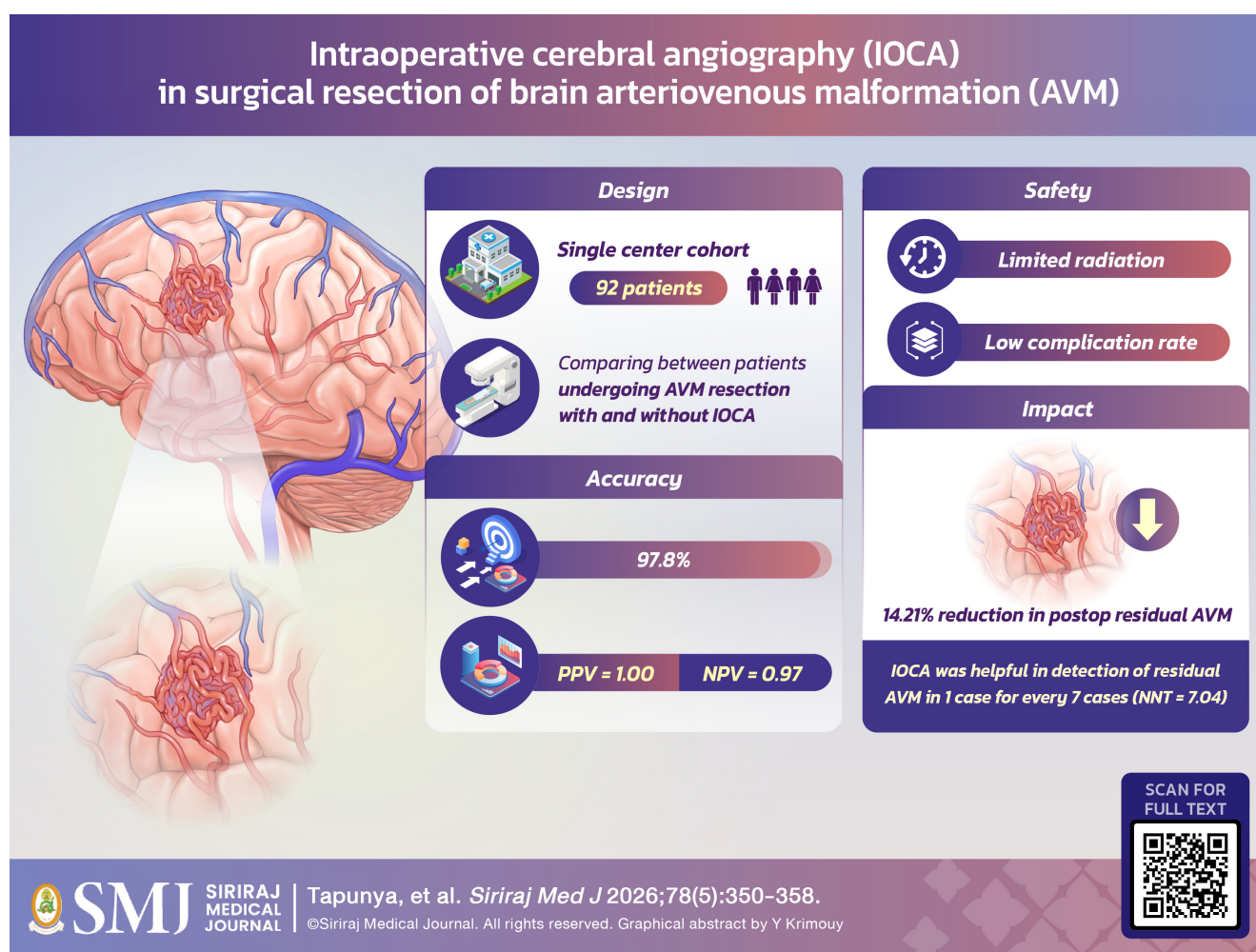


# Intraoperative Cerebral Angiography in the Surgical Resection of Brain Arteriovenous Malformations

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**ABSTRACT**

**Objective:** This study aimed to determine the effectiveness of IOCA in reducing residual AVMs after surgery.

**Materials and Methods:** We retrospectively reviewed all AVM resection surgeries performed at Siriraj Hospital between January 2008 and December 2022. The use of intraoperative cerebral angiography was recorded. The primary outcome was the presence of residual AVM on postoperative imaging.

