Intraoperative Flow Measurement by Microflow Probe During Surgery for Brain Arteriovenous Malformations

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Received, December 22, 2014.
Accepted, February 16, 2015.
Published Online, March 23, 2015.

BACKGROUND: Intraoperative quantitative flow measurement by a microvascular ultrasonic flow probe is an established methodology in aneurysm surgery.
OBJECTIVE: To test the present flow measurement procedure in brain arteriovenous malformation (AVM) surgery.
METHODS: Data from 25 patients with brain AVMs who consecutively underwent microsurgical resection with the assistance of flow measurement by a microflow probe were retrospectively analyzed. Flowmetry was performed on arterial feeders, potentially transit arteries, and venous drainage of AVM in different phases of resection.
RESULTS: A quantitative flow measurement was performed 203 times on 92 vessels. Flowmetry was able to define the flow direction of AVM vessels in all cases, thereby discriminating between arterial feeders and venous drainages, both superficially and deeply located. During AVM dissection, flowmetry identified a transit artery in 12% of cases by detecting a flow drop between 2 points of the same vessel. At the final stage of resection, a residual nidus, potentially missed at surgical dissection, was detected when the flow value of venous drainage was greater than 4 mL/min (20% of patients). Pre-resection microflow probe measurements were concordant with indocyanine green videoangiography data on AVM angioarchitecture in all cases. No microflow probe–induced AVM vessel injury was reported. Complete AVM resection was achieved in all cases with a low morbidity (modified Rankin Scale score ≤1).
CONCLUSION: Multistage intraoperative quantitative flow measurement proved to be a feasible, safe, repeatable, and reliable methodology to assist surgery in different phases of AVM resection. Further studies are needed to assess the impact of this approach on AVM patient outcomes.

KEY WORDS: Brain arteriovenous malformation, Microsurgery, Cerebrovascular surgery, Flow measurement, Microflow probe, Flowmetry

Operative Neurosurgery 11:268–273, 2015 DOI: 10.1227/NEU.0000000000000741

Intraoperative quantitative flow measurement by a microflow probe is a validated technique in aneurysm surgery to detect flow reduction during microsurgical clipping. Its role is to minimize possible ischemic complications, thereby improving the clinical outcome of patients.[1-5] Intraoperative flow measurement has already been applied in settings other than aneurysm surgery,[6,7] but it has not been systematically reported in surgery for brain AVMs (bAVMs).[5,8] Reports on flow-assisted AVM surgery included semiquantitative assessment,[9] arterial feeder pressure evaluation,[10,11] and flow velocity recording by Doppler sonography.[12,13] Unlike previous devices, microflow measurement provides quantitative data on vessel flow. We performed intraoperative systematic quantitative flow measurements in 25 bAVM patients undergoing surgical resection. Our aim was to assess the feasibility and reliability of the technique in bAVM surgery. To our knowledge, this is the first systematic study on the intraoperative application of the microvascular ultrasonic flow probe in bAVM patients.

ABBREVIATIONS: AVM, arteriovenous malformation; **bAVM,** brain arteriovenous malformation; **DSA,** digital subtraction angiography; **ICG-VA,** indocyanine green videoangiography; **mRS,** modified Rankin Scale; **SM,** Spetzler Martin

METHODS

Patients and AVMs

Data from patients with bAVMs who underwent surgical resection from March to October 2014 in our department with the assistance of quantitative flow measurement by microflow probe and indocyanine green videoangiography (ICG-VA) were retrospectively analyzed. Both techniques are routinely used in our department in vascular and oncologic surgery[3,6-8,14] and are included on the institutional informed consent form. AVM grade was defined according to the Spetzler Martin (SM) AVM grading scale,[15] based on preoperative digital subtraction angiography (DSA) and magnetic resonance imaging. AVMs were considered "bleeding" when previous bleeding was reported in clinical or radiological records. Data on previous embolization were also recorded. Intraoperative data on flow value and direction were reviewed in all cases. Pre-resection ICG-VA data were then compared with microflow probe data to assess the reliability of flow direction assessment. The preoperative and postoperative (1 month after surgery) modified Rankin Scale (mRS) scores were compiled in all cases to assess patient outcome. Postoperative resection results were assessed by DSA.

