

# Pediatric bypasses for aneurysms and skull base tumors: short- and long-term outcomes

## Clinical article

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**Object.** Cerebral bypass is a useful microsurgical technique for the treatment of unclippable aneurysms and invasive skull base tumors. The authors present the largest reported series of cerebrovascular bypasses in the pediatric population. They describe the short- and long-term clinical and radiographic outcomes of extracranial-intracranial and local bypasses performed for complex cerebral aneurysms and recurrent, invasive, and malignant skull base tumors in pediatric patients.

**Methods.** A consecutive series of 17 pediatric patients who underwent revascularization were analyzed retrospectively for indications, graft patency, and neurological outcomes.

**Results.** The mean age was 12 years (median 11 years, range 4–17 years), and there were 7 boys (41%) and 10 girls (59%). A total of 18 bypasses were performed in 17 patients and included 10 aneurysm cases (55.5%) and 8 tumor cases (45%). Of these 18 bypasses, there were 11 (61.1%) extracranial-intracranial bypasses (10 saphenous vein grafts [90%] and 1 radial artery graft [10%]), 1 side-to-side anastomosis (5.5%), 2 intracranial reimplants (11.1%), and 4 interposition bypass grafts (22.2%; 2 radial artery grafts, 1 saphenous vein graft, and 1 lingual artery graft). The mean clinical follow-up was 40.5 months (median 24 months, range 3–197 months). The mean radiographic follow-up was 40 months (median 15 months, range 9–197 months). Eighty-two percent of patients (14 of 17) achieved a modified Rankin Scale score between 0 and 2; however, 2 patients died of disease progression during long-term follow-up. The short-term (0- to 3-month) graft patency rate was 100%. Two patients had graft stenosis (11.7%) and underwent graft revisions. Two patients (11.1%) with giant middle cerebral artery aneurysms (> 25 mm) had strokes postoperatively but recovered without a persistent neurological deficit. One patient observed for 197 months showed a stable dysplastic change at the end of the graft. The long-term graft patency was 100% with a mean follow-up of 40 months. There were 2 deaths in the cohort during follow-up; both patients died of malignant tumors (osteogenic sarcoma and chondrosarcoma).

**Conclusions.** The authors conclude that in properly selected cases, bypasses can be safely performed in patients with aneurysms and skull base tumors. The bypasses remained patent over long periods of time despite the growth of the patients.

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**KEY WORDS** • extracranial-intracranial cerebral bypass • complex aneurysm • pediatric neurosurgery • skull base tumor • outcome • vascular disorders

CEREBRAL bypass is a useful microsurgical technique in the treatment of complex intracranial aneurysms<sup>2,4,5,13,19–21,23,27,29,31,33,38,40,41,43–46</sup> and skull base tumors.<sup>1,24,26,27,34,39,42</sup> In well-selected patients, this

*Abbreviations used in this paper:* ACoA = anterior communicating artery; BA = basilar artery; CTA = CT angiography; DSA = digital subtraction angiography; EC-IC = extracranial-intracranial; ICA = internal carotid artery; MCA = middle cerebral artery; mRS = modified Rankin Scale; NF = neurofibromatosis; PCA = posterior cerebral artery; RAG = radial artery graft; STA = superficial temporal artery; SVG = saphenous vein graft.

technique has been successfully used to provide alternative blood flow after carotid artery sacrifice,<sup>39</sup> to preserve flow after small vessel sacrifice, and to provide collateral flow prior to arterial trapping.<sup>23</sup> Various microsurgical series have shown good long-term outcomes and patency rates in adult patients.<sup>2,19,23,30,31,38,45</sup> However, in pediatric patients, there are limited data available to validate the use of high- and low-flow bypasses in complex aneu-

This article contains some figures that are displayed in color online but in black-and-white in the print edition.

rysms and skull base tumors.<sup>3,7,9,11,12,15,16,18,22,25,28,32,33,36,37,47</sup> In particular, the long-term durability of these pediatric grafts as these patients mature into adolescence and adulthood is not well described in the literature beyond case reports and small case series. We analyzed a cohort of 17 children in whom different types of bypass procedures were performed. Perioperative, short-term, and long-term clinical and radiographic outcomes were analyzed.

