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CLINICAL ARTICLE - VASCULAR

Intraoperative angiography reloaded: a new hybrid operating theater for combined endovascular and surgical treatment of cerebral arteriovenous malformations: a pilot study on 25 patients

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Abstract
Background Multimodality treatment suites for patients with cerebral arteriovenous malformations (AVM) have recently become available. This study was designed to evaluate feasibility, safety and impact on treatment of a new intraoperative flat-panel (FP) based integrated surgical and imaging suite for combined endovascular and surgical treatment of cerebral AVM.
Methods Twenty-five patients with AVMs to treat with combined endovascular and surgical interventions were prospectively enrolled in this consecutive case series. The hybrid suite allows combined endovascular and surgical approaches with intraoperative scanner-like imaging (XperCT®) and intraoperative 3D rotational angiography (3D-RA). The impact of intraoperative multimodal imaging on feasibility, workflow of combined interventions, surgery, and unexpected imaging findings were analyzed.
Results Twenty-five patients (mean age 38±18.6 year) with a median Spetzler-Martin grade 2 AVM (range 1–4) underwent combined endovascular and surgical procedures. Sixteen patients presented with a ruptured AVM and nine with an unruptured AVM. In 16 % (n=4) of cases, intraoperative imaging visualized AVM remnants ≤3 mm and allowed for completion of the resections in the same sessions. Complete resection was confirmed in all n=16 patients who had follow-up angiography one year after surgery so far. All diagnostic and therapeutical steps, including angiographic control, were performed without having to move the patients
Conclusion The hybrid neurointerventional suite was shown to be a safe and useful setup which allowed for unconstrained combined microsurgical and neuroradiological workflow. It reduces the need for extraoperative angiographic controls and subsequent potential surgical revisions a second time, as small AVM remnants can be detected with high security.

Keywords Intraoperative angiography · Cerebral arteriovenous malformations · Image guided surgery · Endovascular and surgical suite · Neurovascular surgery

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Introduction

Hemorrhage after incomplete surgical resection of brain arteriovenous malformations (AVMs) is an equally rare and feared complication. Nowadays, postoperative angiographic control imaging is usually performed in patients treated for neurovascular diseases such as AVMs, aneurysms, and arteriovenous (AV) fistulas [3, 13, 15, 23]. The widely available 2D-angiography in operating theaters has limited resolution. Nevertheless, it is considered in many centers as an acceptable intraoperative imaging technique [6, 7, 10, 11, 15, 19, 20], as three-dimensional rotational angiography 3D-RA is usually not directly accessible during surgery in most hospital settings. Thus, to obtain a high-resolution 3D-RA, surgery needs to be terminated and the patient transferred to dedicated neurointerventional suites. Flat panel (FP) technology should allow overcoming those restrictions to limited access and with functional limitations. The aim of this study is to evaluate the feasibility, safety and the impact on treatment of a hybrid operating theater, based on FP technology and 3D-RA for combined endovascular and surgical treatment of patients with cerebral AVMs.

Methods

Twenty-five patients, admitted from April 2008 to February 2011, with cerebral AVMs were prospectively included in this consecutive case series. Clinical data including age, location of AVM, Spetzler-Martin grade, hospitalization time, preoperative and postoperative clinical neurological status, clinical and imaging follow-up, and outcome were recorded. Technical workflow, unexpected angiographic findings, imaging modalities, intraoperative complications, radiation dose, and impact of intraoperative imaging on treatment were assessed.

Technology

The described operating theater is equipped with a ceiling-mounted monoplane FP detector (Allura FD 20®, Philips, Best, The Netherlands), a frameless neuronavigation system (Kolibri®, BrainLab AG, Feldkirchen, Germany), and an operating microscope equipped for intraoperative indocyanine-green (ICG) videoangiography (Pentero®, Carl Zeiss Surgical AG, Oberkochern, Germany). The core part of the integrated imaging and surgical suite is a monoplane FP-detector allowing intraoperative angiography with 3D-RA and 320 or 640 projections around 270° with a rotational speed of 30° or 55° per second. The FP-detector is coupled to a frameless neuronavigation system to facilitate intraoperative data transfer. Intraoperative FP-CT imaging (XperCT®, Philips, Best, The Netherlands) may be acquired for vascular and bone imaging. Brain tissue resolution of FP CT is inferior to standard CT. Both intraoperative angiography with 3D-RA, and XperCT® can be performed at any time during surgery without moving the patient to another table or position. This allows the surgeon and neurointerventional radiologist to work simultaneously, if considered necessary. Neuronavigation can be updated at any time by coregistration with intraoperative 3D-RA or XperCT® datasets. Additional draping of the operation site is needed as the flat-panel detector moves around the patient's head (Fig. 1). The halo of the head fixation device is removed to reduce artefacts when performing an intraoperative 3D-RA or XperCT®. Vascular structures, or AVM remnants can be segmented from intraoperative angiography, 3D-RA and FP-CT datasets (iPlan® 3.0, BrainLab AG, Feldkirchen, Germany), and then be transferred to navigation (Kolibri®,