**Results:** The study included 92 patients, who were divided into two groups: those undergoing IOCA (44) and those undergoing surgery without IOCA (48). The initial incidence of residual AVMs prior to IOCA did not differ between the two groups (15.90% vs. 18.75%,  $p=0.720$ ). However, postoperative imaging revealed significantly fewer missed residual AVMs in the IOCA group compared to the non-IOCA group (4.54% vs. 18.75%,  $p=0.036$ ; absolute risk reduction (ARR) = 14.21% and a number needed to treat (NNT) = 7.04). The overall rate of acute complications did not differ significantly between the two groups ( $p = 0.108$ ), but the mean length of hospital stay was higher in the non-IOCA group (19.31 vs. 8.57,  $p=0.001$ ).

**Conclusion:** Intraoperative cerebral angiography may help reduce the incidence of residual AVMs after surgery and decrease the length of hospital stays.

**Keywords:** AVM; cerebral arteriovenous malformation; intraoperative cerebral angiography; residual; surgical resection (Siriraj Med J 2026;78(5):350-358)

**INTRODUCTION**

Cerebral arteriovenous malformation (AVM) remains a significant condition within the field of neurovascular surgery, despite its relatively low incidence.<sup>1-3</sup> The inherent risks and complications associated with AVMs have prompted extensive research and efforts aimed at improving treatment strategies and patient outcomes.<sup>4,5</sup>

Historically, surgical resection has been a primary treatment approach for cerebral AVMs. However, literature reports show that even at experienced centers, residual AVMs may persist in up to 33% of cases post-surgery, with patients in this category generally experiencing worse outcomes.<sup>6,7</sup> Moreover, the risk of rebleeding may be higher in these cases than in untreated patients, with some rebleeding events occurring as early as during transport from the operating room. These findings underscore the need for effective intraoperative measures to minimize the risk of such undesirable events.<sup>8</sup>

Intraoperative cerebral angiography (IOCA), introduced in the 1970s, has proven to be a valuable adjunct in neurovascular surgery.<sup>9</sup> Its use extends to lesion localization and detection of residual AVMs, thereby supporting a more comprehensive surgical approach.<sup>10,11</sup> However, the adoption of IOCA has varied across medical centers, leading to diverse treatment guidelines.<sup>12,13</sup>

Although several case series and institutional reports have evaluated the role of IOCA in cerebral AVM resection, most studies are limited by small sample sizes and the absence of direct comparisons with surgeries performed without IOCA.<sup>19-21</sup> Consequently, the true effectiveness

of IOCA in improving surgical completeness and patient outcomes remains incompletely defined.

In this context, our study aims to present our institution's experience with cerebral AVM resection performed with and without IOCA. Although this is a single-center retrospective study, it represents one of the largest series to date and one of the few to directly compare outcomes between IOCA and non-IOCA groups. This analysis seeks to provide further evidence regarding the clinical value of IOCA and its impact on residual AVM rates, perioperative outcomes, and overall patient care.