## Methods

### Study Design

All pediatric patients (defined as 0–17 years of age) who underwent bypass procedures for aneurysms and tumors were identified from an institutional review board–approved retrospective cerebrovascular registry. Information regarding clinical presentation and the patient’s neurological status was obtained from patient records or telephone interviews. All patients with unclippable aneurysms and invasive tumors with vascular encasement underwent DSA. When the lesion involved the ICA, ipsilateral angiography with common carotid compression was performed and the collateral vessels were evaluated by injecting the contralateral ICA and 1 vertebral artery.<sup>21,30,31,38</sup> Preoperatively, graft caliber was measured using duplex ultrasonography.<sup>23,38</sup>

Postoperative graft patency was determined by CTA, catheter angiography, and duplex ultrasonography. Digital subtraction angiography or CTA was performed immediately postoperatively, at 6 months, and at 18 months. Patients with tumors underwent MRI follow-up at 6 months, 1 year, and then every 2 years to evaluate for recurrence. All patients underwent CTA at the 2-year postoperative period. Further angiographic follow-up after the 2-year point was less frequent and regular. Information gathered from angiograms included the caliber of the proximal and distal anastomosis, caliber of the graft (graft patency), extent of the collateral circulation, and any other abnormalities such as formation of a new aneurysm. Information about surgical and endovascular repair and pathology reports of the graft tissues were reviewed in cases in which graft repair was done. Any observed narrowing of  $\geq 50\%$  was considered stenosis. The mRS was used to evaluate the clinical outcomes, and scores were assigned to the physical examination reports or telephone interviews by the research fellow (F.T.).

### Indication for Bypass

Indications for bypass for aneurysms included giant aneurysms ( $\geq 25$  mm) with complex anatomy, presence of calcification or thrombosis or perforator or branch vessels arising from the neck or sac of the aneurysm, ruptured aneurysms with unfavorable geometric dimensions for simple coiling (broad neck, dome-to-neck ratio  $< 1.5$ ) or clip reconstruction, fusiform morphology, or the presence of isolated circulation with planned parent vessel occlusion. The main indications for performing bypass procedures for tumors were carotid encasement or invasion with recurrent, malignant tumor and/or poor collateral flow.

### Preoperative Evaluation

The first step after the decision to perform a bypass is to examine the donor as well as the recipient vessel. Donor vessels, for example, external or internal carotid arteries, were evaluated by angiography. Next was the choice of the graft material, which depends on the extent of collateral flow, caliber of the recipient vessel, and availability of the graft material. If the vessel sacrificed was of a small caliber, a local bypass (side-to-side anastomosis, interposition grafts, and reimplantation) was the preferred choice. The donor grafts included the STA, the lingual artery, and the occipital artery in most cases. If a high-flow bypass was deemed necessary, the graft chosen was an RAG or the SVG depending on the availability of the graft vessel. In children younger than 12 years, in whom the RAG was small in diameter, the SVG was the only alternative. Graft vessel diameters were evaluated using duplex ultrasonography; an RAG  $> 2$  mm and an SVG  $\geq 2.5$  mm were the preferred choices.<sup>9,10</sup> When an RAG was considered, an Allen test was performed using Doppler monitoring of the palmar arch to see if it could be safely removed. Age was not an absolute limiting factor considered for RAG extraction as long as the donor RAG was  $\geq 2$  mm. In 1 case, an RAG was extracted from a 4-year-old girl and successfully repaired by saphenous vein interposition bypass graft. Similarly, recipient vessels  $\geq 2$  mm were considered suitable for high-flow bypass. In cases of in situ or side-to-side anastomosis, we select vessels with diameters  $\geq 1$  mm as a suitable recipient.<sup>23,29,31</sup>

### Graft Preparation

The RAG was exposed from the wrist back to the brachial artery bifurcation, along with its accompanying veins. After extraction, the graft was flushed with heparinized saline, and terminal ends were devoided of the veins and adventitia. The graft was expanded using the pressure distension technique.<sup>23,38</sup> In this technique, an oblique arterial cut is fashioned along the distal end of the graft, and a fish mouth technique is used to slightly enlarge the graft tip.<sup>23,38</sup>

Preoperative duplex ultrasonography and marking are used to map the saphenous vein in the leg.<sup>23,38</sup> After extraction, it is flushed through with heparinized saline and distended at slight pressure to release the spasm of the vessel. The flow direction in the vein is verified before anastomosis by flushing the graft with heparinized saline and confirming free flow of fluid from the other end.<sup>38</sup> We do not perform valvotomies prior to use.