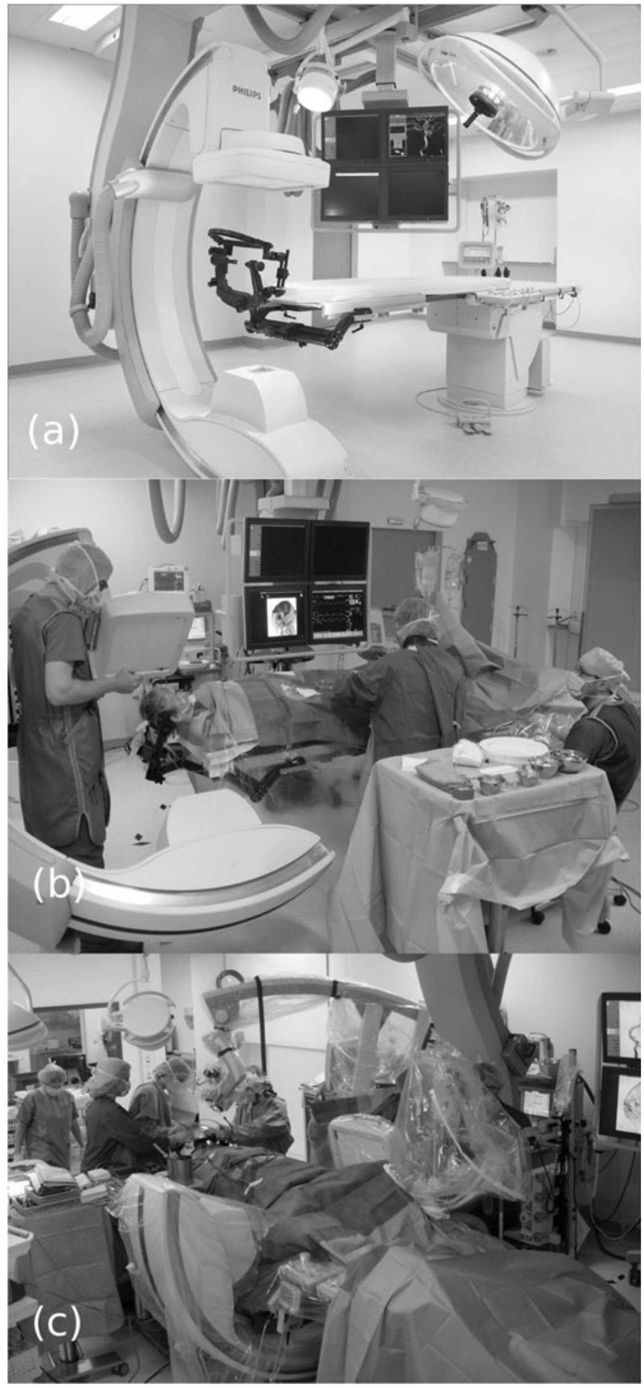

Fig. 1 **a** Hybrid interventional room setup; **b** preparations for combined intervention with the patient positioned on angiography table, the head fixed in a carbon fiber head holder. **c** Setup during surgical part of intervention

BrainLab AG, Feldkirchen, Germany), in order to localize, i.e., have AVM remnants in situ.

Workflow

A multidisciplinary approach for the treatment of cerebral AVMs was used under consideration of the general condition of the patient. Our criteria to stop preoperative embolization were as follows : 1. Stagnation in the main venous drainage vessels. 2. No sufficient large arterial feeders. 3. Difficult venous approach for retrograde embolization. The percentage of embolization was not taken into account for the decision when to stop the embolization procedure.