**MATERIALS AND METHODS****Study design**

This was a single-center, retrospective review of patients with intracranial AVMs who underwent surgical resection at Siriraj Hospital between January 2008 and December 2022. Patient demographic data, as well as all previous treatments, were reviewed. Clinical and functional status were documented using the Glasgow Coma Scale and the Modified Rankin Scale for both preoperative and postoperative evaluations. Additionally, AVMs were graded using the two most widely accepted classification systems — Spetzler-Martin grading and supplementary grading.<sup>14-16</sup>

Most patients underwent postoperative imaging (CTA, MRA, or DSA). Residual AVM was defined as a residual nidus identified on postoperative imaging. Initially, 116 eligible patients were identified. Among them, 14 patients lacked postoperative images, and 10 had received other

intraoperative interventions such as indocyanine green injection (ICG). After excluding these cases, 92 patients remained, who were categorized into two groups based on whether intraoperative cerebral angiography (IOCA) was performed. The decision to use IOCA was made at the discretion of the attending neurosurgeon, based on factors such as anatomical complexity or personal preference. The IOCA group included 44 patients (47.8%) who underwent the procedure, while the conventional group included 48 patients who did not (Fig 1).

### Intraoperative cerebral angiography

As described above, the use of IOCA was based on surgeon discretion and was planned preoperatively in all cases. All procedures were performed in a hybrid operating room equipped with a radiolucent carbon head holder frame, angiography table, and C-arm imaging system. Vascular access for intraoperative angiography was typically established prior to surgical resection. Angiography was then performed after the surgeon deemed the resection complete, allowing for intraoperative confirmation of complete nidus obliteration and immediate detection of residual AVMs, which could prompt further resection during the same procedure.

### Outcomes

The primary objective was to assess the incidence of residual AVM on postoperative imaging, used to assess the effectiveness of IOCA in AVM resection. Our secondary objective was to compare additional perioperative parameters such as hospital stay, operative time, and complications.

### Statistical analysis

Statistical analysis was conducted using SPSS version

18. Data are presented as mean  $\pm$  SD or as frequency (percent). For ordinal and scale parameters, patient age was analyzed using the independent t-test. The number of feeders, drainage pattern, presence of aneurysm, Spetzler-Martin scale, supplementary scale, operative time, blood loss, length of hospital stays, duration of follow-up, pre- and post-operative Glasgow Coma Scale, and pre- and post-operative Modified Rankin Scale were compared using the Mann-Whitney U test. For nominal parameters such as age group, lesion side and location, gender, presenting symptoms, history of prior bleeding or treatment, emergency setting, complications, re-operation rate, and residual AVM, the Chi-square test was used.

## RESULTS

### Patient demographics

Patient demographic data are presented in Table 1. Most demographic factors were not significantly different between the groups, except for the emergency setting, which included 12 cases (25%) in the conventional group compared to one case (2.3%) in the IOCA group (p-value = 0.002). Additionally, the pre-operative Glasgow Coma Scale was significantly lower in the conventional group ( $14.11 \pm 2.53$  vs.  $13.52 \pm 3.16$ , p-value = 0.028). The Spetzler-Martin and supplementary grading scores were comparable between the groups (p-value = 0.481 and 0.224, respectively) (Table 2).

### Residual AVM

In the conventional group, residual AVMs were identified in post-operative imaging in nine cases (18.75%). Notably, all these cases were documented in the operative notes as having undergone complete resection.

In the IOCA group, all patients underwent at least

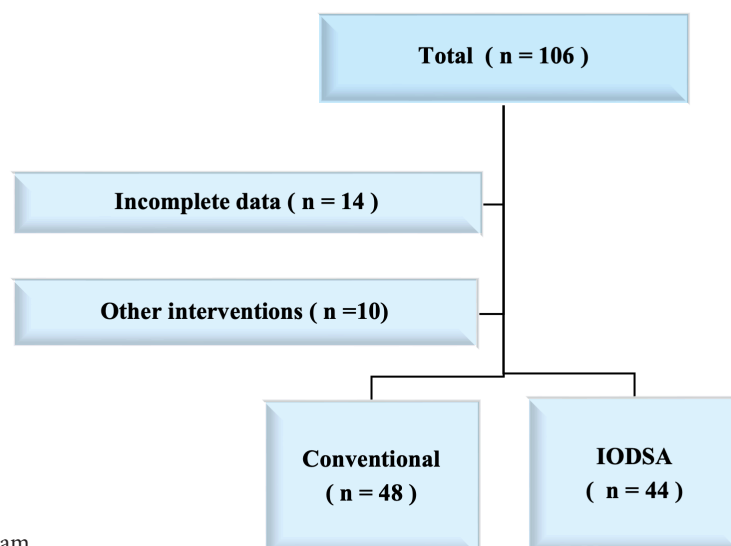


Fig 1. Patient flow diagram.