### Anesthesia and Neuromonitoring

All patients were placed on an aspirin regimen (1–10 mg/kg/day). In 2 cases, clopidogrel was administered in dosage of 2–5 mg/kg/day immediately postoperatively due to mild or moderate graft stenosis identified angiographically. During the anastomosis procedure, all patients were placed in burst suppression with propofol, and intraoperative monitoring (somatosensory evoked potentials, motor evoked potential, and electroencephalography) was routinely performed. Intraoperative heparin was routinely administered as a bolus. Typical anti-

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coagulation regimens included a loading dose of 75–100 U/kg followed by a maintenance dose of 28 U/kg/hr for children younger than 1 year and 20 U/kg/hr for children older than 1 year (based on decreased normal infant anti-thrombin levels. The dose in older children, 18 U/kg/hr, is similar to that in adults.<sup>23,29–31,33,38</sup>

### High-Flow Bypass Technique

There was no difference in the microsurgical technique of pediatric bypasses compared with the procedures in adults.<sup>23,29,31</sup> In the anterior circulation the M<sub>2</sub> segment and in the posterior circulation the P<sub>2</sub> segment were the vessels of choice at the recipient end of the bypass as both are typically devoid of perforators. However, in the case of an SVG, a branch point is selected if possible to facilitate vessel size match. The superior cerebellar artery may be used as a recipient in case of a hypoplastic PCA. In all cases of high-flow bypass, the distal anastomosis was performed first followed by proximal anastomosis using 9-0 or 8-0 nylon for extracranial sutures. A small rubber dam measuring 0.5 × 1 cm was placed under the recipient vessel to isolate it, and the recipient vessel was covered with papaverine-soaked Gelfoam (Pfizer Inc.) to relax vasospasm of the vessel. Temporary clips were applied on the recipient artery, and Spetzler microsuction (NMT Medical, Inc.) was placed in the vicinity of the anastomosis to aspirate CSF on a continuous basis, and an end-to-side anastomosis was performed at the distal end. The proximal anastomosis was performed in an end-to-side fashion when the external carotid artery was the donor vessel, or in an end-to-end fashion, when the ICA was the donor vessel.

### Low-Flow Bypass Technique

Low-flow and local bypasses included the STA-MCA bypass, A<sub>3</sub>-A<sub>3</sub> side-to-side anastomosis, M<sub>3</sub> reimplantation, and an RAG or lingual artery interposition graft between 2 cerebral arteries; 10-0 or 9-0 nylon was used for the anastomosis. After the anastomosis was completed, the flow in the graft was checked using a Doppler flow probe (Mizuho micro Doppler, Mizuho America, Inc.) and indocyanine green angiography.<sup>23,30,31,38</sup>

## Results

A total of 18 bypasses were performed in 17 patients who ranged in age between 4 and 17 years (mean 12 years). Patient ages are shown in Table 1. There were 7 boys and 10 girls. There were 10 aneurysms (3 ruptured and 7 unruptured) and 8 tumors (5 malignant [2 osteosarcomas, 2 chondrosarcomas, and 1 giant cell tumor] and 3 benign [1 recurrent meningioma and 2 recurrent chordomas]). The treated cohort included 6 MCA, 1 PCA, 1 ACoA, and 2 basilar artery aneurysms. There were 3 small aneurysms (3.7, 4, and 6.2 mm) and 7 large aneurysms (mean 24.2 mm, range 14–44 mm). A total of 10 bypasses were performed in patients with aneurysms including 4 end-to-side (4 SVGs), 1 side-to-side, 2 intracranial reimplants, and 3 interposition bypass grafts (2 RAGs and 1 lingual artery graft) (Table 1).

**TABLE 1: Patient demographics and indications for bypass**

Parameter	Value*
age	
mean/median/range	12/11/4–17 yrs
spread (yrs)	
4–6	2
7–9	2
10–12	5
13–15	6
16–17	2
no. of male/female patients	7/10
no. of tumors	8 (47.1)
osteosarcoma	2
chondrosarcoma	2
meningioma (NF2)	1
chordoma	2
giant cell	1
no. of aneurysms	10 (52.9)
ruptured	3
MCA	2
PCA	1
unruptured	
MCA (1 new aneurysm)	3
ACoA (NF1)	1
BA	2
no. of aneurysms treated (mm)	
small (0–6)	3
medium (7–14)	2
large (19–24)	1
giant (>25)	4
mean/median/range size of aneurysms	20.22/20/3.7–44 mm
no. of bypasses	18
EC-IC	11 (61.1)
local	7 (38.8)
interposition	5
side-to-side	1
reimplantation	1
no. of grafts used	
SVG	11
RAG	3
lingual artery	1

\* Values are the number of cases (%) unless noted otherwise.

In the aneurysm group, there was complete occlusion of the aneurysm in 9 (90%) of 10 cases. One 6-year-old girl with a giant fusiform aneurysm involving the vertebral and basilar arteries (2 previous coiling procedures failed) underwent saphenous vein grafting from the V<sub>2</sub> segment of the vertebral artery to the right PCA, followed by proximal occlusion of the aneurysm. The postoperative angiogram showed a residual aneurysm that was treated with endovascular coil embolization with complete oblit-

eration of the aneurysm. One patient (Case 3) had formation of a new aneurysm distal to the graft (RAG) at 6 months postoperatively that was treated by microsurgical resection of the aneurysm and revision using a lingual artery interposition graft.<sup>7,37</sup> Another patient presented with regrowth of a residual aneurysm at 8 months and was treated by endovascular embolization.<sup>7,14</sup> Subsequent 6-month follow-up angiography confirmed persistent obliteration.