Intraoperative Flow Measurements

Vascular flow was measured using a microvascular ultrasonic flow probe (Charbel Micro-flow Probe; Transonic Systems, Inc, Ithaca, New York). This device consists of an electronic flow detection unit and a flow-sensing perivascular probe. Flow measurements appear as a digital display on the detection unit. To evaluate vascular flow, the probe uses the principle of ultrasonic transit time.[2] Flow measurements were performed (1) before resection, after ICG-VA, on cortical both arterial feeders and venous drainages; (2) during dissection on the same vessels when it was considered relevant or on different vessels detected during dissection (deep vessels) or on possible transit arteries; (3) at the end of surgical resection, on venous drainage before section. In all cases, the flow assessment was performed; after that, all arterial feeders and all minor venous drainages were sectioned.

In all cases, both flow direction and value were recorded. Three different diameter ultrasonic flow probes (1.5 mm, 2 mm, and 3 mm) were used according to vessel diameter. Generally, a 3-mm diameter flow probe was suitable for large veins and a 1.5-mm or 2-mm diameter flow probe for arterial feeders and for small venous drainages. End-tidal carbon dioxide (CO_2) and mean arterial blood pressure values were also recorded to determine the stability of anesthetic conditions and thus the comparability of the measurements. Flow data were compared with ICG-VA findings. Any vessel injury by a microflow probe was recorded: minor injury if vessel sacrifice was not required and major injury if the vessel was sacrificed.

RESULTS

Patients and AVMs

Twenty-five patients were enrolled in the study (Table 1); the mean age was 42 years (range, 19-71 years). The mean preoperative mRS score was 0.08 (2 of 25 patients presented with an mRS score of 1). Twenty-three patients presented with a ruptured lesion and 2 with an unruptured AVM. No cases of bleeding AVMs operated on in the acute phase were enrolled in the study. AVMs were supratentorial in 22 and infratentorial in 3 cases. SM grade was I in 7 patients, II in 9 patients, III in 8 patients, and IV in 1 patient.[15] The AVM had been previously embolized in 10 cases.

Intraoperative Flow Measurements

Intraoperative flow measurements are summarized in Table 2. A total of 203 quantitative flow measurements were performed on 92 vessels: 87 before, 88 during, and 28 at the end of resection. The procedure was used in all patients (25 patients) before resection, in 19 patients during resection, and in 18 patients at the end of resection (before permanent venous drainage closure) when it was feasible and safe. Indeed, in few cases of AVMs with deep venous drainages, especially if located in the posterior cranial fossa, the venous drainage flow was not thought safe and feasible to measure at the final stage of resection.

1. Before resection, arterial feeder flow ranged from 3 to 80 mL/min, and median flow was 31 mL/min. Venous drainage flow ranged from 7 to 114 mL/min, and median flow was 45 mL/min. In all cases, flowmetry was able to discriminate between arterial feeders and venous drainages, by indicating flow direction. This was particularly helpful where the flow was quicker and the ICG-VA data were more difficult to interpret. Arterial feeder flow in previously embolized AVMs ranged from 5 to 37 mL/min, whereas venous drainage flow ranged from 8 to 47 mL/min. In AVMs not previously embolized, arterial feeder flow ranged from 3 to 60 mL/min, whereas venous drainage flow ranged from 6 to 114 mL/min. Arterial feeders showed different values depending on SM AVM grade. In all cases, the measurement was helpful for understanding the AVM angioarchitecture by distinguishing between arteries and veins (flow direction) and guiding surgical planning (quantitative flow measurements). The vein flow quantity in AVMs with multiple draining veins helped identify the secondary draining veins (lower flow quantity) that were

TABLE 1. Arteriovenous Malformation Features and Outcome[a]

No. of patients	25
Mean age, y (range)	42 (19-71)
Sex, M/F	11/14
Spetzler-Martin grade	
I	7
II	9
III	8
IV	1
No. of previous bleeding AVMs	23
No. of preoperative embolizations	10
Mean preoperative mRS score	0.08
Mean postoperative mRS score	0.16
DSA resection rate, %	100

[a]M/F, male/female; AVMs, arteriovenous malformations; mRS, modified Rankin Scale; DSA, digital subtraction angiography.

