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Angaben zur Veröffentlichung / Publication details:

Vougioukas, V. I., C. J. Coulin, M. Shah, Ansgar Berlis, U. Hubbe, and V. Van Velthoven. 2006. "Benefits and limitations of image guidance in the surgical treatment of intracranial dural arteriovenous fistulas." *Acta Neurochirurgica* 148 (2): 145–53. https://doi.org/10.1007/s00701-005-0656-6.

Benefits and limitations of image guidance in the surgical treatment of intracranial dural arteriovenous fistulas

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Summary

Background. Despite major advances in endovascular embolization techniques, microsurgical resection remains a reliable and effective treatment modality for dural arteriovenous fistulas (DAVF). However, intraoperative detection of these lesions and identification of feeding arteries and draining veins can be challenging. In a series of 6 patients who were not candidates for definitive treatment by endovascular embolization we evaluated the benefits and limitations of computer-assisted image guidance for surgical ablation of DAVF.

Methods. Of the 6 patients, 5 presented with haemorrhage and one with seizures. Diagnosis of DAVF was made by conventional angiography and dynamic contrast enhanced MR angiography (CE-MRA). All patients were surgically treated with the assistance of a 3D high resolution T1-weighted MR data set and time-of-flight MR angiography (MRA) obtained for neuronavigation. Registration was based on cranial fiducials and image-guided surgery was performed with the navigation system.

Findings. Four of the 6 patients suffered from DAVF draining into the superior sagittal sinus, one fistula drained into paracavernous veins adjacent to the superior petrosal sinus and one patient had a pial fistula draining in the straight sinus. DAVF diagnosed with conventional angiography could be located on CE-MRA and MRA prior to surgery. MRI and MRA images were combined on the neuronavigation workstation and DAVF were located intraoperatively by using a tracking device. In 4 out of 6 cases neuronavigation was used for direct intraoperative identification of DAVF. Brain shift prevented direct tracking of pathological vessels in the other 2 cases, where navigation could only be used to assist craniotomy. Microsurgical dissection and coagulation of the fistulas led to complete cure in all patients as confirmed by angiography.

Conclusions. Neuronavigation may be used as an additional tool for microsurgical treatment of DAVF. However, in this small series of 6 cases, surgical procedures have not been substantially altered by the use of the neuronavigation system. Image guidance has been beneficial for the location of small, superficially located DAVF, whereas a navigated approach to deep-seated lesions was less accurate due to the familiar problem of brain shift and brain retraction during surgery.

* Both authors equally contributed to this work.

Surgical and endovascular treatment of symptomatic dural arteriovenous fistulas (DAVF) remains challenging. Nevertheless, our understanding of the etiology, pathology and clinical course of these vascular malformations has greatly increased over the past decades, mainly due to the development and evolution of modern imaging techniques. Most fistulas appear to be acquired, caused by venous hypertension, trauma or surgical manipulation. Genetic factors affecting the coagulation system, post-traumatic or post-operative neovascularisation and hormonal changes during pregnancy seem to influence DAVF formation [10, 11, 18, 28, 33]. It has been noted that venous drainage patterns are the most important predictors of clinical course and patient outcome and several classifications for DAVF have been proposed based on that observation [3, 5]. The natural course of DAVF varies and ranges from benign lesions without symptoms or with mild symptoms (e.g. tinnitus) to aggressively behaving fistulas that present with haemorrhage and severe neurological deficits [2, 8, 9]. Definitive treatment of this kind of DAVF is required to prevent patients from suffering major brain damage. The goal of therapy has to be complete closure of the fistula. A number of different treatment modalities have been used, the most efficient being surgical removal and endovascular transarterial or transvenous embolization of the DAVF [7, 12, 16, 22].

Microsurgical treatment of DAVF is based on identification of the pathological vessels, followed by careful dissection of feeding arteries and draining veins. Pathological vessels are then obliterated by coagulation (small vessels) or clip ligation (larger vessels). Eventually the devascularized nidus is excised and sent to pathology. Various reports emphasize that, depending on the subtype of DAVF, exclusive division of leptomeningeal venous drainage can be sufficient for microsurgical treatment [7, 13, 30]. The advantages and disadvantages of endovascular versus surgical treatment have to be carefully evaluated for each patient. Moreover, there are still a considerable number of cases where endovascular ablation is not feasible [19].