There were 8 skull base tumors, including 2 chondrosarcomas, 2 chordomas, 1 giant cell tumor, 2 osteogenic sarcomas, and 1 meningioma. Seven EC-IC bypasses (6 SVGs and 1 RAG) and 1 SVG interposition bypass were performed (Tables 1 and 2). Gross-total resection was achieved in 7 of 8 cases. The patient who underwent subtotal resection demonstrated a small residual tumor in the cavernous sinus that required postoperative radiotherapy.<sup>32</sup>

#### *Donor and Recipient Vessel Diameters*

Vessel diameters were measured via preoperative imaging studies (DSA, CTA, or vascular ultrasonography). The average high-flow bypass donor vessel diameter measured 5.4 mm (range 3.6–5.7 mm). High-flow bypass recipient vessel diameters measured an average of 3.2 mm (range 2.6–4.0 mm). The average vessel diameter for in situ or side-to-side bypasses measured 1.5 mm (range 1.2–2.2 mm). These values reflect very similar donor and recipient artery diameters to those reported for cerebral bypasses in the adult population.<sup>23,29,31</sup>

#### *Clinical and Radiographic Outcome and Complications*

Of the initial 17 bypasses performed, 16 patients (94.4%) achieved an mRS score less than 2 at short-term (0–3 months) follow-up. One patient with NF2 had a preoperative mRS score of 5, and this patient was discharged to a skilled nursing care facility. Two patients with giant MCA aneurysms suffered from postoperative ischemic strokes. One patient had a small MCA territory stroke, leading to mild dysarthria that resolved completely on follow-up. The other patient suffered from a frontoparietal stroke with left arm and leg weakness on discharge, which recovered completely without any residual deficit at the 6-week follow-up. There were 2 cases of mild graft stenosis, but no graft occlusions were encountered. The short-term graft patency was 100%. One of the graft stenoses was detected on intraoperative Doppler flow scanning and was repaired by resection and reanastomosis, but mild stenosis was noted again on postoperative CTA as well as on follow-up CTA at 1 year. The second patient developed a focal stenosis in the RAG performed for MCA aneurysm; this patient developed a new aneurysm distal to the graft site involving the recipient artery at the 6-month follow-up. The graft was resected along with the aneurysm and was replaced by lingual artery graft. One patient suffered a vocal cord injury due to intubation, which subsequently recovered.

On long-term clinical follow-up (mean 40.5 months, median 24 months, range 3–197 months), 12 (70.5%) of 17 patients had an outcome mRS score of 0–2. One patient with a WHO Grade I meningioma required lifetime de-

pendent care (a patient with NF2). Two patients died of disease progression within 2 years postoperatively; one had chondrosarcoma and the other had osteogenic sarcoma. On long-term radiographic follow-up (mean 40 months, median 15 months, range 9–197 months), the graft patency rate was 100%. There was formation of one new aneurysm distal to the high-flow graft (RAG), and one residual aneurysm had a rapid recurrence (within 6 months) and was treated by endovascular embolization.<sup>5,19,31,44</sup>

## **Illustrative Cases**

### *Case 1*

This 10-year-old boy with a history of acute lymphocytic leukemia and past cranial irradiation presented with an osteogenic sarcoma of the sphenoclivar region. This extended into the right maxilla and skull base area and involved the right ICA in the petrocavernous segments (Fig. 1A). Surgery was performed to achieve a gross-total resection of the tumor in 3 steps. The first step was cerebral angiography, a right carotid cross-compression study (Fig. 1B and C), and embolization. Following this, a bypass was performed using an SVG from the right cervical ICA to the supraclinoid ICA (Fig. 1D). This was followed by bifrontal craniotomy and biorbital osteotomy, right optic nerve decompression, resection of the sphenoclivar cavernous sinus tumor extradurally including the cavernous ICA, and a transfacial degloving approach from below to resect the tumor (Fig. 1E). At the 6-year follow-up the patient is doing well at school with an mRS of 0, and the bypass is widely patent (Fig. 1F).

