3D Blood Flow Visualization in Patients with High-Grade Carotid Artery Stenosis and Volunteers Using Flow Sensitive 4D MRI at 3T

A. Harloff[1], F. Albrecht[1], J. Spreer[2], A. Hetzel[1], A. Frydrychowicz[3], C. Weiller[1], M. Schumacher[2], and M. Markl[3]

[1]Neurology and Clinical Neurophysiology, Albert-Ludwigs Universität, Freiburg, Germany, [2]Neuroradiology, Albert-Ludwigs Universität, Freiburg, Germany, [3]Diagnostic Radiology, Medical Physics, Albert-Ludwigs Universität, Freiburg, Germany

Introduction: High-grade internal carotid artery stenosis (ICA) are a major source of ischemic stroke. However, current diagnostic tools only provide either good functional (Doppler ultrasound) or morphological data (digital subtraction- ,CT- or MR-angiography) [1]. Furthermore, only little is known about the underlying flow characteristics, such as typical helical flow in the bulb of ICA, predisposing to the development of atherosclerosis [2]. The purpose of this study was to establish and evaluate an MRI protocol integrating non-invasive 3D imaging of 3D blood flow and morphology of carotid arteries. Time-resolved 3D phase contrast MRI with three-directional velocity encoding (flow sensitive 4D MRI [3]) was employed to simultaneously assess blood flow characteristics in the left and right carotid arteries with complete 3D coverage of the carotid bifurcation. Advanced 3D blood flow visualization was used to combine functional and morphological parameters of our MRI protocol and to investigate the influence of disease on hemodynamic factors such as arterial filling and helix formation. Results from a study with 25 volunteers and patients with high-grade ICA stenosis before and after surgery indicate the potential of our MR imaging protocol for the comprehensive assessment of morphology and 3D carotid arterial hemodynamics.

Methods: 10 healthy volunteers and 15 patients with high-grade ICA stenosis were examined using a 3T MR system (TIM TRIO, Siemens, Germany). 10 patients were examined by CT-angiography before carotid endarterectomy or stent implantation and by MRI and Doppler ultrasound before and after intervention. Degree of carotid stenosis was defined according to the ECST (European Carotid Surgery Trial) criteria [4]. For plaque and thrombus localization a T1-weighted fat-saturated 3D gradient echo (GRE) sequence with an isotropic spatial resolution of 1mm^3 was used. Further, contrast-enhanced MR angiography (CE-MRA) was performed after injection of 0.05ml/kg 0.5M Gadolinium contrast agent at 3.5mL/sec. For further analysis of plaque composition T1-weighted GRE imaging was repeated after CE-MRA. Respiration and wall motion artifacts were minimized by ECG gating and respiratory gating. For the assessment of global and local hemodynamics, flow-sensitive 4D MRI was employed. Imaging parameters were: velocity sensitivity =150cm/s, spatial resolution 1.2 x 1.8 x 1.8 mm^3 in an axial 3D volume covering both left and right carotid bifurcations (see also figure 1). Further imaging parameters were as follows: α = 15°, venc = 150 cm/s, TE = 3.7ms, TR = 6.1ms, temporal resolution 48.8 ms. For 3D blood flow visualization, a commercially available software package (EnSight, CEI, USA) was used.

3D blood flow characteristics in a subset of 6 healthy volunteers and 5 patients were semi-quantitatively evaluated in a consensus reading with respect to helical flow pattern in the ICA and ECA (external carotid artery) and luminal filling. Based on time-resolved 3D particle trace visualization we evaluated carotid arteries of both sides and pre- and post-operatively in patients. Categories were as follows: existence of helical flow in the ICA bulb: absent=0, moderate=1, pronounced=2. Vessel lumen filling: none=0, mild=1, moderate=2, complete=3.