Recent studies emphasize the fact that microsurgical treatment of DAVF is a safe and efficient therapeutic option in the hands of an experienced surgeon [32]. Furthermore, there have been reports on the advantages of image-guided resection of cerebrovascular lesions [20, 21, 26, 35]. Shorter operating times, smaller craniotomies and smaller amounts of intraoperative blood loss have been discussed as benefits of computer-assisted microsurgical treatment of cerebro-vascular malformations. We used a frameless stereotaxy system for microsurgical treatment of dural arteriovenous fistulas at different locations, testing the benefits and limitations of image-guided microsurgery for this particular type of vascular malformation.

Clinical material

Patients

Five Patients with DAVF (Patients 2–5) and one patient with a pial AVF (Patient 1) were treated microsurgically with the help of image guidance at our institution between 2001 and 2004. Patient characteristics are summarized in Table 1. Five patients initially presented with cerebral haemorrhage: Four patients suffered from supratentorial subarachnoid (Patients 1 and 5) or intracerebral haemorrhage (Patients 2 and 6) and one patient displayed cerebellar haemorrhage (Patient 4). One patient initially presented with seizures (Patient 3). Intracranial haemorrhage was detected by computed tomographic (CT) scanning or MRI. Two patients additionally showed focal neurologic deficits on admission: Patient 2 had discrete right facial nerve palsy and Patient 4 had left hemiparesis. All patients underwent six-vessel cerebral angiography leading to diagnosis of DAVF or pial AVF. Four fistulas were located near the superior sagittal sinus, one drained into paracavernous veins and the superior petrosal sinus and one was located at the tentorial notch draining in the straight sinus. Fistula location and arterial supply are detailed in Table 1. Lesions on the convexity with contact to the outer brain surface were considered "superficial" DAVF, whereas tentorial DAVF or lesions nearer to the skull base where called "deep" (Table 1). Prior to treatment every case was discussed by a neurosurgeon (VVV) and an interventional neuroradiologist (AB). Endovascular and surgical therapeutic options were evaluated based on the clinical and angiographic presentation of the DAVF, with special attention to venous draining patterns, fistula location and presence of venous varices. In 4 cases preoperative endovascular treatment was attempted but was only partially successful (Table 1).

Surgical planning and image guidance system

Diagnosis of DAVF was made by conventional cerebral digital subtraction angiography (DSA). Preoperatively the following MR examination routine was carried out: TOF-MRA (time-of- flight-MRA), dynamic contrast enhanced MRA, 3D high resolution T1-weighted MR imaging (MP-RAGE, effective thickness 1 mm), pre- and postcon-

Table 1. *Clinical summary of 5 patients with dural and 1 patient with pial arteriovenous fistula treated with image-guided microsurgical excision*

Patient no.	Age (yr)/sex	Clinical presentation	Location (superficial vs deep)	Arterial supply	Venous drainage	Preoperative embolization	Angiographic results	Outcome/ follow up (mo)
1	49/F	hemorrhage	occipital (superficial)	left PCA, left MCA*	SSS	yes	cure	asymptomatic/6
2	21/F	hemorrhage	frontal (deep)	right ICA	paracavernous/ SP	no	cure	asymptomatic/6
3	47/M	seizures	bifrontal (superficial)	right OA, both OCA, left MMA	SSS	yes	cure	asymptomatic/9
4	62/M	hemorrhage	tentorial (deep)	left AICA, left MMA	straight sinus	yes	cure	mild residual post-hemorrhage symptoms/12
5	70/M	hemorrhage	parietal (superficial)	both ECA, both OCA, left MMA	cortical veins/ SSS	yes	cure	asymptomatic/21
6	60/M	hemorrhage	parietal (superficial)	both OCA, both MMA, both VA	subarachnoid veins/SSS	no	cure	asymptomatic/3

AICA Anterior inferior cerebellary artery, *ECA* external carotid artery, *ICA* internal carotid artery, *MCA* middle cerebral artery, *MMA* middle meningeal artery, *OA* ophthalmic artery, *OCA* occipital artery, *PCA* posterior cerebral artery, *SP* superior petrous sinus, *SSS* superior sagittal sinus, *VA* vertebral artery, *Pial fistula.

trast T1-weighted images and T2-weighted images at a 1.5 Tesla MR scanner (*Siemens Magnetom Vision*). Prior to MR imaging 6 cranial fiducial markers were placed on the external surface of the skull with skin adhesive at standard positions: Three fiducials were placed on the forehead, one on each mastoid process and one on the bregma. MR images were then transferred to the neuronavigation workstation for processing by data transfer via intranet. All DAVF could be visualized on TOF-MRA and dynamic CE-MRA by the presence of pathologically dilated draining veins or by detection of the fistula point. In most cases, high-intensity vascular formations adjacent to dural sinus walls or in the immediate vicinity of late-filling venous structures could be identified, indicating the presence of multiple arterial feeders. On the workstation, MP-RAGE were processed to create three-dimensional reconstructed images for surgical planning and intraoperative image guidance. TOF-MRA data was digitally integrated with the 3D-reconstruction images to optimize navigated intraoperative DAVF identification. Dynamic CE-MRA as well as conventional angiography served as plausibility control. For neuronavigation the Stryker Navigation system (*Stryker Instruments*, *Kalamazoo*, *MI*) was used.

