Safety and Efficacy of Intraoperative Angiography in Craniotomies for Cerebral Aneurysms and Arteriovenous Malformations: A Review of 1093 Consecutive Cases

BACKGROUND: In an era of indocyanine angiography, the routine use of intraoperative angiography (IOA) in the surgical treatment of aneurysms and vascular malformations is controversial.

OBJECTIVE: To retrospectively assess the safety and efficacy of IOA and to determine predictors of surgical revision.

METHODS: Between 2003 and 2011, IOA was performed during surgical treatment of 976 aneurysms, 101 arteriovenous malformations (AVMs), and 16 arteriovenous fistulas.

RESULTS: In 80 of 976 aneurysms (8.2%), IOA prompted clip repositioning. The reason for readjustment was residual aneurysm in 54.7%, parent vessel occlusion in 42.9%, and both in 2.4% of cases. In multivariate analysis, increasing aneurysm size (P < .001), ruptured aneurysm (P < .001), and increasing number of vessels injected (P < .001) were strong predictors of clip readjustment. There was a strong trend for posterior circulation aneurysm location to predict clip repositioning (P = .06). IOA revealed residual nidus/fistula requiring further intervention in 9 of 101 AVMs (8.9%) and 3 of 16 arteriovenous fistulas (18.8%). Of 9 AVMs requiring a surgical revision, 2 (22.2%) were Spetzler-Martin grade II, 5 (55.6%) were grade III, and 2 (22.2%) were grade IV. Mean Spetzler-Martin grade was 3.0 in AVMs requiring surgical revision compared with 2.3 in those not requiring revision (P = .05). IOA-related complications were all transient or minor and occurred in 0.99% of patients; none resulted in permanent morbidity.

CONCLUSION: IOA remains a valuable tool in the surgical treatment of brain vascular abnormalities, guiding surgical re-exploration in > 8% of cases. Easy access to an angiographer and routine use of IOA are important factors contributing to procedural safety and efficacy.

KEY WORDS: Aneurysm, Arteriovenous fistula, Arteriovenous malformation, Intraoperative angiography

The use of intraoperative angiography (IOA) in the surgical treatment of brain vascular abnormalities has become common practice in most neurovascular centers. During surgical clipping of intracranial aneurysms, IOA has the potential to confirm complete aneurysm occlusion and patency of parent or branch vessels at a time when any shortcomings can be identified and remedied. Similarly, IOA is an important tool during surgical treatment of arteriovenous malformations (AVMs) and dural arteriovenous fistulas (AVF) and allows the operating surgeon to ascertain complete resection of the lesion and the absence of early draining veins. The routine use of IOA for intracranial aneurysms and vascular malformations, however, remains controversial. Many authors have raised concerns regarding the safety, sensitivity, and efficacy of the technique and have questioned its cost-effectiveness and availability, thus advocating its application in only selected cases.
Others have recommended its routine use for all aneurysms and vascular malformations, citing the high likelihood of finding a correctable abnormality and difficulties in predicting the need for IOA on a selective basis. As complex and surgically challenging aneurysms and vascular malformations (which typically require IOA assistance) are increasingly and consistently being managed with endovascular therapy, the usefulness of IOA could be called into question. In addition, the advent of indocyanine green fluorescence angiography (ICGA), a novel and less invasive technique of intraoperative assistance, has intensified the debate about the role of IOA in the armamentarium of the neurovascular surgeon. We investigate the safety and efficacy of IOA and determine predictors of surgical revision in the largest contemporary series of intracranial aneurysms and vascular malformations. From these data, we give recommendations about the use of IOA during craniotomies for aneurysms, AVMs, and AVFs.