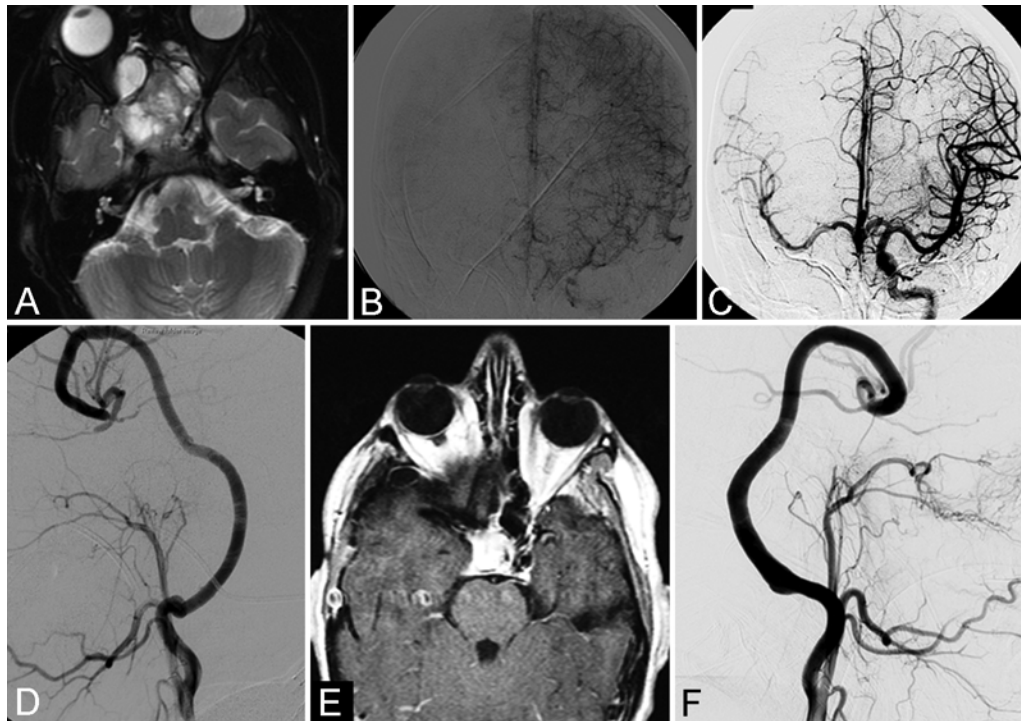
### *Case 2*

This 13-year-old boy had an incidental discovery of a giant calcified, left MCA aneurysm, 3 cm in size, on MRI performed after a minor head injury (Fig. 2A). Cerebral angiography revealed a giant aneurysm that occupied the entire distal M<sub>1</sub> segment and the M<sub>1</sub>-M<sub>2</sub> junction, which arose just distal to the lenticulostriate branches (Fig. 2B). A small inferior M<sub>2</sub> branch arose from the lower aspect of the aneurysm and came around it, and there were 3 perforating vessels arising from the upper aspect of the aneurysm. Because of the complex anatomy of the aneurysm neck, the surgical plan was trapping and bypass. The patient underwent a left frontotemporal craniotomy, orbital osteotomy, and SVG bypass from the cervical ICA to the intracranial M<sub>2</sub> segment, trapping and excision of the aneurysm, and reconstruction of the trifurcation of the MCA by endarterectomy and suturing. Postoperatively, the patient suffered from a left MCA territory stroke (Fig. 2C), with mild dysarthria that resolved completely on the follow-up images. The postoperative angiogram revealed occlusion of the aneurysm, a patent bypass graft (Fig. 2D), and filling of the MCA territory through the SVG (Fig. 2E). Follow-up CTA was performed at 4 years and showed a patent bypass graft (Fig. 2F). The patient had no neurological deficit, and he had an mRS score of 0.

### *Case 3*

This 13-year-old boy presented with a history of





**Fig. 1.** Case 1. **A:** Magnetic resonance image obtained in a 10-year-old boy with a history of acute lymphocytic leukemia and cranial radiation, who presented with sphenoclivar osteogenic sarcoma with involvement of the right ICA. **B:** Preoperative angiogram with left ICA injection showing cross-filling after compressing the right common carotid artery, but poor flow. **C:** Angiogram showing slow venous filling. **D:** The patient underwent a right temporal craniotomy, biorbital osteotomy, and optic nerve decompression. The postoperative angiogram shows an SVG bypass from the cervical ICA to the supraclinoid ICA. **E:** Postoperative MR image obtained after the second-stage surgery, showing a complete tumor resection. The patient had an mRS score of 0 at the 3-month follow-up. **F:** Follow-up MR angiogram obtained at 6 years, showing a patent bypass graft.

severe headaches for 1 month. Workup revealed a large fusiform aneurysm arising from the anterior parietal branch of the right MCA (Fig. 3A). The patient underwent a frontotemporal craniotomy, resection of the aneurysm, and placement of a radial artery M<sub>3</sub>-M<sub>3</sub> interposition bypass graft (Fig. 3B). The postoperative angiogram showed complete exclusion of the aneurysm and a mild focal stenosis of the graft at the proximal anastomosis site (Fig. 3C). Postoperatively, the patient exhibited moderate left-sided weakness, facial droop, and dysarthria from a stroke in the MCA distribution (Fig. 3D). He was discharged to inpatient rehabilitation and ultimately recovered completely. At 4 months, the patient presented with headache recurrence. He underwent cerebral angiography that showed formation of a new aneurysm distal to the RAG (Fig. 3E).<sup>22</sup> The patient underwent additional surgery, and the aneurysm was resected along with the graft and was replaced by a lingual artery graft (Fig. 3F). The patient did well, and a follow-up angiogram at obtained at 32 months showed a patent bypass graft and no new aneurysm formation (Fig. 3G and H).