Patients were positioned for surgery on a modified angiography table. Patients with cerebellar/occipital AVMs were operated in the prone position. The access for the intraoperative angiography was performed obviously before in the supine position. Before turning the patient from supine to prone position, a long femoral introducer was inserted. Theoretically, as alternative, the humoral or radial arteries could be accessed during surgery in the prone position.

A radiolucent carbon fiber head holder (DORO®, Promedics GmbH, Düsseldorf, Germany) was chosen to minimize artefacts in intraoperative imaging data (Fig. 1a). A full spectrum of 3D-RA or XperCT® was available for all patients positioning for surgery except for the sitting position. Positioning of the patient was only limited by the necessity to keep the patient's head close to the C-arm isocenter. The draping procedure was adapted to guarantee optimal sterile conditions for both endovascular and surgical interventions. The procedure started with the introduction of a 5-French femoral sheath that is flushed with saline 0,9 %. All imaging, endovascular interventions and surgeries can be performed sequentially or in parallel without the necessity to move the patient. Usually, a 3D-RA was acquired before surgery, providing vascular imaging information already with the patient positioned for surgery. After a resumed AVM resection, the neurointerventional team performs intraoperative 3D-RA for resection control with the craniotomy site still open. Once complete resection is confirmed by angiography/3D-RA, the craniotomy is closed and the patient transferred to the intensive care unit (ICU).

Results

A total of 25 patients, nine patients harboring unruptured AVM and 16 patients with ruptured AVM, underwent combined endovascular and surgical interventions at the University Hospital of Geneva with intraoperative 3D-RA in the hybrid suite. Patient characteristics are summarized in Table 1. The majority of patients underwent primary surgery (68 %) before an eventual interventional treatment; this concerned mainly the ruptured group. There were $N=8$ (32 %) of the patients who had preoperative embolization before ($N=4$, 16 %) or in the same session, always prior to surgery (Table 2).

All patients underwent angiographic control one year after surgery to avoid false-negative findings [15]. A local wound infection (4 %) occurred in one patient fve days after surgery treated by surgical wound revision.

Unruptured AVM group

Nine patients with an unruptured AVM underwent treatment in the hybrid suite. Of these, six patients underwent primary surgery and one patient underwent endovascular embolization with Onyx first and subsequent surgical resection in the same session. Two patients had partial embolization of AVM in separate sessions prior to surgery (five days and two months before surgery, respectively). The ICG-videoangiography and intraoperative 3D-RA have been performed in all patients for resection control after careful inspection of the resection cavity for remnants. In two patients (22 %), intraoperative 3D-RA revealed unexpected AVM remnants despite negative ICG-angiography. Both AVM remnants could then be resected in the same surgical session with a second intraoperative 3D-RA confirming a complete AVM resection (Table 2).

Ruptured AVM group

Sixteen patients with ruptured AVM underwent interventions in the hybrid suite. A primary neurosurgical intervention was performed for the majority of these patients ($n=11$). Three patients underwent a combined endovascular embolization with Onyx and surgical resection in the same session and two patients had surgery after previous embolization (with a delay between the last embolization and surgery of eight days and six months, respectively). Intraoperative 3D-RA showed unexpected AVM remnants in two patients (13 %). Both AVM remnants were resected and subsequent intraoperative angiography and 3D-RA confirmed complete resection in both cases. In one of the patients of the ruptured AVM group, intraoperative angiography revealed an aneurysm of the medial posterior choroidal artery, not associated with the AVM, and next to the ICH. The aneurysm was trapped in the same session using the intraoperative 3D-RA for image guidance. Retrospective review of imaging showed that the aneurysm was not visible on initial angiography and 3D-RA due to hematoma compression.

Experience with workflow and setup, radiation dose

No complications occurred due to the described workflow or a patient's positioning. Changing from open surgery to angiography or vice versa with additional draping, removal of halo support and instrumentation was uniformly performed in 20 min. Segmentation, data transfer to neuronavigation, image fusion and adding data in the microscope took less than 5 min

