees for each cerebral hemisphere are *simultaneously* generated minimizing the total intravascular volume. Once all the arterial trees were created, a specified number of collateral branches mimicking the LMAs were generated by incorporating connecting arterial branches with a constraint on their radii and length. These parameters can be modified to assess their effect on the resulting collateral pattern. The generation of collaterals was restricted to a region in the surface of the perfusion volume. The *vascular territory* of a given vessel was estimated based on the number of points belonging to each arterial tree that fell within each voxel. The *border zones regions* were then determined by the volume obtained by descending neighboring trees connected by LMAs.

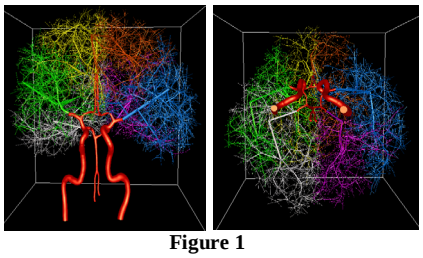

Figure 1

Results: The methodology was tested on MR data of a normal volunteer. Fig 1 shows (from two viewpoints) the reconstructed 3D CoW model, and the arterial trees generated from the left and right hemispheres, with the various arterial trees and LMAs indicated with different colors. The vascular territories of the left cerebral vessels are shown from two viewpoints in Fig. 2. Magenta dots correspond to points along the vascular tree of the given vessel, green points are border zone points (on a different tree but reachable by descending neighboring trees connected by LMAs), and blue points are points on different (inaccessible) trees. The Table presents (in cgs units) the volume V0 perfused by each cerebral vessel, the volume V1 including the border zones (obtained by adding the volume of voxels reachable by descending neighboring trees through collateral vessels), and the radius (r) of the feeding vessels (i.e. the root segment of each arterial tree).

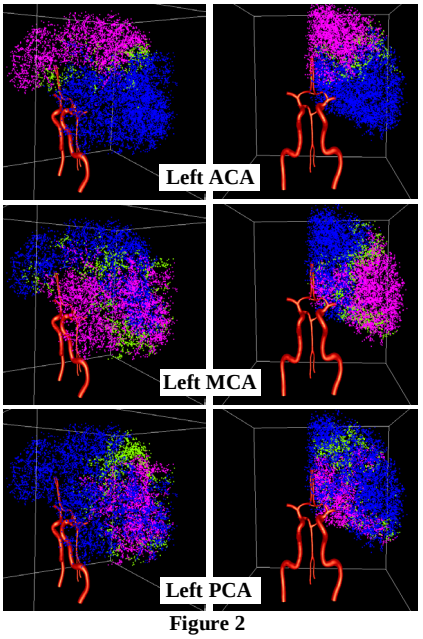

Figure 2

Discussion: The commonly used concept that stroke mechanisms can be inferred from the lesion pattern on MR images is seriously confounded by the variability in the arterial territory distributions. In this study, we developed a novel MR-based method to estimate arterial territories, the distribution of the border zone regions, and to assess the effect of LMA *in vivo* non-invasively. The method is based on the development of subject-specific 3D vascular models reconstructed from MRA images, combined with arterial tree models generated to perfuse the brain volume (specified from MR images). Collateral vessels are then generated near the cerebral cortex to interconnect these arterial trees.

The vascular territories are currently determined only by the presence of collaterals that connect different trees. However, the methodology can be further extended to incorporate our previous work [4,6] to calculate blood flow along the arterial trees in order to determine the distribution of blood among the different branches, and to provide an alternative MR method to estimate cerebral perfusion. This will also allow the calculation of flow redistribution during arterial occlusions and estimate the affected area of the brain. Furthermore, by incorporating a model of autoregulation, effects of stenosis and occlusion on perfusion can be estimated.

The models can also be used to assess the effects of different distributions of collateral vessels; the number, size and location of the collaterals can be varied to further our understanding of the influence of the LMA on the inter-individual variability of arterial territories and the cerebral hemodynamics.

CoW vessel	V0	V1	r
Left ACA	56.2	64.8	0.08
Left MCA	70.2	89.9	0.14
Left PCA	54.0	73.9	0.08
Right ACA	55.6	68.8	0.09
Right MCA	64.9	91.3	0.13
Right PCA	62.9	80.0	0.10

Conclusion: The methodology described could be used to provide a detailed anatomical knowledge of the various intracerebral vascular territories, which is crucial for the differential diagnosis of thromboembolic and borderzone ischemia. It should be emphasized that realistic vascular models are very useful in supporting experimental methods, and often enable the determination of hemodynamic characteristics that are difficult to obtain *in vivo* non-invasively.

References: [1] M Hennerici et al, *AJNR* 1998;19:1067-1074. [2] A van der Zwan et al, *J Neurosurg* 1992;77:927-940. [3] M Brozici et al, *Stroke* 2003;34:2750-2762. [4] JR Cebral et al, *J Eng Math* 2003;47:369-386. [5] R Karch et al, *Ann Biomed Eng* 2000;28:495-511. [6] Calamante et al, *NeuroImage* 2003; 19:341-353.