#### Case 4

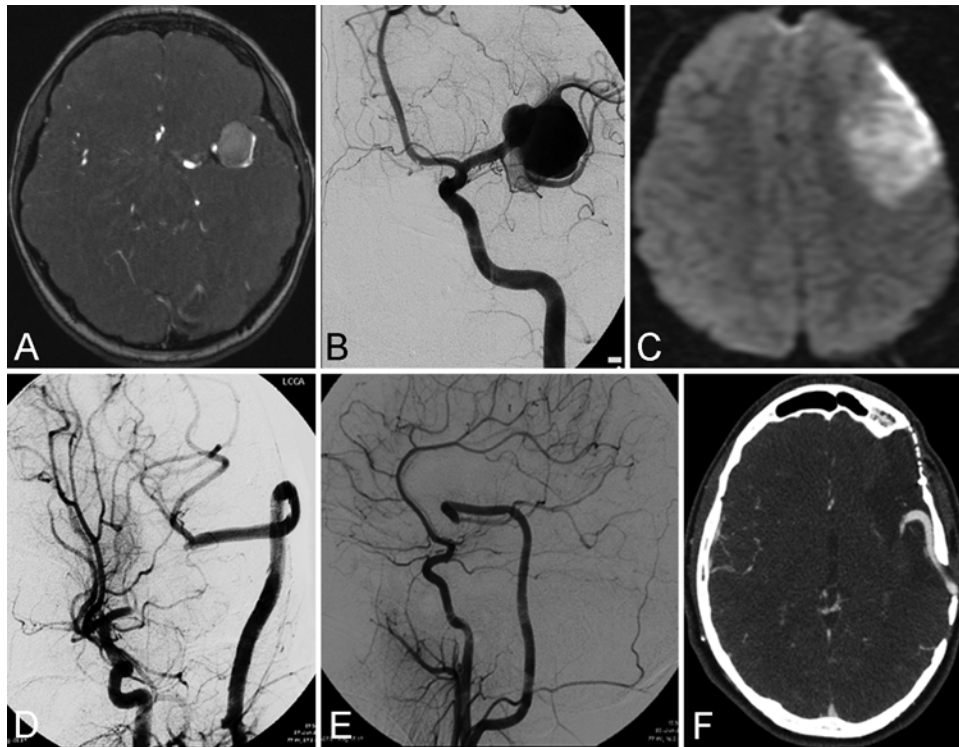
This 15-year-old girl presented with progressive neurological decline, with stupor and quadriparesis. The workup revealed a giant fusiform aneurysm of the BA (Fig. 4A). She underwent aneurysm excision along with saphenous vein grafting from the cervical ICA to the

BA under deep hypothermic circulatory arrest. Postoperatively, her condition gradually improved to an mRS score of 1 at the 3-month follow-up. Her postoperative angiogram revealed complete exclusion of the aneurysm from the circulation and a patent bypass (Fig. 4B). Her last follow-up occurred after 16 years. She had completed a master's degree and was working full time. She had an mRS score of 1, reflecting unilateral hearing loss but no other deficits. Her MR angiography study showed no aneurysm and a patent SVG graft with mild dilation noted at the distal end that remains unchanged for the last several years (Fig. 4C). This patient was previously reported on in a case report with short-term follow-up.<sup>44</sup>

#### Discussion

The use of cerebral bypass for treatment of unclippable intracranial aneurysms and complex skull base tumors is a well-known technique.<sup>1,2,4-21,23,41,42</sup> While a tremendous amount of data is available for moyamoya disease in children, the long-term viability of surgically created bypass grafts in the non-moyamoya pediatric population is only evident anecdotally. Bypass for flow preservation has not been well studied in the pediatric neurosurgery literature, except for in case reports and scattered cases embedded within larger adult patient series.

