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 1 mm3 was used. Further, contrast-enhanced MR angiography (CE-MRA) was performed after injection of 0.05 ml/kg 0.5M Gadolinium contrast agent at 3.5 ml/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 =150 cm/s, spatial resolution 1.2 x 1.8 x 1.8 mm3 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 = 3.7 ms, TR = 6.1 ms, 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 postoperatively 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.

Results: Assessment 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.

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.