TABLE 2. Intraoperative Flow Data (Spetzler Martin)[a]

	Flow Value, mL/min, Median (Range)	
	Arterial Feeders	Venous Drainages
Total flow measurements, total vessels explored	26 (2-80)	34 (3-114)
Before resection	31 (3-80)	45 (7-114)
During resection	12 (3-36)	21 (2-67)
At the end of resection	—	5 (−1 to +12)
SM grade		
I	6 (3-10)	14 (6-30)
II	27 (3-60)	42 (32-114)
III	19 (5-26)	33 (28-100)
IV	18 (7-37)	25 (14-39)
Ruptured AVM	28 (3-74)	34 (6-114)
Unruptured AVM	26 (3-80)	39 (8-98)
Preoperative embolization	21 (5-37)	33 (8-47)
No preoperative embolization	32 (3-60)	43 (6-114)

[a]SM, Spetzler Martin; AVM, arteriovenous malformation.

sacrificed safely, when needed, during the resection without precipitating AVM rupture.[16] In 7 cases, flow data provided by flowmetry clarified ICG-VA data.

2. During dissection, it was helpful to discriminate between deep arterial feeders and venous drainages not exposed at the beginning of resection whenever present. The flow of these deep vessels, measured in all cases after partial AVM dissection and deafferentation, ranged from 3 to 36 mL/min for arterial feeders and from 2 to 67 mL/min for venous drainages. The flow drop along the length of an apparently transit artery could be predictive of en passage vessels to the AVM in 3 cases. The flow drop ranged from 4 to 11 mL/min.
3. In the final stage of resection, before venous drainage section, the flow measurement of venous drainage showed a flow higher than 4 mL/min (range, 12-4 mL/min) in 5 cases in which a residual nidus missed at surgical dissection was then detected. The final flow measurement, when the drainage was sectioned, showed flow data between 1 and −1 mL/min values in all cases.

Minor injury from a vessel (6 venous drainages, 1 artery) during flow measurement was recorded in 7 patients. In all cases, it consisted of minor bleeding easily controlled with low-power coagulation and gentle pressure without final vessel sacrifice or flow decrease at assessment with the microflow probe. No major vessel injury was detected.

Patient Outcomes

No remnants were reported at postoperative DSA after resection. No permanent neurological deficit leading to an mRS score >1 was reported in any of the patients enrolled. Conversely, an mRS score of 1 was reported in 2 patients with SM grades II and III AVM with a preoperative mRS score of 0.

DISCUSSION

Major Results

Before resection, the flow measurement was reliable for understanding the AVM angioarchitecture in all cases, guiding surgical planning and AVM resection. In fact, there was total concordance between ICG-VA and flowmetry findings on flow direction in all superficial vessels. In 7 cases, microflow probe flow data helped to clarify ICG-VA data: indeed, the AVM angioarchitecture was not completely clear on videoangiography for different reasons such as large AVM volume or deep location (interhemispheric) (Figures 1E and 2G). In 76% of cases (19/25 patients), flowmetry was helpful during resection to discriminate between deep small feeders and venous drainages (Figures 1 and 2). In 12% of cases (3/25 patients), a major flow drop between 2 points of the same artery was recorded in the same stage of surgery, even if no apparent change in vessel diameter was evident. In all 3 cases, further dissection revealed a deep afferent artery to the nidus with take off from the transit artery between the points of the previous measurements (Figures 1E-1G). This is an interesting finding considering that identification and preservation of en passage vessels has a major role in improving clinical outcomes in AVM patients.[8,17] At the final stage of resection, 20% of cases (5/25 patients) had persistent flow at drainage vein assessment despite apparent complete AVM dissection. This was helpful in disclosing a residual nidus missed at surgical resection (Figures 2M-2O). Quantitative flow measurement of venous drainage in AVM surgery has been suggested as a potential way to assess the completeness of AVM resection.[5,8] Indeed, an absence of flow in the draining vein confirms that all the arterial feeders have been interrupted, thereby allowing safe section of the drainage and a complete resection of the AVM. If a draining vein is due to be sectioned at a late stage of surgery when flow in the vein is deemed venous (the vein "turned blue") but before all afferents have been sectioned, this could result in significant bleeding. In addition, small AVM remnants are the main cause of postoperative bleeding after AVM resection.[12,17] Finally, microflow probe data changed our surgical planning in 32% of cases: 12% sparing the transit artery plus 20% of further final dissection of the AVM nidus before main venous drainage section.

