Time-Resolved 3D Quantitative Flow MRI of the Major Intracranial Arteries

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Introduction.

3D phase-contrast (PC) MRI measures blood flow velocity in 3D space. In addition to its utility as an angiographic technique, 3D-PC MRI allows one to derive complete flow vector fields that help to further our basic understanding of physiologic blood flow, to derive mechanical properties of the confining vessel walls, and to investigate hemodynamic abnormalities, such as in stenoses or aneurisms. Recently, Markl *et al.* have extended 3D PC MRI by dynamic imaging capabilities so that it is possible to obtain full 3D flow information at multiple instances over the cardiac cycle in the aorta. Except for transcranial Doppler ultrasound and PC-MRA, access to quantitative blood flow information has been limited to the brain. In addition to garnering basic physiological knowledge, 3D flow properties in the major intracranial arteries in patients who have suffered from stroke or related cerebro-vascular diseases may provide valuable etiological information and support treatment decisions. We therefore set out to optimize and investigate the potential of this method for measuring the ICA, Circle of Willis, ACA, PCA, MCA, basilary and vertebral arteries (Fig. 1).

Materials and Methods.

Cine 3D PC MRI was optimized to cover the major intracranial arteries of volunteers on a 1.5T scanner with high performance gradients (50 mT/m, SR = 150) using a dedicated 8-channel head coil: FOV = 180mm, slice thickness=2.5mm, TR=4.5ms, TE=1.9ms, matrix 192x160, ZipX2, bandwidth ±62.5kHz, NEX=1, views per segment=4 slice encodes x 4 phase encodes (temporal resolution= 4·4·4.5ms=73.6ms), velocity encoding (venc) = 70cm/s (all directions). All procedures performed were approved by our institution's review board. Magnitude and direction of blood flow in 3D span a vector field that can be superimposed on anatomic images as small arrows or artificial streamlines. Here, the vectors at each point in space represent local gradients (i.e. tangents) to these streamlines. The parameterized streamline that emanates from a given seed point can therefore be computed by numerical integration methods, such as Euler or Runge-Kutta, and essentially identical processing tools as those used in DTI-based tract-tracing methods and streamline visualization in fluid mechanics can be used. In contrast to DTI, another input comes from the change of the vector field with time. With cine 3D PC MRI, every instance a new vector field is acquired and allows one to compute individual sets of streamlines that can be visualized as 3D objects. However, the most meaningful representation is the so-called particle trace. In the trace, a synthetic particle emanates from a seed region along the direction given by the flow vector. Using the magnitude of the flow as well as the time interval, the distance a particle has traveled can be computed and its location in three-dimensional space in the next time frame can be computed by spline approximation of the vectorfield. To demonstrate this concept a software package developed in-house for DTI-based fiber-tracking (smartTrack) was modified to allow a visualization of the major cranial vessels.

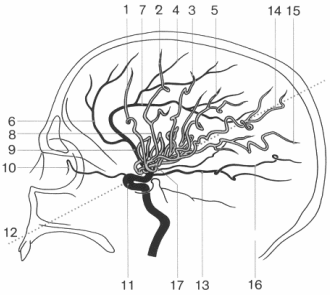

Fig. 1 - Angiography of the internal carotid artery and its major branches.
(1) orbitofrontal artery, (2) precentral artery, (3) artery of the central sulcus, (4) calloso-marginal artery, (5) postcental artery, (6) frontopolar artery, (7) pericallosal artery, (8) insular arteries, (9) anterior cerebral artery, (10) ophthalmic artery, (11) siphon, (12) siphon-incisivum-line, (13) anterior choroidal artery, (14) artery of the angular gyrus, (15) posterior temporal artery, (16) posterior cerebral artery, and (17) middle cerebral artery. (modified from Krayenbühl & Yasargil et al.)

Results.

