Analysis of Cerebral Blood Flow from Small Rodents

Phase Contrast Angiography of Vascular Geometry

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Abstract. The exact knowledge of the blood vessel geometry plays an important role, not only in clinical applications (stroke diagnosis, detection of stenosis), but also for detailed analysis of functional data, such as fMRI or optical imaging data. Here we focus on validating not only the geometry of the extracted vascular pattern, but also its function, namely the fluid dynamics. For validating angiographic data, phase contrast angiography (PC-MRA) sequences are used, as these data contain additionally to the morphological data rheological information. This rheological information can be used to validate the reconstructed geometric model of the vascular system, especially for the detection of missing vessels due to velocity changes in front of bifurcations.

1 Introduction

Phase contrast angiography (PC-MRA) plays an important role in modern diagnosis techniques for the detection of blood vessel diseases such as stenosis or aneurisms. Moreover, exact geometric reconstructions of the blood vessel pattern can also be used for registration of multimodal functional data, such as fMRI and optical image data.

To validate the quality of our automatic reconstruction method we compare different scans from the same animal with each other and with μCT data of the same rat, being the gold standard for vascular geometry [1].

Here, we focus on some functional aspects of the reconstructed vessel pattern, namely its fluid dynamics. Therefore, we use quantitative flow data, gathered with PC-MRA of small rodent brains to i) optimize the calculation and visualization of the measured flow fields and ii) validate the reconstruction of the brain vessel pattern from angiograms. Reconstructed vector fields offer the information of direction and speed of the blood within the vessel. This information can be used i) to validate the reconstructed blood vessel model by analyzing flow, especially in areas of disturbed flow, such as bifurcations, sharp bends and abrupt

diameter changes ii) to indicate missing vessels in the reconstruction because the PC-MRA shows flow changes (speed and velocity) and iii) to indicate faulty reconstructed diameters because the PC-MRA shows constant velocities.

2 Materials and Methods

2.1 Data Aquisition

Scanning was performed at a 4.7 T BRUKER Biospec 47/40 scanner, equipped with an actively RF-decoupled coil system. For the rat scan the RF-signal was transmitted with a whole birdcage coil and received with a 3 cm quadrature surface coil, located directly above the head of the rat. A standard PC-MRA with TE = 7.3 ms, TR = 15.6 ms, flip angle = 30°, field of view = 3.5 cm x 3.5 cm x 3.5 cm, matrix size = 256 x 256 x 256, venc = 40cm/s was used. Animals were anesthetized by Isofluorane, the level of which was adjusted to achieve a stable and physiological respiration rate (60 bpm). For keeping the body temperature of the rat at a constant level, heating was achieved via a water bath.

2.2 Data Visualization

Visualization was carried out using the AMIRA (Mercury inc.) software, where our customized image processing modules were implemented. From PC-MRA modulus images, geometric reconstructions of the blood vessels were automatically generated by a self developed software (patent pending) [1], resulting in a surface description of the vascular system providing diameters and directions (Fig. 1,3).

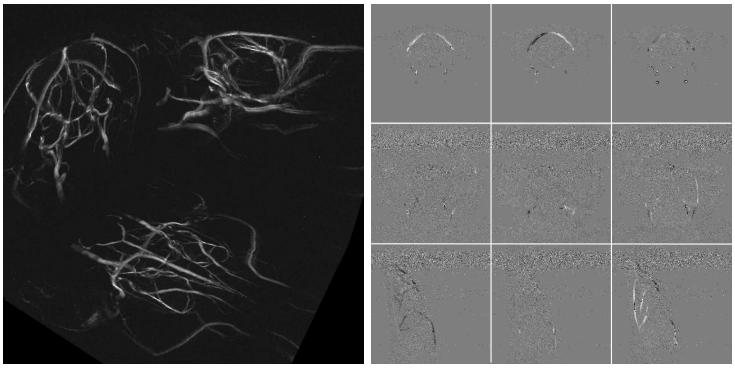


Fig. 1. Maximum intensity projection of a rat brain angiogram, measured with MR-PCA (left); single xy-slice of the measured phases, encoding flow velocity (right top from left: a-p, l-r, h-f direction); same for xz and yz slices (middle bottom)

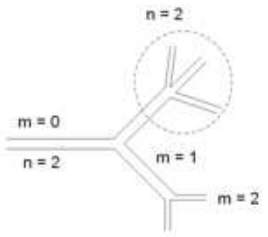
2.3 Simulation (Pressure Drop in the Blood Vessel System)

For reference data, fluid mechanical approaches were applied. From the reconstructed blood vessel system a line set (skeleton) was constructed. This line set was used to generate a simplified model, in which the velocity in each branch of the vessel system could be estimated. Here we make use of the Krämer [2] model, a model to calculate the pressure drop in the vascular system, but as a simplification of the otherwise unsolvable second order partial differential equations that describe the flow formally.

Under the assumption of laminar flow, Newtonian liquid and a rigid tube, the velocity magnitude within the reconstructed vessel system is calculated. Although, in the vessel system there are periodic variations of blood pressure and velocity, the vessels are elastic and blood is a non Newtonian fluid, a stationary Poiseuille- flow allows an estimation of pressure distribution in the vessel system.