Limits and Advantages of the Technique

Flow measurement by microflow probe was feasible and safe with no major procedure-related damage and only a slightly longer surgery time. The different flow probe diameters proved suitable for the different diameters of the vessels encountered. We were comfortable using 1.5-mm diameter flow probes for most of the arterial feeders and 3-mm diameter flow probes for the larger veins. Use of the microflow probe in AVM surgery presented some limitations. First, the very small diameter of deep vessels made most of them unsuitable for measurement. This is a well-known issue already reported in aneurysm surgery where ICG-VA proved more useful.[18] Second, assessment must be done in fragile venous drainages that can be potentially injured during the maneuver. However, gentle temporary pressure on the bleeding vessel, sometimes associated with low-power coagulation, achieved hemostasis without vessel sacrifice in all patients in our cohort. Third, final stage venous drainage flow measurement in deep, especially posterior fossa, AVMs is feasible and safe in most, but not all, cases. Some major advantages were noted. First, flow assessment could be repeated when needed. This was the case for vessels managed during dissection whose function had to be checked repeatedly for difficult dissection (Figures 2I-2L) and to identify transit arteries (Figures 1E-1G). Flowmetry was useful to show the direction of flow when ICG-VA data were unclear. This was particularly important when approaching high-flow AVM due to the high quick flow through the malformation. Another advantage of flowmetry was to check the flow of deep vessels not completely exposed in the surgical field (Figures 1 and 2). This issue is particularly interesting given the well-known limits of ICG-VA in deeply located AVMs.[19,20]

Case Illustration of Intraoperative Microflow Probe Application

A 41-year-old male patient presented with a right parietal grade III AVM according to SM classification (Figures 2 and 3). The patient was operated on in while in the supine position with his head rotated on the left side. After the right paramedian parietal craniotomy was performed, dura was opened as far as the interhemispheric fissure and the AVM was exposed under the microscope (Figure 2B). Before starting AVM dissection, ICG-VA showed the AVM angioarchitecture (Figure 2C). Flow assessment with the Microflow probe on different vessels, already shown by ICG-VA, was then performed to have baseline flow data and to evaluate doubtful ICG-VA data, as illustrated in