**TABLE 1.** Patient demographic data.

| Characteristic             | Total (N=92) | Conventional (N=48) | IOCA (N=44) | p-value |
|----------------------------|--------------|---------------------|-------------|---------|
| Mean age (years)           | 31.7 ± 16    | 31 ± 15.1           | 32.6 ± 16   | 0.631   |
| <b>Sex</b>                 |              |                     |             | 0.714   |
| Female                     | 52 (56.5%)   | 28 (58.3%)          | 24 (54.5%)  |         |
| Male                       | 40 (43.5%)   | 20 (41.7%)          | 20 (45.5%)  |         |
| Underlying diseases        | 27 (29.3%)   | 14 (29.1%)          | 13 (29.5%)  | 0.968   |
| Previous resection         | 11 (12.0%)   | 6 (12.5%)           | 5 (11.4%)   | 0.867   |
| Previous embolization      | 43 (46.7%)   | 22 (45.8%)          | 21 (47.7%)  | 0.856   |
| <b>Side</b>                |              |                     |             | 0.856   |
| Right                      | 49 (53.3%)   | 26 (54.2%)          | 23 (52.3%)  |         |
| Left                       | 43 (46.7%)   | 22 (45.8%)          | 21 (47.7%)  |         |
| <b>Location</b>            |              |                     |             | 0.324   |
| Frontal                    | 35 (38%)     | 21 (43.8%)          | 14 (31.8%)  |         |
| Temporal                   | 18 (19.6%)   | 10 (20.8%)          | 8 (18.2%)   |         |
| Parietal                   | 24 (26.1%)   | 10 (20.8%)          | 14 (31.8%)  |         |
| Occipital                  | 8 (8.7%)     | 5 (10.4%)           | 3 (6.8%)    |         |
| Insular                    | 2 (2.2%)     | 0 (0%)              | 2 (4.5%)    |         |
| Cerebellum                 | 3 (3.3%)     | 2 (4.2%)            | 0 (0%)      |         |
| Corpus callosum            | 2 (2.2%)     | 0 (0%)              | 2 (4.5%)    |         |
| <b>Presenting symptoms</b> |              |                     |             | 0.532   |
| None                       | 1 (1.1%)     | 1 (2.1%)            | 0 (0%)      |         |
| Headache                   | 8 (8.7%)     | 3 (6.3%)            | 5 (11.4%)   |         |
| Hemorrhage                 | 52 (56.5%)   | 31 (64.6%)          | 21 (47.7%)  |         |
| Seizure                    | 24 (26.1%)   | 10 (20.8%)          | 14 (31.8%)  |         |
| Neurological deficit       | 2 (2.2%)     | 1 (2.1%)            | 1 (2.3%)    |         |
| Other                      | 5 (5.4%)     | 2 (4.2%)            | 3 (6.8%)    |         |
| <b>Emergency case</b>      | 13 (14.1%)   | 12 (25%)            | 1 (2.3%)    | 0.002*  |
| <b>Preoperative GCS</b>    | 15 ± 2.53    | 15 ± 3.16           | 15 ± 1.39   | 0.028*  |
| <b>Preoperative MRS</b>    | 1 ± 1.47     | 1 ± 1.65            | 1 ± 1.24    | 0.505   |

\* indicates statistically significant difference (p &lt; 0.05)