Table 1 Patient's characteristics

	All patients (n=25)	Patients with unruptured AVMs (n=9)	Patients with ruptured AVMs (n=16)
Mean Age (years)	38±18.6	39±18	38±19
Gender: Male/Female	13/12	2/7	11/5
Spetzler-Martin Grading Median (Range)	2 (1;4)	2 (1;4)	2 (1;4)
AVM in eloquent areas	5 (20 %)	2 (22 %)	3 (19 %)
Deep venous drainage	8 (%)	2 (22 %)	6 (38 %)
Size (1–3 mm, 3–6 mm, 6–9 mm)	19; 5; 1	6; 2; 1	13; 3; 0
Localisation			
Frontal	8 (32 %)	4 (44 %)	4 (25 %)
Temporal	4 (16 %)	1 (11 %)	3 (19 %)
Parietal	7 (28 %)	2 (22 %)	5 (31 %)
Occipital	2 (8 %)	1 (11 %)	1 (6 %)
Cerebellar	4 (16 %)	1 (11 %)	3 (19 %)
Initial symptoms/focal deficit on admission			
Headache	7 (28 %)	3 (33 %)	4 (25 %)
Seizure	3 (12 %)	3 (33 %)	0
No symptoms/incidental	3 (12 %)	3 (33 %)	0
Loss of consciousness/somnolence	9 (36 %)	0	9 (56 %)
Disorientation	2 (8 %)	0	2 (13 %)
Hemianopsia	1 (4 %)	0	1 (6 %)
Focal neurological deficit due to surgery			
Transient	5 (20 %)	3 (33 %)	2 (13 %)
Permanent	1 (4 %)	1 (11 %)	0
Mean hospitalisation (days ± stdv)	16.6±13.7	12.8±9.8	18.6±15.5
Mortality at 3 months	1 (4 %)	0	1 (6 %)
mRankin at 3 months (median, range)	1 (1–6)	1 (1–5)	2 (1–6)

per intraoperatively acquired dataset. The mean radiation dose was 189 (±210) mSv. No procedure-related complications were encountered. The mean radiation dose for diagnostic procedures only was 95 (±59.8) mSv.

Table 2 Procedures and intraoperative imaging

	All patients (n=25)	Patients with unruptured AVMs (n=9)	Patients with ruptured AVMs (n=16)
Procedures			
Primary surgery	17 (68 %)	6 (67 %)	11 (69 %)
Combined embolization and surgery in same session	4 (16 %)	1 (11 %)	3 (19 %)
Embolization and surgery in 2nd session	4 (16 %)	2 (22 %)	2 (13 %)
Intraoperative 3D-RA	All patients	All patients	All patients
Intraoperative 3D-RA findings			
AVM remnant	4 (16 %)	2 (22 %)	2 (13 %)
Discovery of aneurysm	1 (4 %)	1 (11 %)	0
Complete resection rate of AVM	100 %	100 %	100 %
Intraoperative FP-CT	5 (20 %)	2 (22 %)	3 (19 %)
Overall radiation dose (mSv)	189±210	213±128	171±259
Radiation dose for diagnostic angiography only (mSv)	113±61	147.4±73.1	95.3±48.7

Illustrative case 1

A 39-year old patient presented with multiple secondarily generalized seizures and a left temporal Spetzler-Martin grade IV AVM (Fig. 2a). The patient underwent diagnostic angiography, where the angioarchitecture showed a large dilatated vein with several intranidal aneurysms. Main arterial feeders were posterior temporal branches of the posterior cerebral artery (PCA) and temporal branches of the medial cerebral artery (MCA). The patient underwent one session of embolization, whereby 65 % of the AVM could be occluded (Fig. 2b). The patient was readmitted for a second embolization followed by surgery in the same session. Embolization and surgery were uneventful; inspection and ICG-videoangiography revealed no AVM remnants or suspicious bleeding. Intraoperative angiography with 3D-RA was performed and showed a small AVM remnant somewhat distant from the excised nidus fed by a small temporal branch of the MCA (Fig. 2c, small arrows). The 3D-RA data were transferred to navigation, segmented and injected to the microscope. The AVM remnant was easily localized with neuronavigation and resected. A second intraoperative 3D-RA showed complete resection of the AVM (Fig. 2d). No decreases of motor evoked potentials (MEPs) were observed during surgery.

Illustrative case 2 - emergency craniotomy

A 47-year-old patient sustained a right temporal ICH with significant mass effect and mesencephalic compression from a ruptured temporal Spetzler-Martin grade II AVM. He was admitted for loss of consciousness and motor deficits to a peripheral hospital. An angio-CT was transferred online from the peripheral hospital. Directly upon admission, the patient was transferred to the hybrid operating theater for diagnostic 3D-RA (Fig. 3a). The angioarchitecture showed arterial feeders from the MCA and a superficial venous drainage. During diagnostic 3D-RA, open craniotomy was prepared, and subsequently the hematoma evacuated and the AVM resected. Microscopic control of the resection cavity revealed no remnants and ICG-videoangiography was negative. Intraoperative angiography confirmed complete resection (Fig. 3b).