**PATIENTS AND METHODS**

All procedures were performed at a single high-volume tertiary cerebrovascular center. IOA is the standard of care for surgical treatment of aneurysms, AVMs, and AVFs in our center. We searched our prospectively maintained database for all patients undergoing craniotomies for aneurysms, AVMs, and AVFs between January 2003 and March 2011. Undiagnosed aneurysms treated with a clip-wrap/wrapping technique (n = 26) or trapping/parent vessel ligation (n = 5) were excluded from the analysis. Of 983 consecutive aneurysms treated during this period, IOA was performed in 976 cases (99.3%). IOA could not be performed in 7 patients for the following reasons: lack of vascular access (n = 2), severe atherosclerosis (n = 2), and rapidly deteriorating patient with impending uncus herniation (n = 3). Of 111 consecutive patients with AVMs undergoing surgical resection, IOA was performed in 101 patients (91%). IOA was not obtained in 10 patients for the following reasons: lack of vascular access (n = 1), rapidly deteriorating patient with impending uncus herniation (n = 2), and surgeon preference (n = 7). IOA was also performed in all 16 patients undergoing surgical resection of AVFs during the same period.

**Data Collection**

Institutional Review Board approval was obtained before data collection. Medical charts, including operative notes and relevant imaging, were reviewed to determine the incidence of unexpected findings on IOA leading to surgical revision. Patient age, sex, lesion location, lesion size, ruptured/unruptured lesion status, and the number of catheterized vessels were recorded. Patient charts and imaging studies were also systematically reviewed to identify IOA-related neurological (stroke, arterial dissection) and local (groin hematoma, retroperitoneal hematoma, pseudoaneurysm, and acute limb ischemia) complications.

**Intraoperative Angiography**

All craniotomies and IOA procedures were performed by experienced neurosurgeons trained in both cerebrovascular and endovascular neurosurgery. In all cases, the same operating surgeon performed both the craniotomy and IOA. This allows efficient integration of IOA into the standard of care for aneurysms, AVMs, and AVFs. Subsequently, IOA was performed, analyzed, and repeated as necessary by the operating neurosurgeon. ICGA was not performed on any of the patients in this study.

Bilateral groins were prepared and draped in a standard sterile fashion. A 5F sheath was inserted into the femoral artery via the Seldinger technique and connected to a heparinized saline flush. In patients presenting with subarachnoid hemorrhage, the sheath was inserted in the angiography suite during the patient’s initial diagnostic angiography and remained in place until the time of surgery. In patients undergoing elective procedures, the sheath was inserted in the operating room after induction of general anesthesia. Craniotomy was subsequently performed with different approaches, depending on the location of the lesion. After the aneurysm was clipped or the AVM/AVF resected to the surgeon’s satisfaction, IOA studies were acquired with a 5F Berenstein catheter under a portable single-plane fluoroscopy unit. Two views of the catheterized vessel were routinely obtained, and additional vessels were explored if deemed necessary by the operating surgeon. Angiograms were immediately reviewed by the neurosurgeon for evidence of residual pathology and patency of parent/branch vessels. The presence of early venous drainage was the most common angiographic finding suggesting residual AVM/AVF. When an unexpected abnormality was identified, intraoperative adjustments were performed and angiography was repeated as necessary until the goals of the surgical procedure had been achieved (Figures 1 and 2). All catheters were withdrawn after completion of the procedure, and the sheath was usually removed the same day. Recent advancements in portable digital subtraction technology have allowed high-quality intraoperative imaging, so postoperative angiography is no longer performed at our institution.

The duration of IOA was estimated from the average duration of 10 standard single-vessel procedures.

**Statistical Analysis**

Data are presented as mean and range for continuous variables and as frequency for categorical variables. A multivariate analysis was carried out to determine predictors of unexpected findings and surgical revision for aneurysms, AVMs, and AVFs. Factors predictive of surgical revision in univariate analysis ($P < .15$) were entered into a stepwise backward multivariate logistic regression analysis. Values of $P \leq .05$ were considered statistically significant. Statistical analysis was carried out with Stata 10.0 (StataCorp, College Station, Texas).