Surgical procedure

After induction of general anesthesia the patient head was fixed in the Mayfield clamp. The pointing device was then calibrated by successive registration of each fiducial on the patient head and comparison with the 3D-reconstructed and axial MRI on the computer screen. The location of the craniotomy was chosen according to the position of the DAVF as determined on plain angiographic films and MR sequences and was confirmed with the neuronavigation system. For the patient with the tentorial notch DAVF (Patient 4, Fig. 4) a suboccipital craniotomy with a lateral infratentorial supracerebellar approach was performed. The paracavernous fistula (Patient 2) was approached by a pterional craniotomy. After craniotomy and opening of the dura, the pointing device was placed on the cortical surface to determine the amount of brain shift occurring after craniotomy. The trajectory leading to the fistula was then determined with the help of the neuronavigation system. The position of the fistula point and draining veins were confirmed by image guidance when the suspected pathological vessels were visible. DAVF were excised by proximal and distal coagulation and/or clipping and the excised tissue was sent for pathology.

Results

Microsurgical resection of DAVF was successful in all cases and led to complete obstruction of the fistulas as shown on postoperative cerebral angiograms (Patients 1, 3–6). Patient 2 was pregnant (11 weeks of gestation) when acute severe intracranial haemorrhage from a right frontal DAVF occurred. After careful evaluation of the risk of repeat haemorrhage surgery was performed despite the early pregnancy. Surgical ablation of the DAVF was confirmed by postoperative TOF-MRA, CE-MRA and conventional angiography was postponed until after delivery.

No technical difficulties related to the navigation system occurred during the surgical procedures. Brain shift as determined by comparison with the indicated position of the pointer on the screen was acceptable (<3 mm) for Patients 1, 3, 5 and 6. However, accuracy was low (>5 mm) for Patients 2 and 4, who had deep-seated DAVF which required brain retraction during surgery. Superficial fistulas could easily be located using the navigation pointing device (Patients 1, 3, 5, 6; Figs. 1–3). However, navigation accuracy was below average for Patient 2 with an anterior fossa DAVF draining into deep paracavernous veins and Patient 4 (Fig. 4) with a tentorial DAVF. Secondary to brain retraction and brain shift, image guidance was less efficient and the pointing device could only be used to determine the trajectory leading to the fistula in these patients. Setting up of the neuronavigation workstation and calibration of the pointing device did not consume more than 20 minutes in each case and was mostly done during patient positioning and preparation. Mean operating time was 190 minutes (skin incision to skin sutures) and blood loss was minimal. Neither patient position – sitting (Patient 4), prone (Patient 1) or supine (Patients 2, 3, 5, 6) – during surgery nor craniotomy location (suboccipital, frontal or pterional) had significant influence on the accuracy and efficiency of image guidance. No surgical complications occurred. Clinical outcome was excellent for Patients 1, 3, 5 and 6, who were asymptomatic before and after surgery and on follow-up examinations. Patient 4, who initially presented with severe left cerebellar and intraventricular haemorrhage and left hemiparesis, had persistent mild hemiparesis postoperatively and became shunt-dependend due to post-hemorrhagic hydrocephalus several weeks after surgery. The initial right facial nerve palsy of Patient 2 resolved postoperatively and was no longer noted on follow-up examination.

Case illustration

This 49-year-old woman (Patient 1) had suffered from recurrent episodes of strong headaches prior to admission. After acute subarachnoid haemorrhage (SAH) with somnolence cranial computed tomography (CCT) was performed and revealed extensive SAH around the basal cisterns and interhemispherically. A right external ventricular drain was placed. Digital subtraction angiography was performed in cardiopulmonary and neurologically stable condition, showing a very small left occipital pial arteriovenous fistula located in close proximity to the tentorium and transverse sinus with high flow arterial feeders from an occipito-temporal branch of the left posterior cerebral artery (PCA) and drainage by a cortical vein into the superior sagittal sinus (Fig. 1A, C). An attempt to treat endovascularly via a transarterial approach to the distal feeding branch of the PCA failed.