Discussion

Multidisciplinary treatment of patients with cerebral AVMs was evaluated for feasibility, safety and the impact on treatment in 25 patients. Intraoperative angiography with 3D-RA revealed unexpected findings of AVM remnants and led to complementary resections in four patients. A complete AVM removal, confirmed by intraoperative angiography, has been

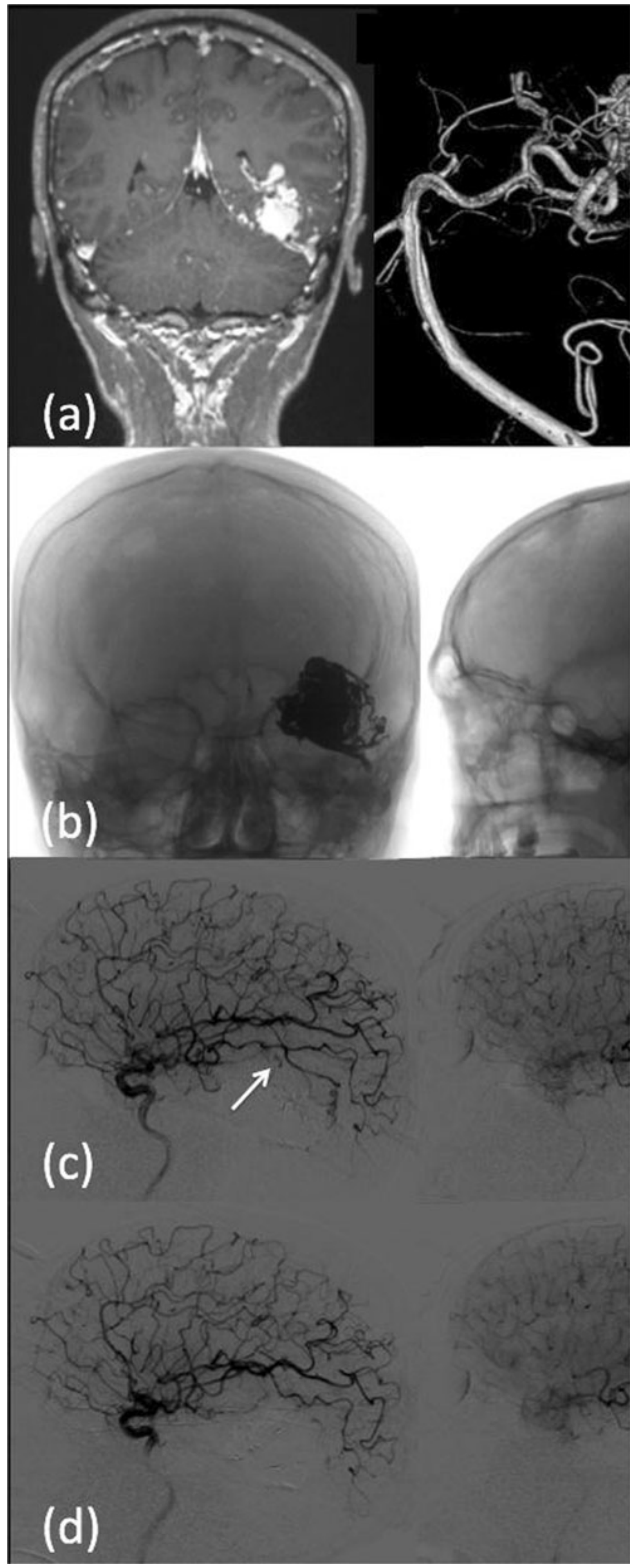

Fig. 2 Illustrative case 1: **a** Diagnostic 3D-RA and preoperative IRM showing angioarchitecture of a left temporal AVM Spetzler-Martin grade IV; several intranidal aneurysms are located around a dilated vein; **b** AVM after partial embolization; **c** Intraoperative control angiography showing a small AVM remnant; **d** 2nd intraoperative control angiography after complementary resection in the same session