**RESULTS**

### Aneurysms

A total of 976 aneurysms in 886 patients were treated with the adjunctive use of IOA. Nine of these patients underwent bypass procedures. Mean age in the series was 51.6 years, and the proportion of female patients was 67.8% (601 of 886). The proportion of patients treated in the setting of subarachnoid hemorrhage was 40.6% (360 of 886).

Mean aneurysm size was 6.7 mm. The majority of aneurysms were located in the middle cerebral artery (432 of 976, 44.3%) and the anterior communicating artery (301 of 976, 30.8%). The rate of unexpected findings on IOA requiring clip readjustment was 8.2% (80 of 976). Aneurysm locations and their respective clip readjustment rates are summarized in Table 1. The reason for the readjustment was a residual aneurysm in 53.8% (43 of 80), parent or branch vessel occlusion in 42.5% (34 of 80), and both findings in 3.7% (3 of 80) of cases. Ten aneurysms (12.5%) required multiple clip readjustments (2 adjustments in 8
aneurysms and 3 adjustments in 2 aneurysms). In all cases in which parent or branch vessel occlusion was identified on IOA, clip readjustment resulted in adequate flow restoration. Of the 46 cases with angiographic evidence of residual aneurysm, complete aneurysm obliteration was achieved in 41 cases (89.1%) after clip readjustment. In the remaining 5 cases (10.9%), additional wrapping of the neck of the aneurysm was performed. A single vessel was catheterized in 800 patients (90.3%), 2 vessels in 82 patients (9.3%), 3 vessels in 3 patients (0.3%), and 4 vessels in 1 patient (0.1%). No graft occlusion/stenosis was found on IOA in patients undergoing bypass procedures.

Factors predictive of surgical revision in univariate analysis were older age, increasing aneurysm size, ruptured aneurysm, posterior circulation aneurysm location, and increasing number of vessels.
Arteriovenous Malformations

A total of 101 patients with AVMs underwent surgical excision with the assistance of IOA. Mean age was 41.7 years, and the proportion of female patients was 56.4% (57 of 101). Forty-three patients (42.6%) had a ruptured AVM. Mean AVM size was 24.8 mm (range, 6-55 mm). The mean Spetzler-Martin grade was 2.4, with 20 (19.8%) grade 1 lesions, 33 (32.7%) grade 2 lesions, 32 (31.7%) grade 3 lesions, and 16 (15.8%) grade 4 lesions. Forty-nine patients (48.5%) underwent prior endovascular embolization. AVM locations and their respective surgical revision rates are summarized in Table 3. In 9 of 101 patients (8.9%), IOA demonstrated residual AVM requiring additional resection. Two of these patients (22.2%) required a second surgical revision. Successful excision of the residual AVM was confirmed by repeat IOA in all 9 patients. A single vessel was injected in 79 patients (78.2%), 2 vessels were injected in 19 patients (18.8%), and 3 vessels were injected in 3 patients (3%). Of the 9 patients requiring a surgical revision, 2 (22.2%) had a grade 2 lesion, 5 (55.6%) had a grade 3 lesion, and 2 (22.2%) had a grade 4 lesion. Four of these patients (44.4%) had a ruptured AVM. Mean Spetzler-Martin grade was 3.0 in AVMs requiring surgical revision and 2.3 in those not requiring a revision (P < .05).

Of the factors tested for predicting surgical revision (patient age, sex, AVM size, ruptured/unruptured AVM status, AVM location, Spetzler-Martin grade, prior embolization, and number of vessels injected), a higher Spetzler-Martin grade was the only factor found to be statistically significant in univariate analysis.

Dural AVFs

IOA was performed in 16 patients undergoing surgical resection of AVF. There were 8 women and 8 men with a mean age of 54.7 years. Ten patients (62.5%) presented with a ruptured AVFs. Fistulas were located at the transverse-sigmoid sinus (n = 4), temporal-middle fossa (n = 3), tentorium (n = 3), superior sagittal sinus (n = 2), foramen magnum (n = 1), cavernous sinus (n = 1), and torcular (n = 1). Ten patients (62.5%) had cortical venous drainage. Thirteen of 16 patients (81.3%) underwent prior embolization with liquid embolic agents and/or coils.