Our preliminary results demonstrate the feasibility to measure the components of intracranial blood flow using 3D PC MRI at multiple time points. Compared to 2D methods, the 3D PC MRI used in this study provides higher SNR which provides better absolute flow quantification and diminished orientation uncertainty. Quantitative flow values measured from the 3D PC MRI were in good agreement with what one usually finds with Doppler flow measurements (carotid siphon=44±14cm/s, MCA=80±13cm/s, PCA=54±11cm/s, ACA=67±14cm/s, vertebral arteries=50±12cm/s). The fidelity of the vector fields generated from these data is sufficient to support streamline computations even in vessels with rapid orientation changes, such as in the siphon of the ICA at the level of the Sella Turcica (Figure 2), which is impressive insofar that the vessel calibers in the brain are considerably small and susceptible to partial volume artifacts. If the voxel size is chosen too big, flow in the opposite direction will cancel but this effect was never observed in this study. Significant improvements in streamline tracking with smartTrack could be made by adaptive changes in maximum tolerable angular deviations between tracking steps and spline interpolation of the vector field. The VTK environment used for smartTrack allows for 3D rendering of the tracks and interactive viewing from essentially all perspectives.

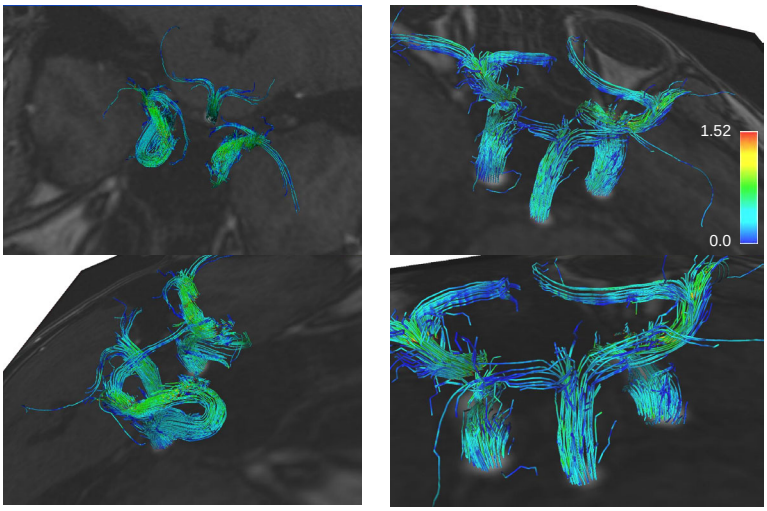

Fig. 2 - *Streamline visualization of the flow-vector field in the ICA siphon at different points in time and from four different viewing perspectives. The magnitude of the flow is represented by the color of the streamlines (red=high, blue=low flow).*

Conclusion.

3D PC MRI in the major intracerebral arteries is possible and provides flow vector fields of useful quality. DTI methods, previously used for tract tracing, can be applied to increase the sensitivity of flow visualization in 3D PC MRI. One limitation of the technique used is related to the fixed velocity encoding value over the entire cardiac cycle. At certain instances during the cardiac cycle the full dynamic range of flow encoding could not be fully utilized. Along these lines further investigation is warranted and adaptive flow-encoding gradients that adjust optimal encoding during the RR interval are desired. From the T1 shortening of contrast material, we anticipate further improvements in terms of SNR. Future improvements include developing a method to avoid confounding effects from venous overlay.

References. (1) Markl M., *et al*. Time-resolved 3-dimensional velocity mapping in the thoracic aorta: visualization of 3-directional blood flow patterns in healthy volunteers and patients. J Comput Assist Tomogr. 2004 Jul-Aug;28(4):459-68. (2) Bammer R., *et al*. In vivo MR tractography using diffusion imaging. Eur J Radiol. 2003 Mar;45(3):223-34. **Acknowledgements.** This work was supported in part by the NIH (1R01EB002771, 1R01NS35959), the Center of Advanced MR Technology at Stanford (P41RR09784), Lucas Foundation, and Oak Foundation.