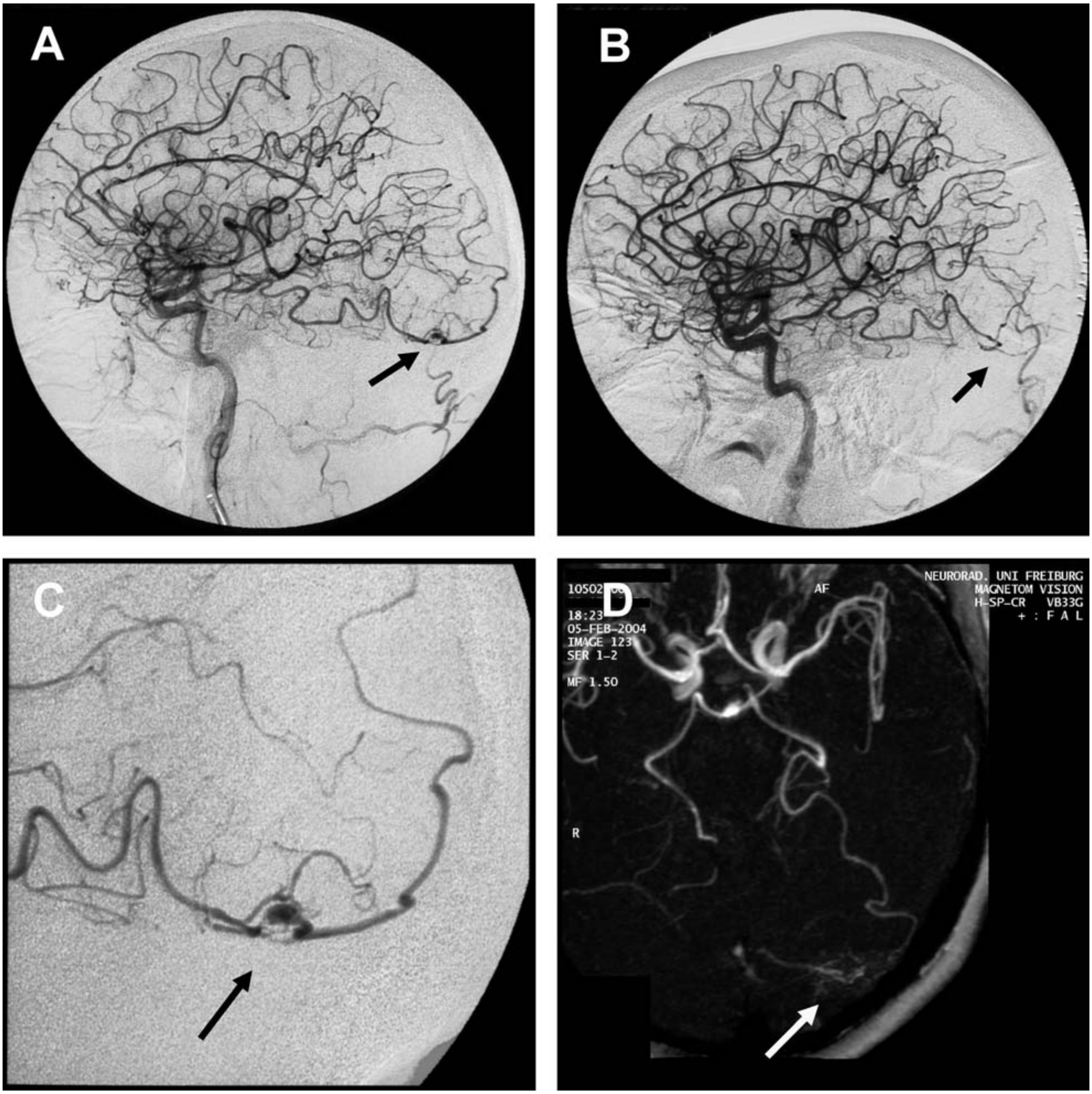


Fig. 1. A 49-year-old woman with a left occipital pial arteriovenous fistula (Patient 1). (A) Preoperative angiogram (lateral view), showing the fistula (arrow) fed by a left posterior cerebral artery branch. (B) Postoperative angiogram showing complete resection of the fistula. (C) Close-up view of the fistula shown in A. (D) TOF-MRA showing the left occipital pial arteriovenous fistula (arrow)

TOF-MRA was obtained, which showed the left PCA and the fistula point (Fig. 1D). The fistula point was estimated on MP-RAGE and the data were transferred to the neuronavigation workstation for intraoperative image guidance. Surgery was performed with the patient in the prone position. A left occipital craniotomy was performed using the pointing device to estimate fistula location prior to dural incision. After dural incision the fistula point was again located by neuronavigation. The feeding artery was found to extend from the pial surface to the tentorium. Successively the fistula point was coagulated and excised from the sinus wall. The aneurysmatic venous part of the fistula point was coagulated close to the brain surface and dissected from the tentorium. The patient had an uneventful postoperative course and did not display any neurological deficits on discharge. Postoperative cerebral angiography showed complete resection of the DAVF (Fig. 1B).