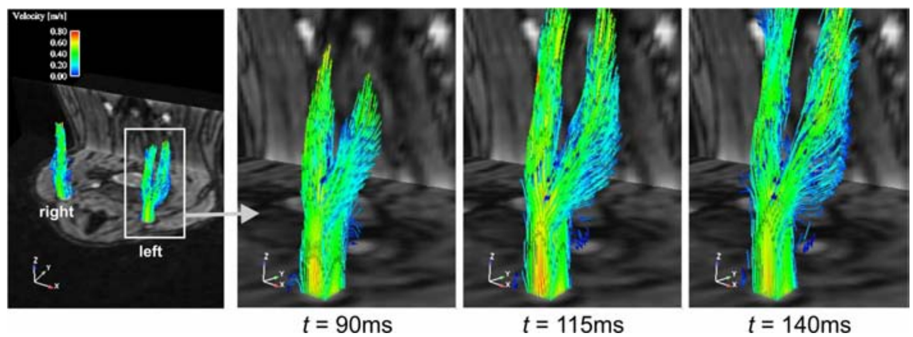

Figure 1: 3D visualization of blood flow in the carotid bifurcation for a healthy volunteer during early systole (90 ms, 115 ms, 140 ms following R wave in ECG). Note the spreading of blood flow and consecutive helical flow pattern in the temporal and spatial domain originating in the ICA bulb as a result of the physiological dilatation. Development of helical flow in the ICA bulb was graded as pronounced (=2) and filling in ICA and ECA was classified as complete (=3). Color coding = absolute mean flow velocities in m/s.

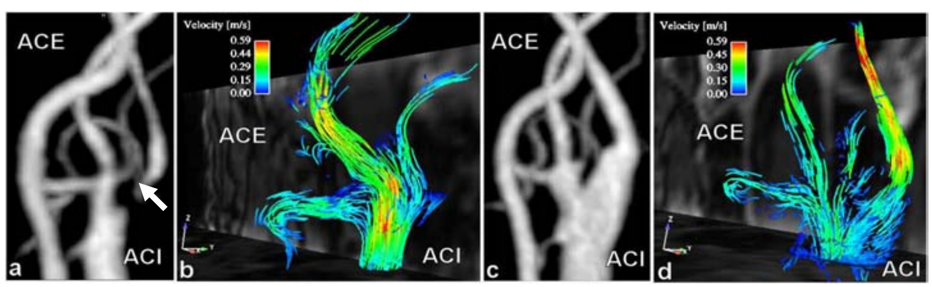

Figure 2: Patient with left-sided pre-occlusive (95%) ICA stenosis. **a:** CE-MRA revealing a short and high-grade luminal narrowing (arrow) of the ICA with a poststenotic collapse of the vessel lumen. **b:** corresponding 3D MRI flow visualization. In contrast to external carotid artery (=ACE) branches, no flow can be visualized in the internal carotid artery (=ACI): filling of the vessel lumen=0, helical flow=0) **c:** CE-MRA after patch angioplasty of the common and internal carotid arteries. **d**: Restoration of helical flow pattern in the ICA bulb (grading=1) and complete and clear filling of the ICA vessel lumen postoperatively (grading=3). Color coding = absolute mean flow velocities in m/s.

Results: Assessement of carotid artery morphology and blood flow was successfully performed in all subjects. In all volunteers flow in ICA was moderate to complete and complete in all ECA (n=12). A helical flow pattern (at least moderate) was visible in 11/12 ICA. For the evaluated patient, degree of ICA stenosis was 70-95%. Luminal filling was none or mild in 4/5 ICA and restored to moderate or complete filling after revascularization (Table 1). Moreover, even typical moderate helical flow was restored after surgery. A moderate to complete filling of the vessel lumen was found in the contralateral ICA of 4/5 patients and in all ECA. Blood flow visualization and typical flow patterns of a healthy volunteer are displayed in Figure 1. Pre- and postoperative MR-angiography and corresponding 3D MRI blood flow visualization in a patient undergoing carotid endarterectomy with patch angioplasty are shown in Figure 2.

	Volunteer ICA (left & right)	Patient– pre op stenosed ICA	Patient – post op repaired ICA
Filling	2.7 +/- 0.5	1.0 +/- 0.7	2.8 +/- 0.4
Helix	2.3 +/- 0.7	1.0 +/- 0.0	2.0 +/- 1.0

Table 1: Summary of semi-quantitative ICA image grading for both volunteers and patients before and after revascularization.

Discussion: Our initial results demonstrate the feasibility of combined 3D MRI flow and anatomy measurement in both healthy volunteers and patients with high-grade ICA stenosis. By means of semi-quantitative evaluation a marked improvement due to revascularization with regard to restoration of absolute flow and physiological flow pattern (helix) could be demonstrated. Flow sensitive 4D MRI at 3T is a promising tool for an improved understanding of local hemodynamics (i.e., wall shear stress) and its influence for the development and progression of atherosclerotic plaques in the carotid bifurcation. Thus the precise characterization of flow patterns resulting from individual anatomical properties could help to identify patients at high risk for the development of carotid artery stenosis in further studies.

References: 1. Nonent M, et al. Stroke 2004;36:682-6. 2. Ku DN, et al. Ultrasound Med Biol 1985;11:13-26. 3. Markl M, et al. J Comput Assist Tomogr 2004;28:459-468. 4. Rothwell PM, et al. Stroke. 2003;34:514-23.