**TABLE 2.** Spetzler-Martin grade and supplementary score.

| Characteristic                 | Total<br>(N=92) | Conventional<br>(N=48) | IOCA<br>(N=44) | p-value |
|--------------------------------|-----------------|------------------------|----------------|---------|
| <b>Size of AVM</b>             |                 |                        |                | 0.946   |
| < 3 cm                         | 56 (60.9%)      | 30 (62.5%)             | 26 (59.1%)     |         |
| 3-6 cm                         | 34 (36.9%)      | 17 (35.4%)             | 17 (38.6%)     |         |
| > 6 cm                         | 2 (2.2%)        | 1 (2.1%)               | 1 (2.3%)       |         |
| Eloquent area                  | 15 (16.3%)      | 8 (16.7%)              | 7 (15.9%)      | 0.922   |
| Deep venous drainage           | 18 (19.5%)      | 7 (14.6%)              | 11 (25%)       | 0.208   |
| <b>Spetzler-Martin grading</b> |                 |                        |                | 0.481   |
| 1                              | 39 (42.4%)      | 20 (41.7%)             | 19 (43.2%)     |         |
| 2                              | 36 (39.1%)      | 23 (47.9%)             | 13 (29.5%)     |         |
| 3                              | 16 (17.4%)      | 4 (8.3%)               | 12 (27.5%)     |         |
| 4                              | 1 (1.1%)        | 1 (2.1%)               | 0 (0%)         |         |
| <b>Age group</b>               |                 |                        |                | 0.360   |
| < 20 years                     | 28 (30.4%)      | 16 (33.3%)             | 12 (27.3%)     |         |
| 20-40 years                    | 39 (42.4%)      | 17 (35.4%)             | 22 (50%)       |         |
| > 40 years                     | 25 (27.2%)      | 15 (31.3%)             | 10 (22.7%)     |         |
| Prior bleeding                 | 61 (66.3%)      | 35 (72.9%)             | 26 (59.1%)     | 0.161   |
| Compact nidus                  | 91 (98.9%)      | 47 (97.9%)             | 44 (100%)      | 0.336   |
| <b>Total score</b>             |                 |                        |                | 0.224   |
| 2                              | 7 (7.6%)        | 3 (6.3%)               | 4 (9.1%)       |         |
| 3                              | 28 (30.4%)      | 19 (39.6%)             | 9 (20.5%)      |         |
| 4                              | 24 (26.1%)      | 11 (22.9%)             | 13 (29.5%)     |         |
| 5                              | 19 (20.7%)      | 9 (18.8%)              | 10 (22.7%)     |         |
| 6                              | 13 (14.1%)      | 5 (10.4%)              | 8 (18.2%)      |         |
| 9                              | 1 (1.1%)        | 1 (2.1%)               | 0 (0%)         |         |

one session of intraoperative cerebral angiography after the surgeon initially deemed the resection complete. Residual AVMs were identified intraoperatively in seven patients (15.90%), a rate comparable to that of the conventional group. In most of these cases, additional resection was performed, reducing the number of residual AVMs confirmed on postoperative imaging to three cases (6.81%). When further resection was undertaken, repeat intraoperative angiography was performed selectively rather than routinely.

In the first case, intraoperative imaging revealed a residual AVM, but it was considered unresectable. So, the operation was terminated and residual AVM was expected in postoperative images. This patient was later treated by stereotactic radiosurgery. In the second case, a small nidus was initially overlooked during IOCA, which was falsely interpreted as complete resection (a false-negative result). The residual AVM was later identified on postoperative imaging. In the last case, a residual AVM was observed, and additional resection

was performed. However, repeat angiography was not performed after the additional resection, and postoperative imaging later revealed residual AVM. This case was also classified as a false negative due to the lack of post-resection confirmation during surgery.