Overall in the literature, a total of 33 cases of pediatric bypasses have been reported.<sup>3,7,9,11,14-16,18,22,25,28,32,33,47</sup>



**FIG. 2.** Case 2. **A:** Magnetic resonance image obtained in a 13-year-old boy, showing a giant, calcified thrombosed MCA aneurysm. **B:** Preoperative angiogram showing perforator branches arising from the aneurysm. **C:** Postoperative MR image showing a left MCA territory infarct. **D:** Postoperative angiogram showing an SVG bypass from the cervical ICA to the intracranial M<sub>2</sub>-MCA. **E:** Postoperative angiogram showing the MCA branches being filled up by the graft. **F:** Follow-up CT angiogram obtained at 4 years, showing a patent graft.

Twenty-two cases<sup>3,7,14,15,22,33</sup> had no clear reported radiographic follow-up. Of the remaining 11 cases,<sup>7,14,28,32,33,47</sup> the mean radiographic follow-up is 49 months, with a range of 5–155 months. In comparison, our series contributes 17 additional patients with follow-up ranging from 6 months to more than 16 years and a mean of 38.6 months. Hence, this single series represents the largest follow-up reported in the literature, permitting us to make some observations about long-term findings in this rare subgroup.

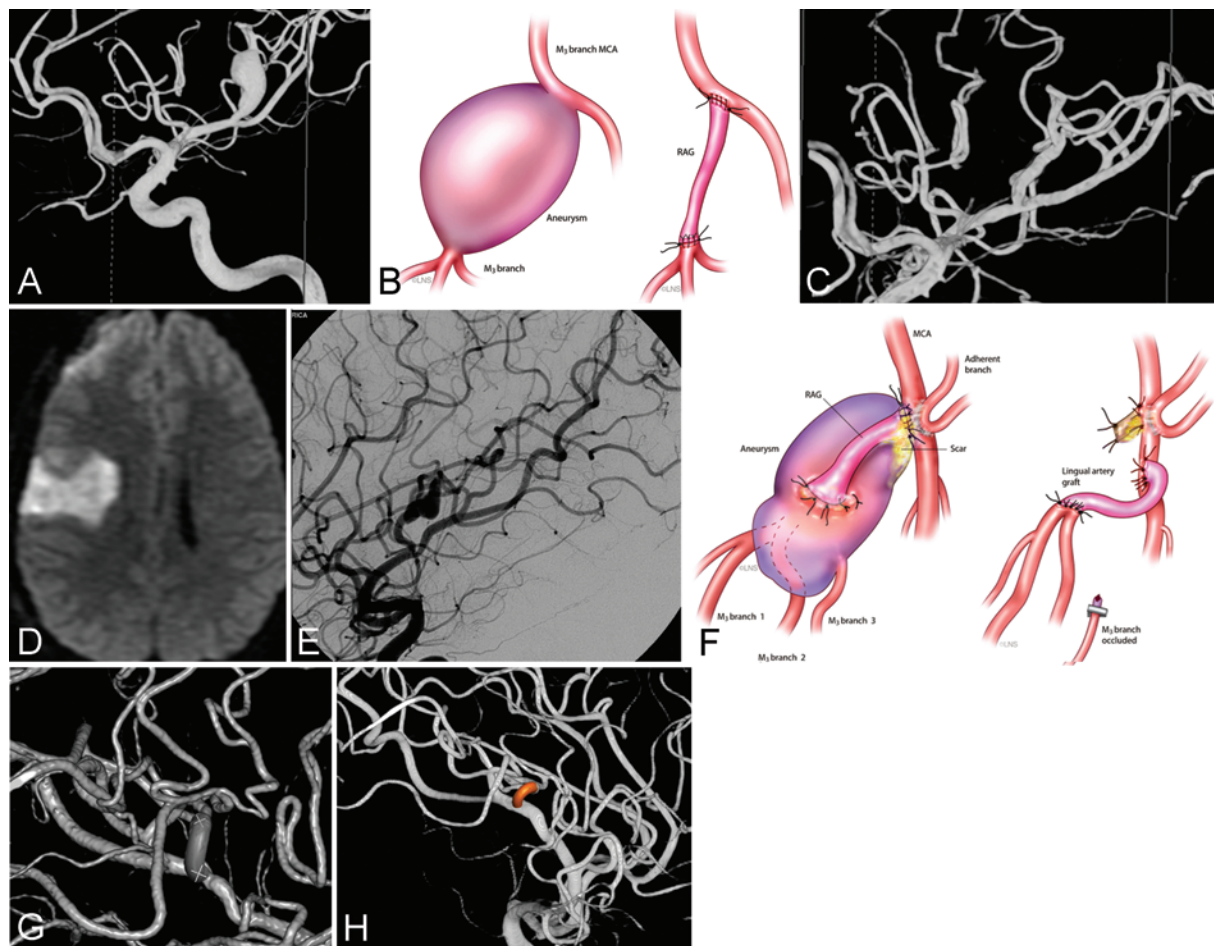
We report these data in an attempt to analyze these long-term outcomes. The obvious concern in young patients is the durability of a bypass graft as the child matures into adulthood. Questions exist regarding procedural complication rates, graft durability over many years, the fate of grafts (particularly EC-IC bypasses during pubertal growth), and whether collateral flow develops over time that obviates the need for the bypass.