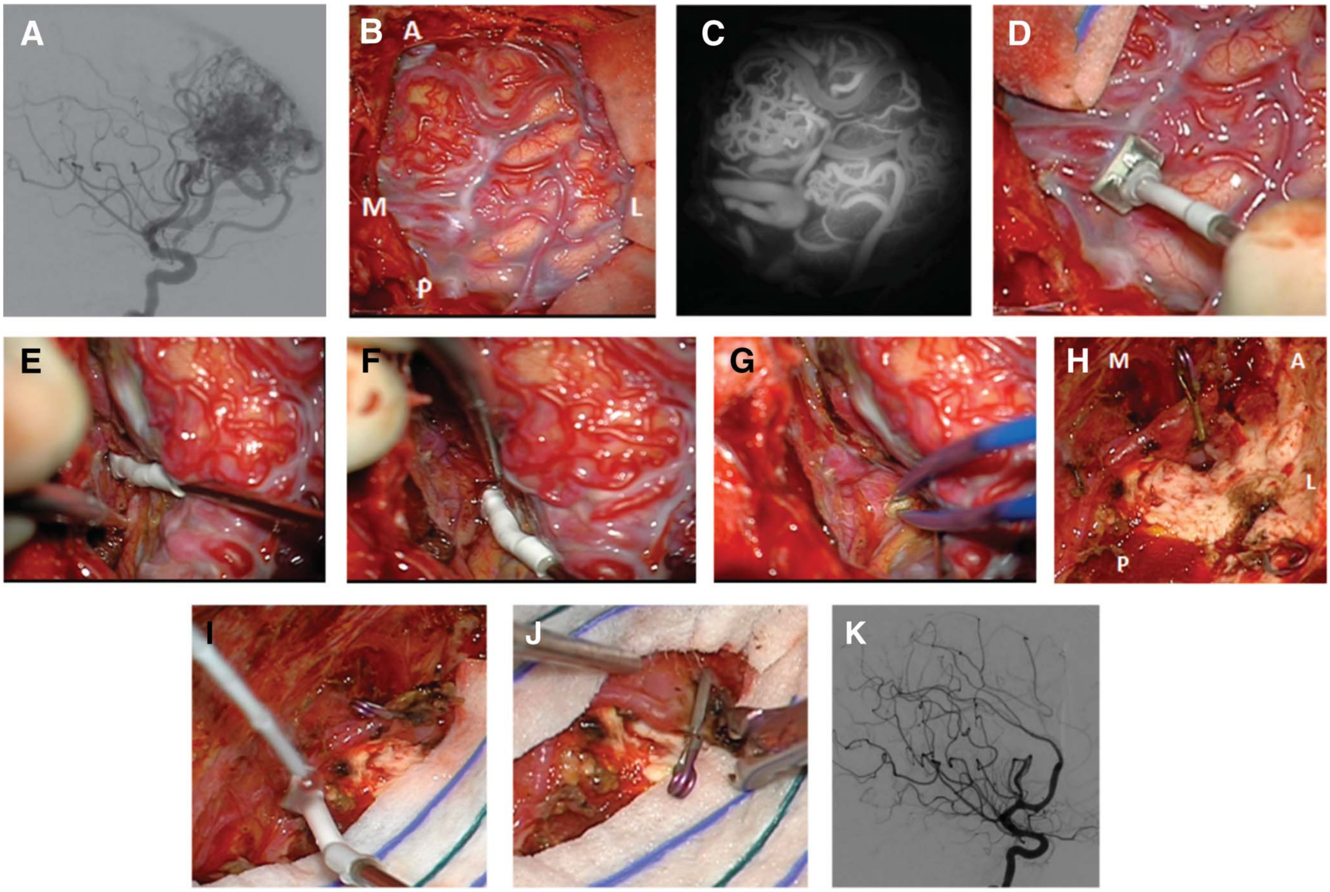

FIGURE 1. *The patient is a 37-year-old woman with a previously embolized right frontal arteriovenous malformation (AVM) (Spetzler Martin grade II).* **A**, *preoperative digital subtraction angiography (DSA).* **B-J**, *intraoperative microscopic images: pre-resection view (***B***), indocyanine green videoangiography image (***C***), flow assessment by microflow probe of a venous drainage (***D***);* **E-G**, *transit artery identification by detecting a flow drop between 2 points of the same artery (***E** *and* **F***) and consequent coagulation and section of an AVM feeder (***G***);* **H-J**: *main AVM feeder clipped and sectioned (***H***); detection of flow absence at assessment on pericallosal artery, distal to clip (***I***) and consequent clip repositioning (***J***) until a normal flow is detected at flowmetry;* **K**, *postoperative DSA (A, anterior; P, posterior; L, lateral; M, medial).*