### Secondary outcomes

There was no significant difference in acute complications or long-term deficits between the two groups (45.8% vs 29.5%,  $p$ -value = 0.108 and 70.8% vs 59.1%,  $p$ -value = 0.237, respectively). No angiography-related complications were reported. Operative time was significantly longer in the IOCA group ( $6.36 \pm 2.33$  vs  $4.83 \pm 1.98$ ,  $p$ -value 0.001). Postoperative Glasgow Coma Scale scores and length of hospital stay were worse in the conventional group ( $14.29 \pm 1.91$  vs  $15 \pm 0$ ,  $p$ -value = 0.009 and  $19.31 \pm 22.80$  vs  $8.57 \pm 3.73$ ,  $p$ -value = 0.001) (Table 3).

### Radiation exposure

In the IOCA group, the mean DAP was  $35.02 \pm 17.07$  Gy-cm<sup>2</sup>, with a mean effective dose of  $1.4 \pm 0.68$  mSv.

### Rebleeding rate and other complication

Among the 12 cases with residual AVMs across both groups, there were three instances of rebleeding (25%),

whereas no rebleeding occurred in the complete resection group ( $p$ -value < 0.001). Additionally, postoperative seizures during the same admission were more frequent in the incomplete resection group (two cases, 16.6%) compared to the complete resection group (five cases, 6.3%) ( $p$ -value 0.204).

### DISCUSSION

Our findings demonstrate several advantages of intraoperative cerebral angiography (IOCA) in the surgical resection of arteriovenous malformations (AVMs). First, IOCA served as a reliable tool for confirming complete AVM resection. In our study, IOCA demonstrated a positive predictive value of 1.0, a negative predictive value of 0.97, and an overall diagnostic accuracy of 97.8%, respectively. These findings are consistent with a previous study and comparable to standard postoperative imaging.<sup>6</sup> These results highlight the utility of IOCA, particularly in cases where complete resection is difficult to assess visually, such as in anatomically complex or ambiguous lesions. IOCA may also offer significant advantages for less experienced surgeons and in cases involving patients referred from remote areas where follow-up is challenging or access to advanced imaging facilities is limited.

Second, IOCA significantly impacted intraoperative decision-making by identifying residual AVMs and

**TABLE 3.** Secondary outcomes.

| Characteristic                                        | Conventional<br>(N=48) | IOCA<br>(N=44)       | p-value |
|-------------------------------------------------------|------------------------|----------------------|---------|
| Acute complication                                    | 22 (45.8%)             | 13 (29.5%)           | 0.108   |
| Long-term deficit                                     | 34 (70.8%)             | 26 (56.9%)           | 0.237   |
| Missed residual AVM                                   | 9 (18.7%)              | 2 (4.5%)             | 0.036   |
| Operative time (hours), mean $\pm$ S.D.               | $4.83 \pm 1.98$        | $6.36 \pm 2.33$      | 0.001*  |
| Blood loss (mL), mean $\pm$ S.D.                      | $962.71 \pm 1406.36$   | $843.64 \pm 1126.42$ | 0.526   |
| Hospital stay (days), mean $\pm$ S.D.                 | $19.31 \pm 22.80$      | $8.57 \pm 3.73$      | 0.001*  |
| Postoperative GCS, mean $\pm$ S.D.                    | $14.29 \pm 1.91$       | $15 \pm 0$           | 0.009*  |
| Postoperative MRS, mean $\pm$ S.D.                    | $1.46 \pm 1.58$        | $0.95 \pm 1.03$      | 0.198   |
| Time to postoperative image (months), mean $\pm$ S.D. | $11.58 \pm 18.64$      | $13.86 \pm 14.59$    | 0.035*  |
| <b>Modality of follow-up</b>                          |                        |                      |         |
| Cerebral angiography                                  | 28 (58.3%)             | 32 (72.7%)           | 0.328   |

\* indicates statistically significant difference ( $p < 0.05$ )

prompting further resection. In six out of the seven cases with intraoperatively detected residual lesions (13.64%), the surgical procedure was modified to pursue additional resection. Notably, intraoperative imaging also aided the surgeon in precise localization and navigation to the residual nidus. As a result, only two residual AVMs were observed on postoperative imaging in the IOCA group compared to nine in the conventional group. This corresponds to an absolute risk reduction of 14.21% in residual AVMs and a number needed to treat (NNT) of 7.04 ( $p = 0.036$ ).