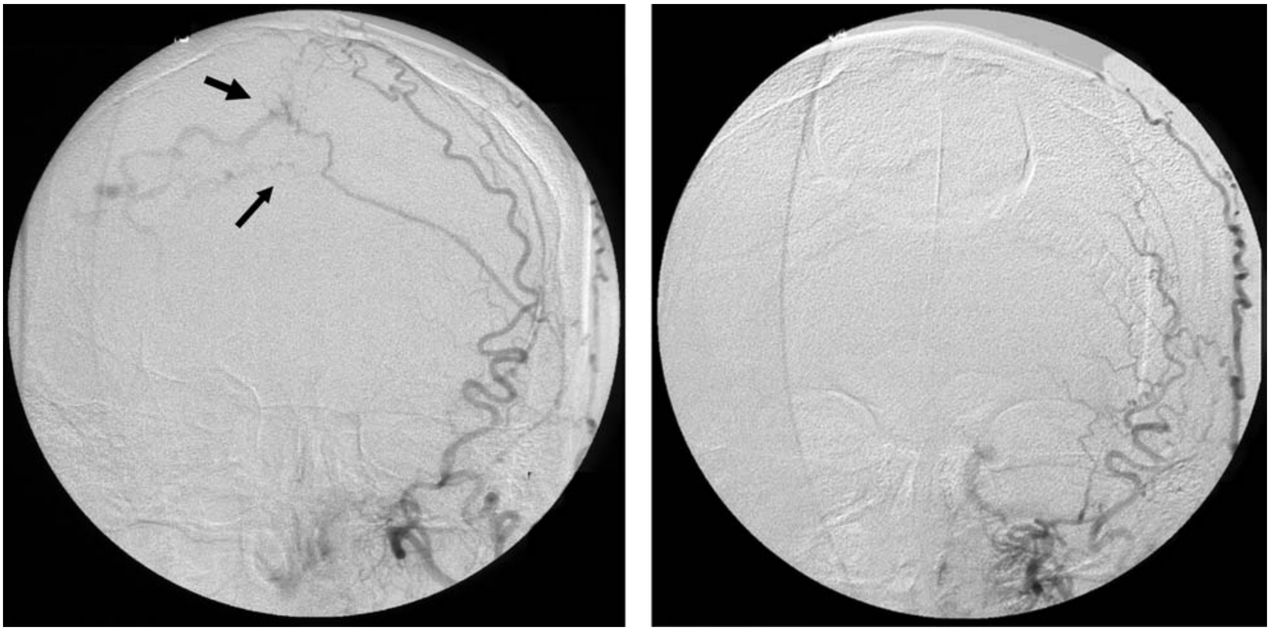


Fig. 2. Cerebral angiograms of a 60-year-old man with a right parietal parasagittal DAVF (Patient 6). (*Left*) Preoperative angiogram of left external carotid artery (anteroposterior view) showing drainage into the superior sagittal sinus and dilated elongated cortical veins. Note that there are two fistula points, one in the vicinity of the lambdoid suture and another very small fistula point 2–3 cm rostral to the suture (arrows). (*Right*) Postoperative angiogram with complete obstruction of the DAVF

Discussion

Surgical treatment of DAVF

Most intracerebral dural arteriovenous fistulas are rather benign vascular lesions. Yet a considerable number of DAVF display an aggressive nature, presenting with severe intracerebral haemorrhage and neurological deficits. Along with the increase in knowledge about DAVF, transarterial and transvenous embolisation techniques have been established and described as alternatives to microsurgical treatment of DAVF with high success rates and good clinical outcome [14, 16, 27]. However, feasability and success rates of endovascular techniques depend on a number of factors, such as fistula location, draining patterns and initial clinical presentation, and there is a considerable number of DAVF where endovascular treatment alone does not lead to satisfactory therapeutic results [19].