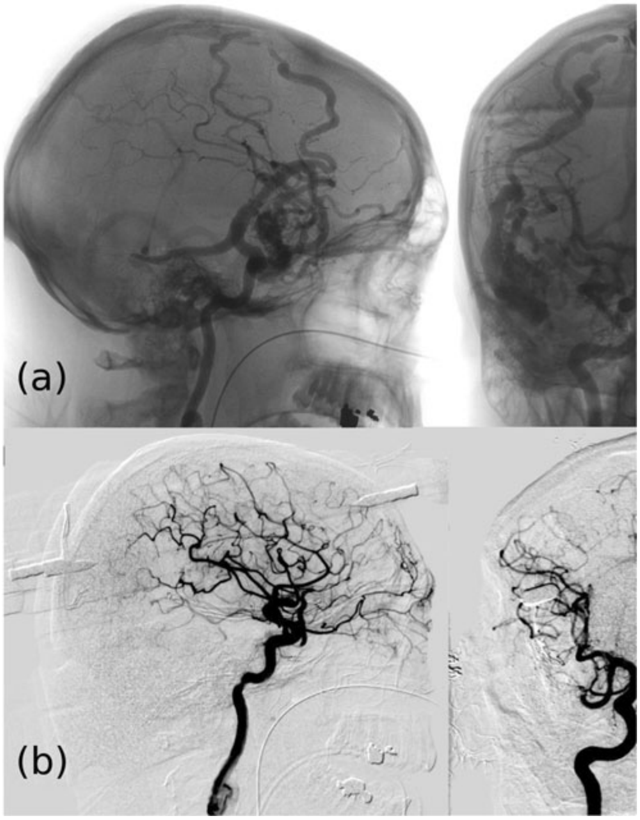

Fig. 3 Illustrative case 2: **a** 3D-RA of a ruptured temporal AVM Spetzler-Martin grade II; preoperative 3D-RA with the patient already positioned for surgery; **b** intraoperative angiography after resection confirmed complete AVM removal

achieved in all cases in the same surgical session. The combined treatment in the hybrid FP suite was of particular usefulness in two patients who had arrived in acutely critical neurological states following AVM rupture. Here, the dedicated setup had allowed for diagnosis and assessment of the size of the intracerebral hemorrhage by Xper-CT, for fast analysis of the AVM angiostructure by 3D-RA, emergency treatment by microsurgical removal of the ICH and the AVM, and for final control – all without the necessity for additional transport of the patient.

In general, the actual incidence of incomplete surgical resection of AVMs is not well-documented in the literature. The moderately elevated incidence of intraoperatively diagnosed small AVM remnants in our series (16 %) is in contrast to its previously reported incidence in large AVM series, where 1.8–8 % of residual AVM are reported on postoperative 2D-DSA [9, 16]. A higher incidence of AVM remnants (up to 21.4 %) has been reported after total AVM resection by Derdeyn [3]. This discrepancy may be caused by several factors. First, the number of patients reported in our study is small. Second, the reported incidence of 1.8 to 8 % in the literature is based on postoperative 2D-DSA studies. The four detected AVM remnants in our study were all smaller or equal to 3 mm. One could question that sensitivity of 2D-DSA and 3D-RA for the detection of small postoperative AVM remnants could differ and, thus, small remnants were missed on 2D-DSA if they were overlying with other vessels in the same plane. Sensitivity analysis comparing 3D RA and 2D DSA with larger patient numbers would be needed in order to test this hypothesis.

It is unclear whether the lack of perioperative high-resolution 3D-RA has an influence on the degree and completeness of resection. Intraoperative high-resolution 3D-RA, neuronavigation and pre-embolization may also allow for more tailored AVM resection of AVMs in eloquent brain areas. The risk for permanent postoperative neurological deficit was reported to be 14.8 % for eloquently localized Spetzler-Martin °III AVMs [4]. Thus, one may be more hesitant to go for primary aggressive perinidal resection if high-resolution intraoperative 3D-RA imaging is available for precise intraoperative control.