Lastly, although the overall rate of acute complications did not differ significantly between the two groups ( $p = 0.108$ ), the nature of the complications varied. Among the three patients who experienced rebleeding, two were in the conventional group; both events occurred during the same hospital admission and resulted in severe outcomes. In contrast, the single rebleeding case in the IOCA group presented only with a headache and no neurological deficits. These findings further underscore the importance of achieving complete AVM resection — an outcome that IOCA can help facilitate during the initial surgery — potentially reducing the risk of severe postoperative complications.

Despite the demonstrated benefits of IOCA, false-negative results remain a recognized limitation. In our cohort, IOCA failed to detect residual AVMs in two cases (4.5%), a finding consistent with previously reported in the literature. Both cases highlight important technical and procedural factors that may contribute to missed residual lesions during intraoperative angiography.

Several mechanisms may underlie false-negative IOCA findings. Small residual nidus size, low-flow shunts, transient vasospasm, or temporary thrombosis following resection may obscure residual arteriovenous shunting at the time of angiography. In addition, complex angioarchitecture, deep-seated lesions, or overlapping vascular territories may limit visualization. In one case in our series, a small nidus was initially overlooked and misinterpreted as complete resection, while in another case, residual AVM was identified and further resection was performed but not followed by repeat angiography, ultimately resulting in persistent residual disease on postoperative imaging.

Several strategies may help mitigate the risk of false-negative IOCA results. First, routinely repeat angiography after additional resection may improve diagnostic confidence. Second, obtaining multiple angiographic projections and selectively injecting feeding arteries may enhance detection of small or anatomically complex residual lesions. Third, close collaboration between the operating surgeon and

an experienced neurointerventionalist during image acquisition and interpretation may reduce the likelihood of misinterpretation. Finally, adjunctive intraoperative tools such as indocyanine green (ICG) videoangiography or intraoperative Doppler ultrasonography may provide complementary information.

Additionally, concerns regarding radiation exposure during intraoperative angiography are valid. However, the radiation dose associated with IOCA in our cohort was relatively low (mean:  $1.4 \pm 0.68$  mSv), which is significantly lower than in standard postoperative imaging ( $3.79 \pm 1.77$  mSv). This level of exposure is roughly equivalent to 6–7 months of background natural radiation or a single-phase CT scan, according to established reference data. Thus, the potential risk from radiation appears minimal when weighed against the diagnostic and therapeutic advantages offered by IOCA (Table 4).<sup>17–19</sup>

We also examined outcomes in patients who underwent emergency surgery, recognizing that the urgent nature of these cases often limits the feasibility of comprehensive intraoperative evaluation such as IOCA. Of the 13 emergency cases, only one received IOCA. Although these patients demonstrated significantly different initial and final Glasgow Coma Scale (GCS) scores compared to elective cases, the rate of complete AVM resection did not differ significantly (23.1% vs. 10.1%,  $p = 0.182$ ). This suggests that while emergency status may influence clinical presentation and outcomes, it does not generally impact resection completeness (Table 5).

### Limitations and future directions

This study has several limitations that warrant consideration. First, its retrospective design is inherently associated with limitations such as reliance on existing medical records, potential missing data, and limited control over confounding variables. In addition, as a single-center study, the results may reflect institutional practice patterns, surgeon experience, and available resources, which could limit the generalizability of the findings to other centers with different patient populations or treatment approaches.

Second, selection bias cannot be entirely excluded. The decision to perform IOCA was not standardized and may have been influenced by surgeon preference, lesion characteristics, or intraoperative findings. Furthermore, some patients were excluded due to the absence of postoperative imaging or the use of other intraoperative adjuncts, which may have affected group comparability and introduced additional bias.