Since surgical ablation of DAVF remains one of the most important treatment modalities, efforts should be directed towards optimizing the precision, efficacy and reliability of surgical procedures. Computer-assisted image guidance has been established over the past years as a valuable new technique in neurosurgery and the usefulness of neuronavigation has been described for a wide array of neurosurgical procedures, including vascular neurosurgery [21, 35]. The surgical treatment of arteriovenous malformations (AVM) with the help of image guidance has been previously described by different authors [20, 26, 31]. Use of frameless stereotaxy for surgical ablation of DAVF has been suggested previously [1]. The aim of this study was to assess the benefits and limitations of neuronavigation in assisting microsurgical ablation of DAVF.

Superficial vs deep DAVF

In this series, image guidance was used to surgically treat DAVF at various intracranial locations. Different patient positions during surgery and craniotomy sites were chosen according to DAVF location. Image guidance was helpful in determining the trajectory leading to the fistula in all cases. However, we found that neuronavigation was more efficient in assisting surgery of superficial DAVF (see Case Illustration, Figs. 1–3). For superficial lesions brain shift and brain retraction were minimal and therefore the pointing device could be used to identify arterial feeders and draining veins visible on MR-Angiography. In contrast, deep-seated lesions (Patients 2 and 4) could not be tracked directly with the navigation system since considerable brain shift had occurred secondary to the surgical approach which