Starting point for the calculation were the two arteries entering the brain (carotids). The starting velocity was set to 40cm/s (maximum from our MR-protocol). The calculation of volume flow and mean velocity after each branching point was calculated with the formulas mentioned in (Fig. 2). The following assumptions were done; i) Starting velocity is the mean velocity in the inflow area of the carotids, ii) In case of interrupted, but ongoing flow, the velocity of the preceding segment is used, iii) In case of non ongoing flow, a new start point velocity was used, namely the MR-measured velocity in the new start point, iv) For circle structures, as they exist often in rat brains, the volume flow in front of and behind the ring structure must be the same (no friction losses).

The line set of the vessel structure was used to determine the direction. Having calculated the velocity in the different branches of the vessel system this mean velocity in each branch was mapped on the reconstructed vessel system (Fig. 4).



$\Delta\dot{V}_m = \frac{\dot{V}}{n^m}$

where

$\Delta\dot{V}_m$	Volume flow in a tube of order m
n	Number of branches
m	Order of branching
$\dot{V} = vA$	inflow (bi- or multifurcation)

where

v	mean velocity in the vessel
A	cross section of the vessel

Fig. 2. Krämer model of pressure drop for estimation of the mean velocity in each branch of the reconstructed vessel system

3 Results

3.1 Flow Visualization

For visualization of the rheological data (flow velocity and direction) phase images of the PC-MRA are used. As these phase images are noisy and flow quantification does only work correctly in areas where flow is existing, the phase images need to be segmented, using the above mentioned reconstruction method ([1], patent pending) as a mask image. After segmentation the phase images were combined into a three dimensional vector field and streamlines (Fig. 3,4) were generated using a standard streamline algorithm [3]. Due to turbulent flow, small vessel diameters and measurement errors, the calculated vectors are erroneous. This is clearly visible, both in the direct vector visualization and in the streamlines (Fig. 3,4). Due to the curved vessel structure and many bifurcations, streamlines do not follow the vessel structure anymore and when they reach background tissue, the streamlines stop, as background tissue is set to zero. To have streamlines in most parts of the brain vessel system, it is necessary to start the streamlines in different parts of the brain.

3.2 Flow Simulation

As the streamline algorithm is erroneous, and the number of pixels within a vessel is too small to obtain reliable results the mean velocity is mapped on the reconstructed vessel system. This results in a presentation of the velocity in the blood vessel system, but the direction information is lost (Fig. 4).) Based on these observations and the variance of the measured vectors within small test volumes, we derive a confidence measure accessing the quality of a given MR-PCA measurement (noise/diameter, directional variance/diameter etc.).

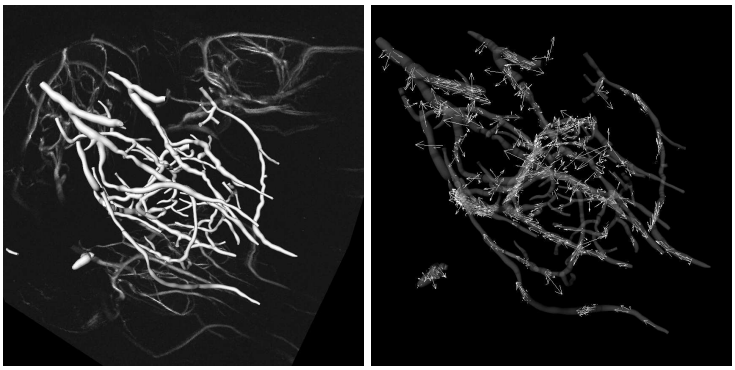
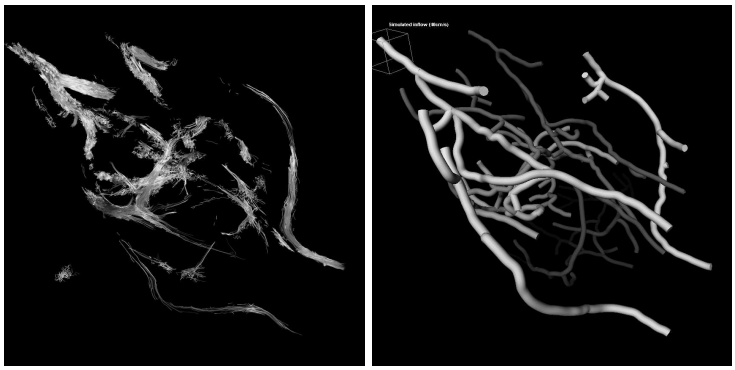


Fig. 3. Blood vessel reconstruction from MR-PCA angiogram (left); direct visualization of vectors, reconstructed from individual phase measurements (right). As reference, the vessel reconstruction is also shown (shaded)

Fig. 4. Flow field visualization using illuminated streamlines (left); visualization of simulated flow as result of an inflow from the right carotid (right). Higher flow is shown using larger diameters and brighter color



4 Discussion

Numerical errors and image quality remain the main problems for streamline visualization of PC-MRA images. To get meaningful and accurate streamline images the method and the used parameters need to be adapted. However, the proposed method offers an additional tool for accurate registration of small vessels, as both morphological and rheological data are used. The Krämer model, being optimized for low branching orders and relatively large vessels, shows problems due to oversimplified assumptions. The quality of PC-MRA measurements is best in vessels with laminar flow whereas in vessels with turbulent flow signal blackout due to partial volume effects can occur. However, if enough vectors exist in a given vessel and flow is mostly laminar, main flow direction and velocity can be obtained. Based on this information, missing vessel branches can be reconstructed. Moreover, the simulation can be used to correct the measured flow vectors, such that signal voids and other errors can be corrected.

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