Third, certain data elements were incomplete. In

**TABLE 4.** Radiation exposure.

| Procedure                           | Study                             | Mean DAP (Gy-cm <sup>2</sup> ) | Energy (mSv) |
|-------------------------------------|-----------------------------------|--------------------------------|--------------|
| Intraoperative cerebral angiography | Our study                         | 35.02 ± 17.07                  | 1.4 ± 0.68   |
| Diagnostic cerebral angiography     | Our study                         | 94.93 ± 44.30                  | 3.79 ± 1.77  |
| Diagnostic cerebral angiography     | Ihn YK. et al, 2016 <sup>17</sup> | 106.2 ± 66.4                   |              |
| CT brain single phase               | Wonglao et al, 2022 <sup>18</sup> |                                | 1.6-2.08     |
| CTA brain multiphase                | Wonglao et al, 2022 <sup>18</sup> |                                | 2.89-5.46    |

**TABLE 5.** Subgroup analysis of emergency cases.

| Characteristic                            | Emergency (N=13) | Elective (N=79) | p-value  |
|-------------------------------------------|------------------|-----------------|----------|
| Preoperative Glasgow coma scale (median)  | 8 (3,15)         | 15 (13,15)      | < 0.001* |
| Postoperative Glasgow coma scale (median) | 15 (7,15)        | 15 (9,15)       | < 0.001* |
| Residual AVMs                             | 3 (23.1%)        | 8 (10.1%)       | 0.182    |

\* indicates statistically significant difference (p < 0.05)

particular, detailed information regarding hospital costs and cumulative radiation exposure was unavailable for some patients, limiting a comprehensive evaluation of the economic implications and radiation-related risks associated with IOCA.

Finally, postoperative imaging modalities were not uniform across all patients. Although digital subtraction angiography (DSA) is considered the reference standard for detecting residual AVMs, approximately one-third of patients in this study were evaluated using CTA or MRA alone. Previous studies have reported that MRI has a sensitivity of approximately 75–90% and a specificity of 90–100% for detecting AVMs, while CTA demonstrates higher sensitivity, around 90%, with specificity ranging from 95–100%.<sup>22,23</sup> Despite these favorable diagnostic performances, both modalities may be less sensitive than DSA in identifying small residual nidus, particularly in small or complex AVM lesions. As a result, the use of CTA or MRA alone may have led to an underestimation of residual AVM rates in a subset of patients.

Future studies with prospective designs, standardized criteria for IOCA utilization, and uniform postoperative imaging protocols would help address these limitations.

Multicenter collaborations may further improve generalizability and allow for larger sample sizes, facilitating subgroup analyses and adjustment for confounding factors. In addition, randomized controlled trials comparing IOCA with other intraoperative adjuncts could provide valuable alternatives for centers without access to IOCA.

## CONCLUSIONS

Although not infallible, intraoperative cerebral angiography appears to be a safe and potentially effective adjunct during AVM resection, with a low observed complication rate and limited additional radiation exposure. Its use facilitates the detection of residual disease and enables immediate corrective action, which was associated with a lower incidence of residual AVMs, as well as reduced postoperative rebleeding and shorter hospital stays.

## Data Availability Statement

None.

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None.

## DECLARATIONS

### Grants and Funding Information

No grants or funding.

### Conflict of Interest

No conflicts of interest.

### Registration Number of Clinical Trial

Not applicable.

### Author Contributions

Conceptualization and methodology, K.T., T.A. ; Formal analysis, Visualization and writing – original draft, K.T. ; Writing – review and editing, T.A. ; All authors have read and agreed to the final version of the manuscript.

### Use of Artificial Intelligence

Use of artificial intelligence (ChatGPT version 5.0-5.2) for checking the manuscript for grammatical errors.

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