

4D Flow MRI in Arterio-Venous Malformations

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Introduction: Arterio-venous malformations (AVM) are an important cause of hemorrhagic stroke. AVM risk stratification is based on the Spetzler-Martin grade (SMG) combining information on AVM size, location, and venous drainage patterns¹. A high SMG, large AVM size, deep location, deep venous drainage, and flow-induced (arterial, nidus or venous) aneurysms are widely accepted as major risk factors. However, these parameters represent empirical measures and do not provide insights in individual AVM hemodynamic factors and their effect on clinical presentation (e.g. hemorrhage, ischemia, seizures)^{2,3}. AVM treatment often requires staged X-ray angiography guided embolization (interventional occlusion of AVM feeding arteries) and/or surgical resection^{4,5}. Selective iodine contrast injections provide excellent AVM vascular imaging and information on flow distribution. However, interventional procedures are associated with high radiation dose. Moreover, non-invasive pre-operative assessment or post-operative monitoring of embolization induced changes has been limited by the lack of imaging techniques to quantitatively measure flow with full coverage of the arterial feeders, draining veins, and within the AVM nidus itself. We investigated the feasibility of 4D flow MRI to gain further insights into AVM hemodynamics and to investigate the potential to monitor post-embolization changes in AVM vascularization and hemodynamics⁶⁻⁸.

Methods: 12 patients with AVM (age=38±13 years, 6 female) were examined using 1.5T and 3T MR systems (Avanto & Trio, Siemens, Germany). The study cohort included n=3 ruptured and n=8 unruptured AVMs with Spetzler-Martin grades SMG=1 (n=2), SMG=2 (n=5), SMG=3 (n=4), and SMG=4 (n=1). X-ray angiography demonstrated deep AVM location in 4 patients and deep venous drainage in 8 patients. Additional follow-up 4D flow MRI after interventional treatment by staged embolization was performed in 3 patients. ECG gated 4D flow MRI covering the AVM (axial 3D slab, venc=100cm/s, flip angle=15°, temp. res.=45ms, spatial res.=(1.2-1.6)mm³) was used to calculate a 3D PC-MR angiogram. AVM hemodynamics was visualized using time-resolved 3D pathlines originating from 15000-25000 emitter points equally distributed within the 3D-PC-MRA vessel lumen (EnSight, CEI, USA). For patients with follow-up 4D flow MRI after embolization, peak velocities were quantified in arterial feeders, draining veins, the sagittal sinus and contralateral arteries.

Results: Time-integrated pathlines (fig. 1) illustrate the complex distribution of blood flow inside the AVM and surrounding vessels for 9 patients with different AVM sizes, location, and draining patterns. AVM vascularization and intra-nidus velocity distribution could be clearly visualized even for large and highly complex lesions (figure 1 A,C,D,G) and variable AVM sizes and locations. Large deep and superficial draining veins were clearly identified in all cases. Note that blood flow velocities in the entire head were highly variable between patients. Particularly, venous blood flow velocities were substantially different and often unusually high (>30-50cm/s) compared to normal venous flow (15-25cm/s)⁹ in the sagittal and transverse sinuses.

For n=3 patients with follow-up after embolization, 4D flow analysis depicted substantial changes in AVM vascularization, velocity distribution and draining patterns as illustrated for an SMG=3 AVM in fig. 2. 3D pathlines demonstrate embolization induced changes including a successively more compact AVM with reduced blood flow velocities (fig. 2, yellow arrows). Similar results (compaction of AVM, altered velocity distribution) were seen in all 3 patients undergoing AVM treatment. Quantitative analysis (fig. 3) revealed marked changes in peak velocities in all vascular territories. Note that peak velocities were also changed in the sagittal sinus and contralateral arteries indicating the systemic impact of embolization therapy on cranial hemodynamics.

Discussion: 4D flow MRI revealed intricate vascularization of AVMs of different size, location, and severity as specified by the SMG. Different patterns of venous drainage with high variability in regional blood flow velocities indicate the complex nature of AVMs and the need for individual evaluation of flow characteristics. Moreover, we were able to identify changes in AVM hemodynamics following embolization demonstrating the sensitivity of the technique for comprehensive hemodynamic monitoring during therapy.