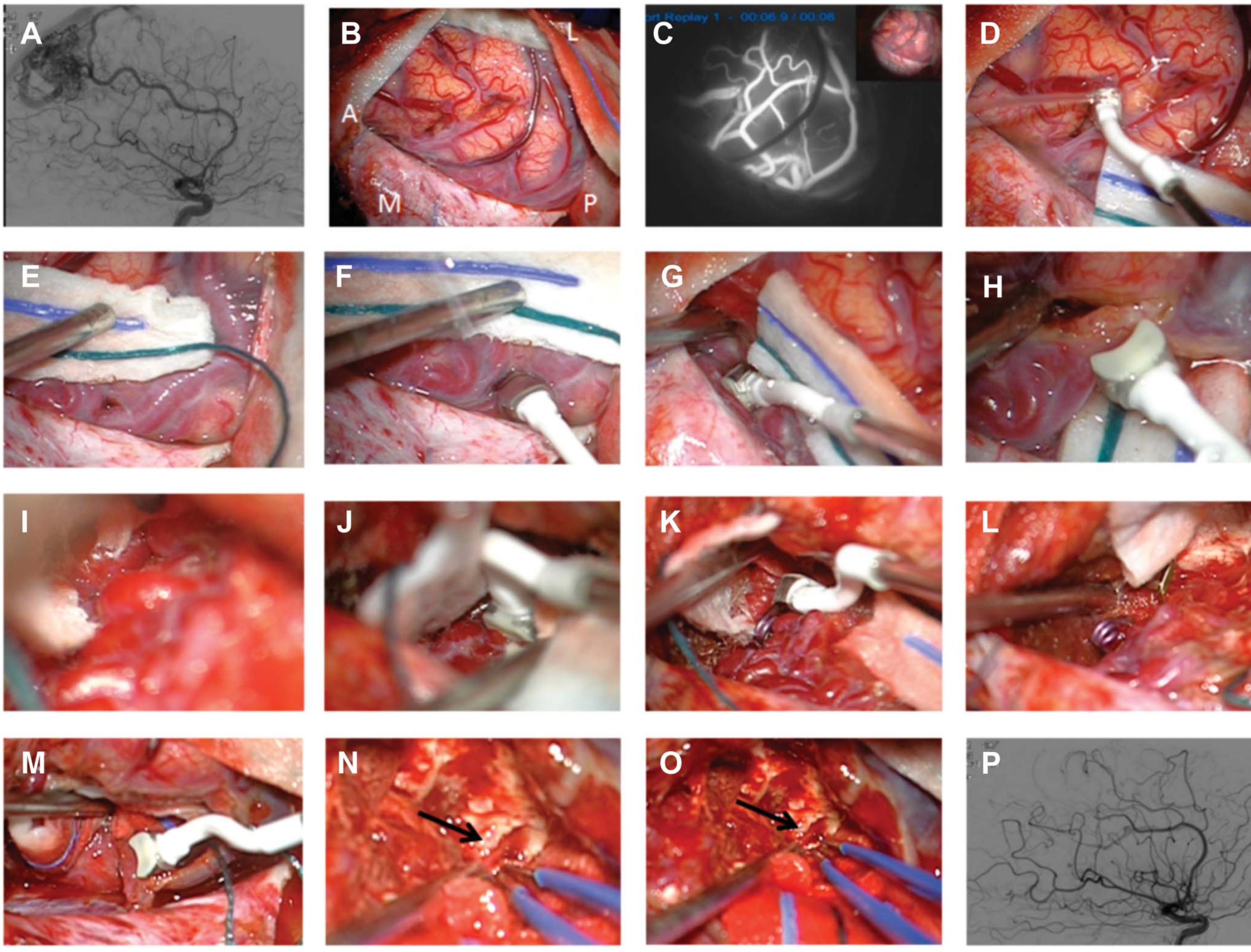

FIGURE 2. *The patient is a 41-year-old man. Right parietal arteriovenous malformation (AVM) (Spetzler Martin grade III).* **A**, *preoperative digital subtraction angiography (DSA);* **B-O**, *intraoperative microscopic images: pre-resection view (***B***), indocyanine green videoangiography (ICG-VA) image (***C***), flow assessment by microflow probe of different vessels not completely exposed at initial ICG-VA (***D-H***); during deep AVM dissection (***I***), flowmetry (***J***) allowed differentiation between feeder and venous drainage enabling safe section of the feeder first and then venous drainage (***K-L***); at the end of resection, flowmetry (***M***) detected an unexpected high flow (7 mL/min) that allowed detection of a deep residual nidus with an AVM feeder (***N***) that was then dissected and sectioned (***O***): postoperative DSA (***P***) (A, anterior; P, posterior; L, lateral; M, medial).*

Figure 2D, when the issue was to understand whether a vein surrounding the malformation was involved in the AVM hemodynamic. In this case, the low flow of the vein (3 mL/min) showed that it was not involved in the AVM. Then, flow measurement was performed on AVM vessels not completely exposed on initial ICG-VA because of their deep interhemispheric location (Figures 2E-2H) to distinguish between arterial feeders and venous drainages. During deep subcortical AVM dissection (Figure 2I), flowmetry (Figure 2J) allowed differentiation between feeder and venous drainage, enabling safe section of the feeder first (16 mL/min, flow to the AVM) and venous drainage (23 mL/min, flow from the AVM) (Figures 2K and 2L). At the end of resection, flowmetry (Figure 2M) detected an unexpected high flow (7 mL/min) that allowed detection of a deep residual nidus with an AVM feeder (Figure 2N, black arrow) that was then dissected and sectioned (Figure 2O, black arrow). The postoperative DSA (Figure 2P) showed the complete AVM resection.