General considerations

The role of intraoperative 2D-angiography for surgery of cerebral AVMs and aneurysms has been previously described [3, 5, 12, 22]. While the use of intraoperative magnetic resonance imaging (iMRI) is an established and widespread method for brain tumor surgery, literature on hybrid concepts for combined endovascular and surgical suites is rare [2, 17–19]. Multidisciplinary neurovascular treatment of cerebral AVM has become standard of practice [8], whereas integrated angiography systems for multidisciplinary treatment in the operating theater are not routinely used in clinical practice so far. The concept of a hybrid room solution for treatment of neurovascular diseases that allows neurosurgeons and interventional neuroradiologists to combine endovascular techniques and surgical procedures is a logical step and appears straightforward. The advantages are immediate postoperative angiographic controls with an open craniotomy, and with the possibility for immediate revision if unexpected AVM remnants are found, and in sparing a second operation with the related burden for the patient. The present setting facilitates uncomplicated combined surgical and endovascular treatment. The workflow is very efficient since intubated patients do not need to be transferred between different imaging and interventional, or surgical, facilities, as usually required for multidisciplinary treatment of cerebral AVM. Additionally, known associated complications of intrahospital transfer of critically ill patients [1, 14, 24] are minimized.

There is an increasing use of intraoperative ICG-angiography for detection of AVM remnants. The ICG-angiography was negative in our series in two cases with unruptured AVMs because of their small size. As shown by Killory et al., intraoperative angiography showed residual AVM in two of ten patients (20 %) requiring further resection of AVM not visualized during surgery by ICG-angiography [11]. They concluded that ICG angiography is recommended as a complement rather than as a replacement of DSA. In a more recent study, Tagagi and collegues report the benefits specially detecting the nidus while the feeders were seen only in three of nine cases predissection [21]. Probably the high use of ICG-angiography in this study (27 times in 11 patients) increased the sensitivity of this method. In our opinion, difficulties in visualization of remnants in ICG-angiography are generally due to the small size, as suggested, not to a deeper location.

Technical considerations of FP technology

The described operating theater is equipped with a ceiling-mounted monoplane FP detector. For visualization of the AVM using Onyx, as used in the present study, a two view embolization technique is recommended. Onyx density is high and is rapidly opaque to X-rays [19]. To assess a complete AVM occlusion, multiple projections are needed. The two simultaneous projections technique is necessary when reflux in eloquent vessels that may be hidden in the embolisation shadow is feared. When designing the hybrid theatre, a mono-plane FP detector was favored over a biplane angiographic suite because of the important difference in space occupation between the two apparatus.

Dehdashti et al. [2] described a surgical suite with an angiography table moving from the operating position to imaging position into the gantry of a conventional biplane rotational angiography. Six patients harboring AVM have been operated on in this pilot setup. In one patient, a small residual AVM could be identified intraoperatively and required further resection. The completeness of treatment was confirmed on intraoperative 3D rotational angiography in all cases, and there were no procedure-related complications. The tested setup proved to be safe and reliable for combined surgical and neurointerventional treatment of cerebral AVMs. In our series no adverse events due to the particular combined neuroradiological and neurosurgical setups were observed. In this study, the availability of intraoperative 3D-RA and intraoperative XperCT® allowed for diagnosis and adaption of surgical strategy without additional risks to the procedural patient's safety. Furthermore, XperCT is available at any time during surgery and can be used to rule out major complications like significant bleeding or edema formation.

A major advantage of a combined interventional and surgical suite is the management of all vascular emergency interventions as illustrated by the second patient. Patients suffering from a ruptured AVM with ICH and mass effect can be transferred for diagnostic CT and angiography, followed immediately by an emergency intervention in the hybrid suite, either surgical or endovascular, without delay in time. Additional diagnostic procedures such as CT, perfusion CT as well as AVM occlusion/resection and, if necessary, CT-guided, external ventricular drainage placement can be performed instantly in the same setting, on the same table, thereby saving important time. The patient enters the hybrid room, and all aspects of diagnostics and treatment can be taken care of.

Conclusion

The described interdisciplinary FP-based hybrid joint surgical and neuroradiological setting allows for a new perspective of joint endovascular and surgical treatment with high quality intraoperative imaging. It is a safe, reliable setup and beneficial for the management of AVMs in terms of the peri-interventional workflow, detection of unexpected AVM remnants and tailored image-guided AVM resection, especially in eloquent areas. It minimizes the need for extraoperative post-operative angiographic controls, helps to avoid rebleeding from unexpected AVM residuals and saves time on patient transport between facilities, especially in emergency situations. Such kind of hybrid rooms may stipulate changes of workflow in the care of neurovascular emergencies in the overall hospital setting. Further investigations are needed to define the state-of-the-art intraoperative imaging suite for joint neurovascular interventions beyond the treatment of cerebral AVMs.

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Conflicts of interest None.

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