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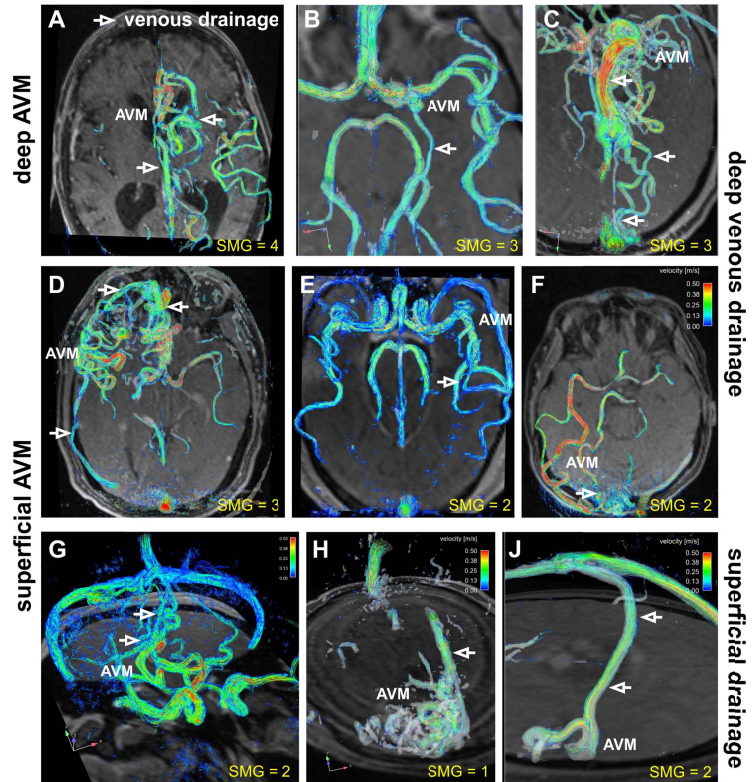


Fig. 1: AVM hemodynamics visualized by time-integrated 3D pathlines in 9 of 12 patients (A-J). Different AVM sizes and draining patterns (white arrows) can clearly be appreciated. A-C: Deep AVM location with high SMG and deep venous drainage. D-F: Superficial AVMs with deep venous drainage. G-J: Lowest risk AVMs with superficial draining veins. Color coding = absolute blood flow velocity

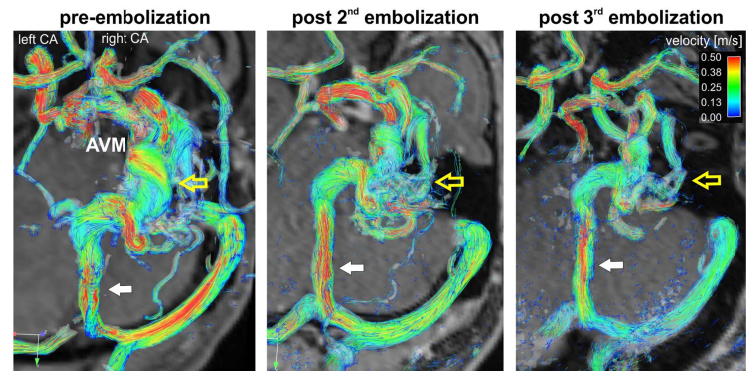


Fig. 2: 3D blood flow in a patient with a large non-ruptured AVM centered in the right mesial temporal lobe (SMG=3, size=4-5cm). Complex arterial feeding and convoluted hemodynamics in the AVM nidus as well as differences in pre-and post-embolization hemodynamics are clearly visible. Multiple embolization procedures resulted in a more compact AVM with reduced blood flow velocities (yellow arrows) and high draining velocities (white arrows).

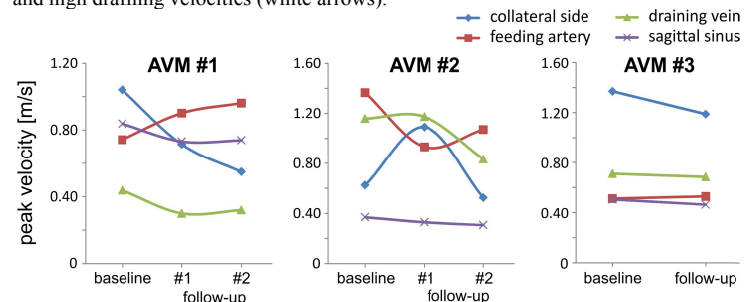


Fig. 3: Quantification of post-interventional changes in AVM hemodynamics based on 4D flow MRI after multiple (AVM 1 & 2) and one (AVM #3) embolization.