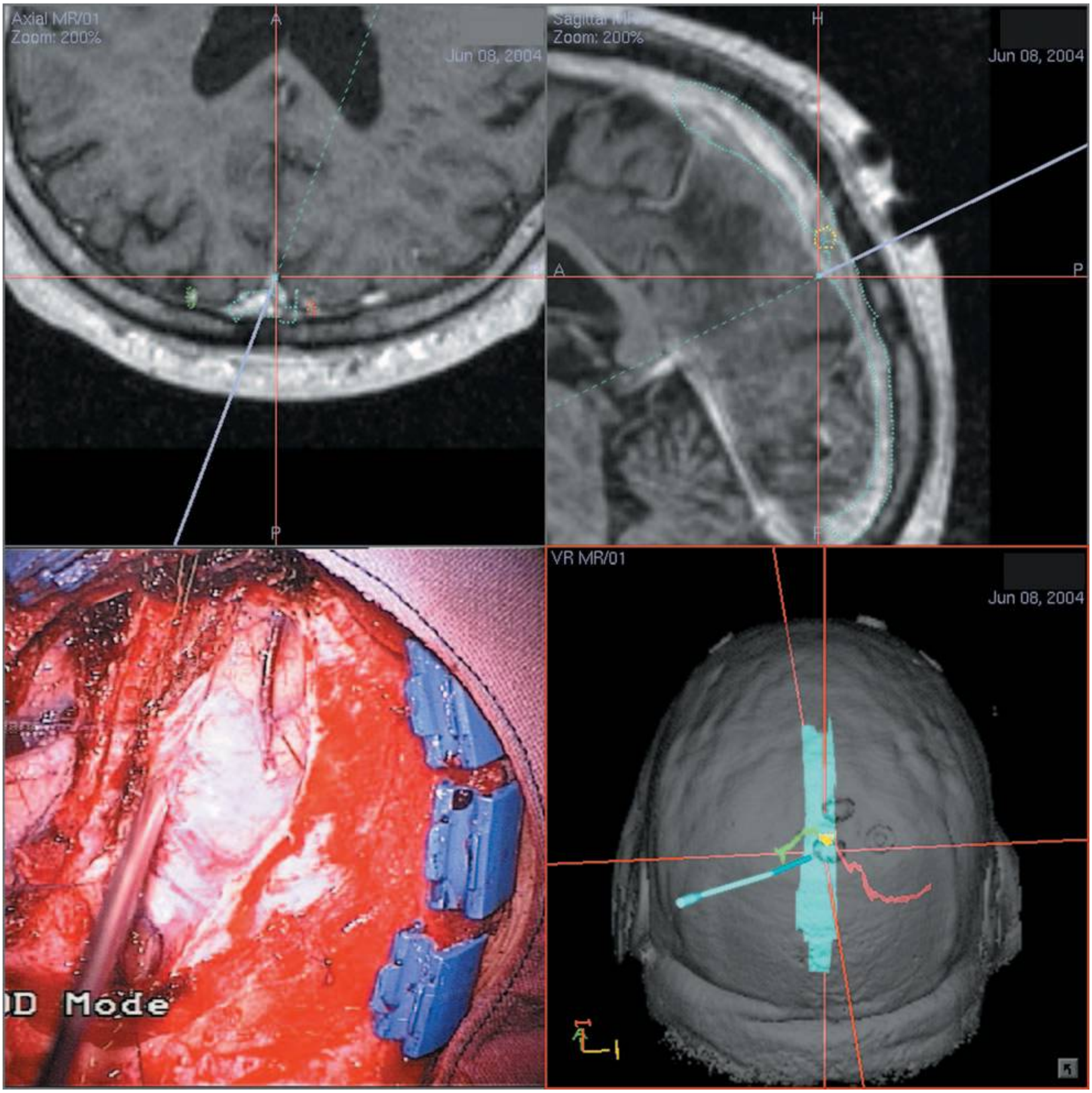
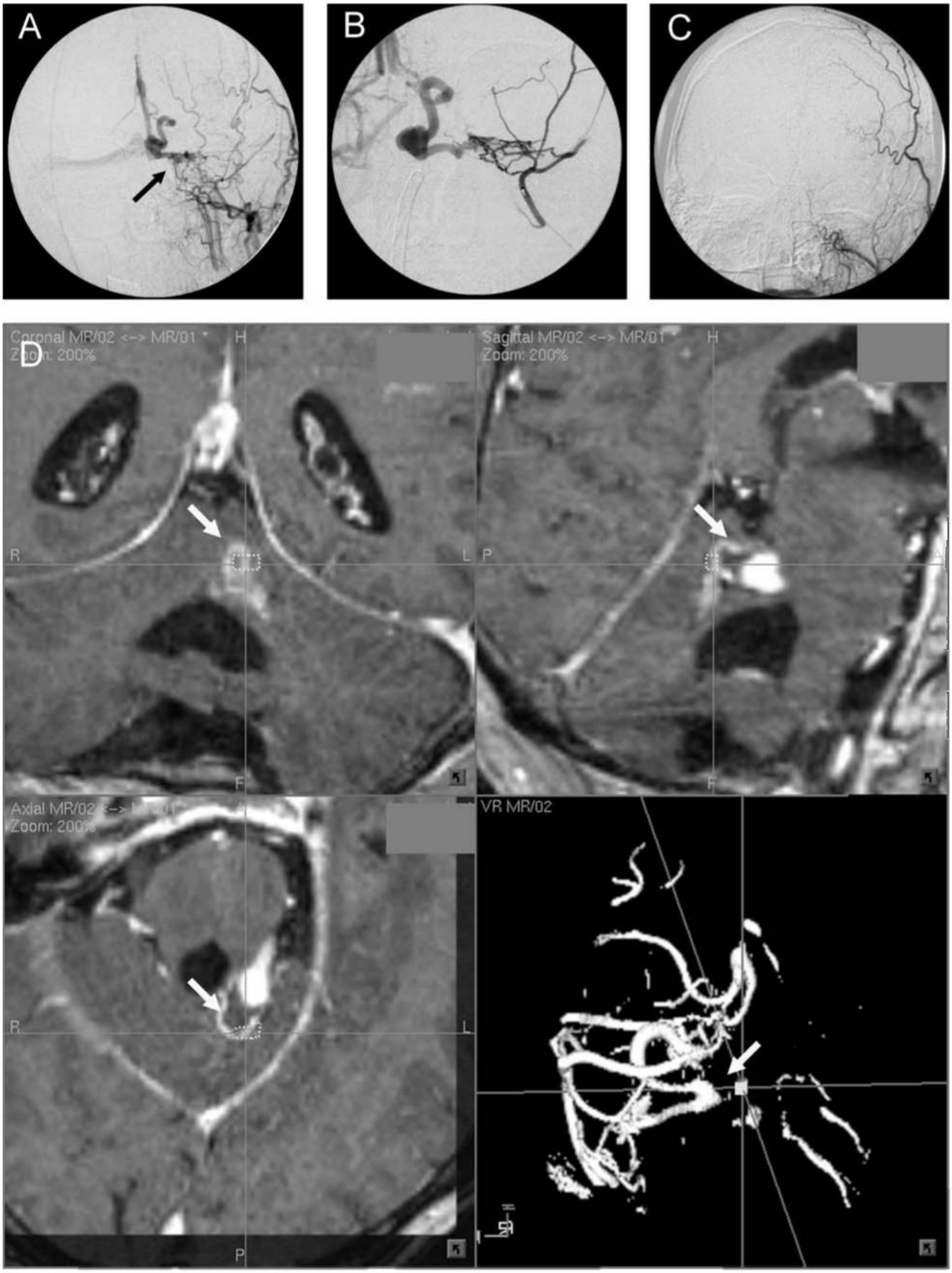