Possible Fields of Microflow Probe Flowmetry Application in AVM Surgery and Further Studies

Preoperative angiographic assessment of the AVM angioarchitecture remains crucial for surgical planning. ICG-VA plays a helpful role in showing the AVM angioarchitecture before and after dural opening[14] to achieve a more accurate bone and dural aperture, define the intraoperative strategy, and confirm or better

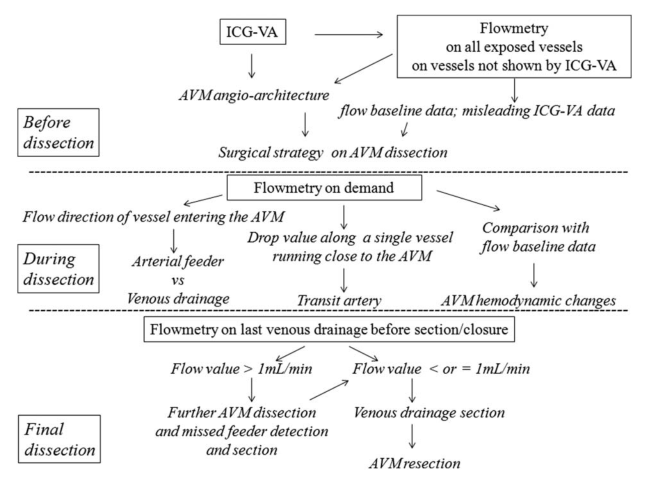

FIGURE 3. *The diagram shows the intraoperative application of the flowmetry by a microflow probe at the different stages of surgery and for the different issues to be addressed. AVM, arteriovenous malformation; ICG-VA, indocyanine green videoangiography.*

understand misleading preoperative DSA findings. The design of this study precludes a comparison of ICG-VA with microflow probe data. However, we think that the 2 techniques could be complementary, leading to helpful flow-guided AVM surgery. Indeed, flowmetry can play a role in some stages of AVM surgery when doubt may arise as to the surgical dissection strategy and ICG-VA is unable to provide the answers, as in the case of a deep AVM location and deep surgical field during microscopic dissection. Unlike IVG-VA, flowmetry measurements can be repeated quickly in real time during dissection. The measurement of flow drop at the venous drainage to check complete AVM resection and disclose an arteriovenous fistula or missing nidus remains a major issue to be confirmed by larger studies. This study does not answer the question of whether the microflow probe improves the outcome of bAVM patients. Indeed, larger studies with a different design are needed to evaluate the real impact of flowmetry on patients undergoing challenging AVM surgery.

CONCLUSION

With the limits of our small series, multistage intraoperative quantitative flow measurement during brain AVM surgical resection is a feasible, safe, repeatable, and reliable methodology, in both small arterial vessels and large drainage veins, in superficial and usually in deep surgical fields.