### Table 1. Location of Aneurysms and Respective Surgical Revision Rates

<table>
<thead>
<tr>
<th>Aneurysm Location</th>
<th>Aneurysms, n (%)</th>
<th>Surgical Revisions, n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middle cerebral artery</td>
<td>432 (44.3)</td>
<td>35 (8.1)</td>
</tr>
<tr>
<td>Anterior communicating artery</td>
<td>301 (30.9)</td>
<td>26 (8.6)</td>
</tr>
<tr>
<td>Posterior communicating artery</td>
<td>92 (9.4)</td>
<td>6 (6.5)</td>
</tr>
<tr>
<td>Carotid terminus</td>
<td>41 (4.2)</td>
<td>2 (4.9)</td>
</tr>
<tr>
<td>Carotid ophtalmic artery</td>
<td>26 (2.7)</td>
<td>1 (3.8)</td>
</tr>
<tr>
<td>Pericallosal artery</td>
<td>22 (2.3)</td>
<td>2 (9.1)</td>
</tr>
<tr>
<td>Posterior carotid wall</td>
<td>16 (1.6)</td>
<td>2 (12.5)</td>
</tr>
<tr>
<td>Paracalodin</td>
<td>13 (1.3)</td>
<td>1 (7.7)</td>
</tr>
<tr>
<td>Verteobasilar</td>
<td>12 (1.2)</td>
<td>3 (25)</td>
</tr>
<tr>
<td>Anterior choroidal artery</td>
<td>11 (1.1)</td>
<td>1 (9.1)</td>
</tr>
<tr>
<td>Anterior cerebral artery</td>
<td>10 (1.0)</td>
<td>1 (10)</td>
</tr>
<tr>
<td>Total</td>
<td>976</td>
<td>80</td>
</tr>
</tbody>
</table>

### Table 2. Predictors of Surgical Revision for Aneurysms

<table>
<thead>
<tr>
<th>Aneurysms Not Requiring Surgical Revision</th>
<th>Aneurysms Requiring Surgical Revision</th>
<th>P (Multivariate Analysis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>51.3</td>
<td>53.2</td>
</tr>
<tr>
<td>Aneurysm size, mm</td>
<td>6.5</td>
<td>9.2</td>
</tr>
<tr>
<td>Ruptured aneurysms, % (n/N)</td>
<td>35.4 (317/896)</td>
<td>53.8 (43/80)</td>
</tr>
<tr>
<td>Posterior circulation aneurysms, % (n/N)</td>
<td>1.0 (9/896)</td>
<td>3.8 (3/80)</td>
</tr>
<tr>
<td>&gt;1 vessel injected, % (n/N)</td>
<td>9.1 (73/806b)</td>
<td>28.8 (13/80)</td>
</tr>
</tbody>
</table>

*Statistically significant values.

### Table 3. Location of Arteriovenous Malformations and Respective Surgical Revision Rates

<table>
<thead>
<tr>
<th>AVM Location</th>
<th>AVMs, n (%)</th>
<th>Surgical Revisions, n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal</td>
<td>29 (28.7)</td>
<td>3 (10.3)</td>
</tr>
<tr>
<td>Brainstem</td>
<td>27 (26.7)</td>
<td>3 (11.1)</td>
</tr>
<tr>
<td>Temporal</td>
<td>25 (24.8)</td>
<td>3 (12.0)</td>
</tr>
<tr>
<td>Parietal</td>
<td>11 (10.9)</td>
<td>1 (9.1)</td>
</tr>
<tr>
<td>Occipital</td>
<td>7 (6.9)</td>
<td>0</td>
</tr>
<tr>
<td>Cavernous</td>
<td>2 (2.0)</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>101</td>
<td>10</td>
</tr>
</tbody>
</table>

AVM, arteriovenous malformation.