Fig. 3. Patient 6. High resolution 3D data set (MP-RAGE) with reconstructed biplanar MR-images (*top*), and 3D image of the cranial surface (*bottom right*), and intraoperative photograph (*bottom left*). DAVF location is marked yellow, superior sagittal sinus in blue, dilated draining veins are traced in green and pink. The trajectory leading to the DAVF that was used for neuronavigation is indicated on the MR images. The intraoperative situation with the navigation tracker on the operation site is shown on the photograph

required retraction. Similar observations have been published by Sisti *et al.* [29], who used frame-based stereotaxy for resection of deep AVMs of small size. This is in contrast to results published by Russell *et al.*, who used image guidance for surgical treatment of arterio-venous malformations and found the benefits of frameless

Fig. 4. Patient 4, a 62-year-old patient presenting with severe cerebellar haemorrhage. (*A*) Preoperative angiogram. Anteroposterior view of left external carotid artery showing a complex tentorial DAVF (arrow) draining in the straight sinus with feeders from the left middle meningeal artery and the left anterior inferior cerebellary artery (not shown). (*B*) Enlarged view of *A* with microcatheter positioned in the left middle menigeal artery. (*C*) Postoperative angiogram showing complete obstruction of the fistula. (*D*) Reconstructed MP-RAGE (*top*, *bottom left*) and MRA image (*bottom right*) used for intraoperative neuronavigation. The dilated draining vein (arrow on A, B) is clearly visible on MR images as well as on TOF-MRA and was used for preoperative planning and craniotomy performance. However, due to significant intraoperative brain shift, the dilated DAVF draining vein could not be tracked intraoperatively with the navigation pointer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stereotaxy most helpful for small, deep-seated arteriovenous malformations [26].

Benefits and limitations of image guidance

Visualization of the pathology on MR or CT images is a prerequisite for the efficient use of image guidance in microneurosurgery. To date, diagnosis of DAVF is still mostly based on conventional digital subtraction angiography (DSA). So far, conventional angiographic images have not been routinely integrated in neuronavigation workstations. Moreover, unlike AVM, DAVF are usually small in size and may consist of only a few pathological vessels that are not easily identified on T1- or T2 weighted MRI. However, there are promising reports about detection of DAVF with MR-Angiography [6, 15, 23, 34], especially with dynamic CE-MRA [17]. We thus used TOF-MR-Angiography which can easily be transferred to the workstation to visualize pathological vessels and provide accurate localisation of DAVF (Fig. 4D). In our series, all DAVF were identified on TOF-MR-Angiography by detection of arterial feeders and/or pathologically dilated veins. However, the fistula point as represented by nodular high-intensity vascular structures adjacent to pathologically dilated veins and/or early filling of the adjacent dural venous sinus could only be seen on TOF-MR-Angiography for Patient 1 (Fig. 1D). Similar to results published by Noguchi *et al.* [23], retrograde cortical venous drainage as seen with DSA could not be visualized on TOF-MR-Angiography but could be detected with dynamic CE-MRA. However, similar to conventional angiography, dynamic CE-MRA could not be transferred to the workstation because of absence of a 3D data set. Advances in neuro-imaging with dynamic 3D CE-MRA would be helpful for exact localisation of the fistula point. Moreover, there have been previous reports about superimposition of DSA and MRI images on the same PC workstation [24, 25], which would also be benefitial in intraoperative localisation of DAVF and improve the accuracy of image guidance. Another possible approach to intraoperative identification of DAVF would be integration of computed tomographic angiography (CTA) data in the neuronavigation workstation as has been described for small cerebral arteriovenous malformations with large hematomas by Coenen *et al.* [4]. Unfortunately, these superimposition techniques were not available in our department.

The overall additional benefits of image guidance in the microsurgical treatment of DAVF were found to be rather small. Superficial lesions can be identified by visual inspection if the craniotomy site is chosen appropriately based on angiographic and MRI data obtained preoperatively. Navigation-assisted determination of the trajectory leading to the lesion and location of the fistula point are an additional clue, however, identification and microsurgical dissection of the arteriovenous fistula at the operative site still largely depends on the clinical experience of the surgeon, since the majority of pathological vessels are not clearly demonstrated on the present imaging data and can not readily be identified with the tracking device, even more so if the lesion is deep-seated and significant brain shift occurs during the operation.

Conclusions

The main benefit of image guidance for the surgical treatment of DAVF is improvement of the planning precision and accuracy of surgical procedures. The additional benefit of image guidance depends on the fistula location and was most pronounced in assisting microsurgical ablation of superficial DAVF. In this series, image guidance did not significantly alter the overall course, duration or efficiency of the surgical procedures.

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