Disclosure

The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

REFERENCES

1. Amin-Hanjani S, Meglio G, Gatto R, Bauer A, Charbel FT. The utility of intraoperative blood flow measurement during aneurysm surgery using an ultrasonic perivascular probe. *Neurosurgery*. 2006;58(4 suppl 2):ONS-305-ONS-312; discussion ONS-312.
2. Charbel FT, Hoffman WE, Misra M, Ostergren L. Ultrasonic perivascular flow probe: technique and application in neurosurgery. *Neurol Res.* 1998;20(5):439-442.
3. Della Puppa A, Volpin F, Gioffre G, Rustemi O, Troncon I, Scienza R. Microsurgical clipping of intracranial aneurysms assisted by green indocyanine videoangiography (ICGV) and ultrasonic perivascular microflow probe measurement. *Clin Neurol Neurosurg.* 2014;116:35-40.
4. Fagundes-Pereyra WJ, Hoffman WE, Misra M, Charbel FT. Clip readjustment in aneurysm surgery after flow evaluation using the ultrasonic perivascular probe: case report. *Arq Neuropsiquiatr.* 2005;63(2A):339-344.
5. Kirk HJ, Rao PJ, Seow K, Fuller J, Chandran N, Khurana VG. Intra-operative transit time flowmetry reduces the risk of ischemic neurological deficits in neurosurgery. *Br J Neurosurg.* 2009;23(1):40-47.
6. Della Puppa A, d'Avella E, Volpin F, Rustemi O, Gioffre' G, Scienza R. Indocyanine green videoangiography (ICGV) in parasagittal meningiomas surgery. Considerations on veins management and brain function preservation. *Acta Neurochir (Wien).* 2013;155(8):1475-1476.
7. Della Puppa A, Rustemi O, Gioffrè G, et al. Application of indocyanine green video angiography in parasagittal meningioma surgery. *Neurosurg Focus.* 2014;36(2):E13.
8. Della Puppa A, Scienza R, Rustemi O, Gioffré G. Can the efficacy of indocyanine green videoangiography in cerebral arterio-venous malformations surgery be further improved? *Neurosurgery*. 2014;75(6):E732-E734.
9. Fukuda K, Kataoka H, Nakajima N, Masuoka J, Satow T, Iihara K. Efficacy of FLOW 800 with indocyanine green videoangiography for the quantitative assessment of flow dynamics in cerebral arteriovenous malformation surgery. *World Neurosurg.* 2014. pii: S1878-8750(14)00671-8. doi: 10.1016/j.wneu.2014.07.012.
10. Duong DH, Young WL, Vang MC, et al. Feeding artery pressure and venous drainage pattern are primary determinants of hemorrhage from cerebral arteriovenous malformations. *Stroke*. 1998;29(6):1167-1176.
11. Spetzler RF, Hargraves RW, McCormick PW, Zabramski JM, Flom RA, Zimmerman RS. Relationship of perfusion pressure and size to risk of hemorrhage from arteriovenous malformations. *J Neurosurg.* 1992;76(6):918-923.
12. Dempsey RJ, Moftakhar R, Pozniak M. Intraoperative Doppler to measure cerebrovascular resistance as a guide to complete resection of arteriovenous malformations. *Neurosurgery*. 2004;55(1):155-160; discussion 160-161.
13. Hassler W, Steinmetz H. Cerebral hemodynamics in angioma patients: an intraoperative study. *J Neurosurg.* 1987;67(6):822-831.
14. Della Puppa A, Rustemi O, Gioffrè G, Causin F, Scienza R. Transdural indocyanine green video-angiography of vascular malformations. *Acta Neurochir (Wien).* 2014;156(9):1761-1767.
15. Spetzler RF, Martin NA. A proposed grading system for arteriovenous malformations. *J Neurosurg.* 1986;65(4):476-483.
16. Lawton MT. *Seven AVMs: Tenets and Techniques for Resection*. New York: Thieme; 2014.
17. Hashimoto N, Nozaki K, Takagi Y, Kikuta K, Mikuni N. Surgery of cerebral arteriovenous malformations. *Neurosurgery*. 2007;61(1 suppl):375-387; discussion 387-389.
18. de Oliveira JG, Beck J, Seifert V, Teixeira MJ, Raabe A. Assessment of flow in perforating arteries during intracranial aneurysm surgery using intraoperative near-infrared indocyanine green videoangiography. *Neurosurgery*. 2007;61(3 suppl):63-72; discussion 72-73.
19. Scerrati A, Della Pepa GM, Conforti G, et al. Indocyanine green video-angiography in neurosurgery: a glance beyond vascular applications. *Clin Neurol Neurosurg.* 2014;124:106-113.
20. Zaidi HA, Abla AA, Nakaji P, Chowdhry SA, Albuquerque FC, Spetzler RF. Indocyanine green angiography in the surgical management of cerebral arteriovenous malformations: lessons learned in 130 consecutive cases. *Neurosurgery*. 2014;10(suppl 2):246-251.