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INTRAOPERATIVE ANGIOGRAPHY

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IOA revealed residual fistula (early draining vein) requiring additional intervention in 3 patients (18.8%). One of these patients required a second surgical revision. Of these 3 fistulas, 2 were located at the tentorium and 1 was located at the superior sagittal sinus. After surgical revision, 2 patients had complete obliteration of their fistulas and 1 had significant reduction of the fistulous flow (> 90%). A single vessel was catheterized in 7 patients (43.8%), 2 vessels were catheterized in 8 patients (50%), and 3 vessels were catheterized in 1 patient (6.2%).

No factor was found to be predictive of surgical revision in univariate analysis.

**IOA Duration**

The mean duration of a single-vessel IOA was 16.7 minutes with a range of 15 to 19 minutes.

**Complications**

IOA-related complications were all minor and occurred in 10 of 1003 patients (0.99%). The overall rate of symptomatic postoperative ischemic stroke was 4.1% (41 of 1003), but the only neurological complication attributable to IOA in the series (0.09%) was a visual transient ischemic attack resolving within 24 hours. There were also 5 retroperitoneal hematomas (3 not requiring any intervention, 2 requiring blood transfusion), 3 minor groin hematomas, and 1 acute limb ischemia successfully treated by thromboendarterectomy. None of these complications resulted in permanent morbidity.

Five other patients in whom a preoperative angiography was performed and the sheath was left in place developed local complications (3 retroperitoneal hematomas not requiring any intervention, 1 minor groin hematoma, and 1 acute limb ischemia treated by thromboendarterectomy). These complications were not included in the overall rate of procedural complications because they were mostly related to the preoperative diagnostic angiography.

**DISCUSSION**

This is the largest study to date assessing the safety and efficacy of IOA in intracranial aneurysms and vascular malformations. Given the large sample size of our study, we were able to detect predictors of surgical revision and to evaluate procedural safety. The consecutive nature of this series is another strong point that addresses the selection bias inherent in previous studies. In addition, this contemporary series of patients undergoing craniotomies at a center where endovascular therapy is a main treatment modality for a wide array of brain vascular abnormalities has the potential to assess the efficacy of IOA taking into account the changing pattern of lesions referred for open surgery.

**Safety of IOA**

The results of this study demonstrate that IOA can be performed with minimal risk of morbidity. In fact, the rate of procedural complications was < 1%, with neurological complications occurring in only 0.09% of cases. Moreover, most complications were clinically insignificant, mild, or transient, and none resulted in permanent morbidity. This potentially crucial finding is a strong argument in favor of the routine use of IOA during craniotomies for brain vascular abnormalities. Some authors have reported higher complication rates (1.5%-3%), but most of these studies were small and prone to sampling error. Nevertheless, we acknowledge that in smaller centers where IOA is performed on only a selective basis, the morbidity rate can be higher.

**Aneurysms**

Achieving complete aneurysm obliteration during surgical clipping is of paramount importance to prevent aneurysm regrowth and rupture. The occlusion of a major or branch vessel during aneurysm surgery can also lead to significant postoperative morbidity and mortality. In a large series of patients undergoing surgical clipping, Kivisaari et al reported a 12% rate of residual aneurysms and a 5% rate of major vessel occlusion on postoperative angiography. IOA is therefore necessary to make immediate adjustments to the surgical technique. Tang et al had previously published the largest series of IOA in 517 aneurysms, reporting a surgical revision rate of 12.4%. In other IOA series, the rate of surgical revision has ranged from 11% to 34%,.

In our study, IOA led to clip readjustment in 8.2% of aneurysms with up to 10% of these lesions requiring multiple clip readjustments. We attribute the lower surgical revision rate in our study mainly to the difference in aneurysm location and complexity. In fact, vertebralbasilar and paracallosal aneurysms, which typically have higher clip readjustment rates, are underrepresented in our study because they are managed primarily with endovascular therapy at our institution. These 2 locations accounted for 30.2% of all clipped aneurysms in the Tang et al’ series (from 1997-2000) compared with only 2.5% in the present series (from 2003-2011). Thus, significant practice variations over time are likely to influence the rates of clip readjustment at different institutions. Nevertheless, we believe that IOA is still a powerful tool guiding surgical clipping in a substantial number of patients.

We found that larger aneurysms were significantly more likely to require clip readjustment, which corroborates the findings of previous studies. The strong association between ruptured aneurysms and the need for surgical revision even after controlling for potential confounding variables like aneurysm size is an important finding of our study that has not previously been reported. This could be related to operative challenges in aneurysm dissection (mainly as a result of cerebral swelling) and clip application in unstable, recently ruptured aneurysms. The number of vessels explored was another strong predictor of surgical revision that has not been reported in previous IOA series. It makes intuitive sense that the likelihood of finding an angiographic abnormality increases with the number of vessels explored. Previous studies reported a 5% to 8% rate of false negatives with IOA compared with postoperative angiography.
Accordingly, we suspect that the rate of false negatives and the sensitivity of IOA can be improved by the routine catheterization of multiple vessels. However, this requires further investigation and should also take into account the additional operative time and the additional risk of neurological complications associated with the catheterization of multiple vessels. Moreover, recent improvements in portable digital subtraction technology have allowed the creation of high-quality intraoperative images, thus minimizing the rate of false negatives to a great extent. Despite a higher incidence of clip readjustment in posterior circulation aneurysms, no location was immune from surgical revision in our series. Importantly, middle cerebral artery and anterior communicating artery aneurysms, which constitute the bulk of aneurysms referred for surgical clipping, were found to benefit from IOA in > 8% of cases in this series.

In light of these findings and given the safety of IOA, it would be reasonable to recommend its routine application during aneurysm clipping procedures. Although selective use of IOA is an option, it is associated with difficulties in predicting the cases requiring IOA, as previously demonstrated by Klopfenstein et al.13 The routine use of IOA could prove challenging, however, if logistic support or access to neuroradiology staff is limited. In this case, patients with large and ruptured aneurysms would benefit the most from IOA.

Arteriovenous Malformations

Surgical treatment of AVMs is directed toward complete resection of the AVM nidus with preservation of normal vessels. Incomplete resection may expose patients to the subsequent risk of hemorrhage with its potentially devastating consequences.26 At our institution, surgical treatment of AVMs is indicated for Spetzler-Martin grade I through III lesions and a few select grade IV lesions after endovascular embolization.27 IOA can localize small AVMs, detect an AVM during emergent evacuation of a hematoma, characterize arterial feeders and en passage vessels, and document residual lesions. A negative finding on IOA is equally important during AVM surgery because it avoids unnecessary surgical exploration in eloquent areas and the associated morbidity. In the present study, IOA findings led to surgical re-exploration and additional AVM resection in 8.9% of cases, thus obviating the need for repeat surgery in these patients. Surgical revision rates in previously published series have ranged widely from 3.7% to 27.3%.27,19,28,29 The small number of patients included in previous studies has precluded the identification of predictors of surgical revision. We found an important association between the Spetzler-Martin grade and the need for surgical revision: Up to 77% of AVMs requiring surgical revision were grade III or higher. Interestingly, none of the grade I AVMs required a revision, which could possibly indicate the lower yield of IOA in this group. No specific AVM location was found to carry a higher risk of surgical revision.

From our findings, the routine use of IOA during surgical treatment of AVMs may be justified, except perhaps for grade I lesions, per the surgeon’s discretion. Patients with high-grade AVMs appear to benefit the most from IOA.

Dural AVFs

AVFs are less common than AVMs and account for only 10% to 15% of all intracranial vascular malformations.26 Most AVFs are currently managed with endovascular techniques using a transarterial, a transvenous, or a combined approach.31 However, surgery may still be required in certain patients who fail endovascular embolization or in those with complex angioarchitecture of the AVF.32 Surgical treatment often consists of ligation of the fistulous communication followed by excision of the fistula, along with adjacent arteries and draining veins.31 Complete obliteration of the fistula must be achieved to confer proper protection against future hemorrhage.33,34 In the present study, almost 1 in 5 patients had a residual AVF on IOA requiring further resection. This high rate of residual AVF is probably due to the complexity and great number of arterial feeders, the lack of a true localizing nidus, and the often complex vascular anatomy of the lesions. Given that arterial feeders may arise from bilateral carotid or vertebral arteries, multiple vessels may need to be explored during IOA. In fact, 56.2% of AVFs in the present report required cannulation of > 1 vessel. We are aware of only 1 study investigating the efficacy of IOA in AVFs specifically. In this study, which included 29 patients with 31 AVFs treated between 1990 and 2010, Pandey et al.35 reported that IOA revealed residual fistula requiring additional resection in 37.9% of cases. One factor that could explain the lower rate of surgical revision in our study is the higher proportion of patients undergoing preoperative embolization (81.3% in the present report vs 41.3% in the Pandey et al study).35 In fact, transarterial embolization plays an important role in decreasing flow through AVF before surgical intervention and facilitates operative exposure of the involved segment of the dural sinuses, thus affecting the quality and completeness of surgical excision.36

Because of the complexity of AVF and the high rate of residual lesion, we recommend the routine use of IOA during surgical treatment of AVFs.

Limitations of IOA

The availability of an angiographer is perhaps the most important challenge hampering the routine implementation of IOA in many centers. At an increasing number of institutions, IOA is performed by a dual-trained neurosurgeon, which facilitates its application on a routine basis. There have been some concerns about radiation exposure to the medical staff during IOA.37 Lopez et al.37 measured the amount of radiation sustained by personnel during IOA and found a negligible annual dose of radiation similar to that of a dedicated angiography suite. Our study and others have also shown that IOA adds only 15 to 20 minutes to the total operative time. In fact, rapid imaging acquisition is essential to allow timely clip readjustment and to prevent ischemic stroke in the event of parent vessel occlusion. False negatives are another possible limitation of IOA that occur in 5.3% of aneurysms,1 1.8% to 5.2% of AVMs,27 and 6.8% of AVFs.35 In our experience, the accuracy of IOA is excellent and obviates the need for postoperative angiography. There have been...
conflicting reports regarding the cost-effectiveness of IOA for surgical clipping of aneurysms. Using a Markov model, Kallmes and Kallmes found that IOA is cost-effective if performed with a low morbidity rate ($19,000/quality-adjusted life-year), whereas Katz et al argued that the high cost-to-benefit ratio should preclude its routine application and recommended its use only for patients with complex or large aneurysms and some middle cerebral artery aneurysms. However, it should be noted that there is actually no additional cost associated with IOA because it substitutes for the traditional postoperative angiogram. Finally, we have demonstrated in this large series of IOA that the procedure can be performed with an extremely low complication rate and minimal morbidity when used on a routine basis.

Recently, microscope-based ICGA has been introduced as a simple, noninvasive, and quick method of intraoperative neurovascular imaging. High-spatial-resolution images can be obtained within minutes after dye injection by the anesthesiologist and repeated as necessary without the need to move the microscope from the surgical field. The technique is inexpensive, has a very low complication rate (0.1%), and allows the visualization of small perforators that would otherwise not be visible with IOA during aneurysm surgery. Importantly, ICGA does not require radiology support and has the potential to be more widely available than IOA. The technique has now been used not only for aneurysms but also for AVMs and AVFs. Despite its appealing nature, the technique has several serious limitations that should be emphasized. First, angiographic views provided by ICGA are restricted to the field of view through the operating microscope. Consequently, any abnormality outside the field of view of the microscope will consistently be missed. This is unquestionably the most important limitation of ICGA and the one that precludes its use as a standalone imaging technique during craniotomies for neurovascular disorders. Likewise, vessels covered by clips, brain tissue, aneurysm, or hematoma will not be visible to the operating surgeon. Calcifications, atherosclerotic vessels, and aneurysm thrombosis also can attenuate fluorescence signals. Diagnosing vascular stenosis from clip impingement can be very challenging, especially when surrounding vessels are not within the field of the microscope. Because it may take 15 to 20 minutes for ICGA fluorescence to dissipate, repeat studies are obviously time-consuming. In the largest experience thus far with ICGA, Raabe et al clipped 124 aneurysms and reported a 10% false-negative rate, including 1 hemodynamically relevant stenosis and 2 residual aneurysm necks. The authors acknowledged the limitations of the technique and recommended its use as a complement to IOA. De Oliveira et al assessed the usefulness of ICGA for the intraoperative assessment of perforators during surgical clipping of 64 aneurysms. ICGA led to clip readjustment in only 1 patient in their series, whereas 4 patients (6.7%) developed postoperative perforating artery infarcts despite ICGA assistance. The usefulness of ICGA in this regard is therefore far from being established, and the need for further investigation is apparent. Killory et al examined the utility of ICGA during surgical excision of 10 AVMs and found that the technique can help distinguish AVM vessels from normal vessels and arteries from veins on the basis of the timing of fluorescence. However, 2 of the 10 patients (20%) showed residual nidus on IOA (requiring further intervention) after initial ICGA-guided surgical resection. The authors also noted that ICGA is less useful for deep-seated AVMs and concluded that the technique “complements rather than replaces” IOA. ICGA is admittedly an innovative and attractive method for intraoperative imaging assistance, but further studies are needed to confirm its accuracy. Meanwhile, IOA remains the gold standard for guiding surgical treatment of aneurysms, AVMs, and AVFs.

Limitations of the Study

Our study has some limitations pertaining to its retrospective design and the absence of comparison to a control or ICGA group. It would be of interest in the future to compare patients undergoing IOA and those undergoing ICGA in terms of postoperative stroke, risk of rehemorrhage, and clinical outcome. Because postoperative angiography is not performed at our institution, we are unable to provide a false-negative rate. Additionally, our results reflect the experience of a single, high-volume, cerebrovascular referral center and may not be applied to other centers. Lastly, because computed tomography/magnetic resonance imaging studies were not routinely obtained after surgical procedures, some clinically silent infarcts related to IOA could theoretically have been missed.

CONCLUSION

In this article, we presented the results of the largest study to date investigating the safety and efficacy of IOA during craniotomies for aneurysms and vascular malformations. We found that the routine use of IOA is associated with a very low complication rate and minimal associated morbidity. Our results support the routine use of IOA during surgical treatment of aneurysms, AVMs, and AVFs. Patients with large and ruptured aneurysms, high-grade AVMs, and AVFs benefit the most from IOA. Easy access to an angiographer and routine use of IOA are important factors contributing to procedural safety and efficacy.

Despite the ever-changing pattern of brain vascular abnormalities referred for surgical treatment, IOA is still a powerful and valuable tool in the armamentarium of the neurovascular surgeon. In an era of advanced imaging techniques, our results reaffirm the safety and high yield of IOA in the surgical treatment of aneurysms and vascular malformations.

Disclosures

Dr Jabour has been a consultant for ev3, Codman, and Mizuho. Dr Tjournimakar has been a consultant for Stryker. Dr Gonzalez has been a consultant for ev3. Dr Dumont has been a consultant for ev3 and Stryker. Dr Rosenwasser has been a consultant for Boston Scientific. The other authors have no personal financial or institutional interest in any of the drugs, materials, or devices described in this article.
REFERENCES


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