Our data indicate that the durability of pediatric bypass grafts is excellent. The patency rate of pediatric bypasses for aneurysm or tumor was high, with 100% of the grafts patent postoperatively (Table 2). During follow-up, 2 of 18 bypasses developed stenosis within 1 year of initial treatment. One of these required intraoperative revision but no further therapy, and the other was treated successfully with antiplatelet therapy. However, no other case developed flow limitations or graft occlusions in a follow-up period averaging nearly 3.5 years and extending up to 16.4 years (Fig. 4). The delayed development of significant collateral flow was not observed angiographically

during this extended follow-up in any case. In our series, 2 patients (11%) suffered a perioperative stroke, both of whom recovered completely in the follow-up period. A comparison of these results with other series in the adult bypass literature where perioperative stroke and graft occlusion rates ranged from 4% to 14% and 5% to 13%, respectively,<sup>17,31,33</sup> indicates that the technical feasibility of pediatric bypasses is equal to or higher than adult counterparts despite the smaller anatomical size of donor and recipient arteries. Because these bypasses preserve and maintain normal flow, they are vital to proper cerebral hemodynamics, and collateral channel formation appears to be unnecessary. Unlike revascularization bypasses for moyamoya disease or ischemia, successful preservation of flow does not appear to trigger growth factors for collateral flow development. Hence, these grafts do not progressively attenuate or occlude over time, a phenomenon that can be seen in adult bypasses that “temporize” ischemia until collaterals develop.

This leads to several observations: 1) These conduits were imperative for not merely proper short-term but also long-term blood flow to the bypassed vascular territory. 2) The pediatric cerebral vasculature may be more adaptable to bypass grafts given the low rate of perioperative complications and the high rate of graft patency during follow-up compared with adult bypasses. 3) The high long-term patency in this pediatric cohort illustrates that graft stenosis from intimal hyperplasia or hemodynamic shear stress appears to be an early (within 1 year

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**FIG. 3.** Case 3. **A:** Three-dimensional angiogram showing a large saccular aneurysm arising from the anterior parietal branch of the MCA. **B:** Intraoperative drawing showing the RAG interposition graft. **C:** Postoperative angiogram showing occlusion of the aneurysm and RAG interposition bypass with proximal focal stenosis of the graft. **D:** Magnetic resonance FLAIR sequence showing an infarct. **E:** Follow-up angiogram obtained at 4 months, showing a new aneurysm distal to the anastomosis site. **F:** Intraoperative drawing showing resection of the aneurysm along with the graft and replacement by a lingual artery graft. **G:** Postoperative angiogram showing graft along with the aneurysm resected and replaced by lingual artery graft. **H:** Angiogram obtained at 32 months, showing a patent bypass and no aneurysm evidence. Panels B and F are printed with permission from Dr. Laligam N. Sekhar.

postoperatively) phenomenon, and does not manifest in late follow-up. 4) Physical growth of pediatric patients with EC-IC bypasses occurs without long-term effect on the graft, which elongates proportionately. Although this is a small cohort, thereby making subgroup analyses problematic, there do not appear to be any differences in bypass durability based on graft donor type or bypass technique, such as high flow, interposition, or other local types. These data are extremely reassuring given the longevity expected and required of these grafts. Of 14 EC-IC bypasses 8 were performed in children 13 years of age or younger, and the remainder were performed in patients older than 13 years.

Zhang et al.<sup>47</sup> reported 2 cases of pediatric EC-IC bypasses for giant aneurysms; one of these patients was only 10 months old and the other was 23 months old. In their several-year follow-up, graft patency was angiographically documented in both cases. Our series provides additional support to these authors' astute observations that concerns about stretching or scarring down of the graft

during periods of childhood growth fortunately are unfounded. Goedee et al.<sup>9</sup> reported a single case of a giant MCA aneurysm treated with an STA-MCA bypass. Technical success was achieved; however, no long-term radiographic follow-up was reported. In our series, we did not use this technique because of the diminutive size of STA in those patients who were considered. However, it is an identical technique to that used in moyamoya disease in children,<sup>10,35,36</sup> which has a well-published record of durability. In 6 cases, we performed an in situ bypass, consisting of side-to-side, reimplantation, or intracranial-to-intracranial interposition grafts. These types of bypasses have been reported primarily in adult patient series as being at lower risk for long-term occlusion.<sup>14</sup> Based on our outcome data, we concur that pediatric patients tolerated these in situ-type bypasses quite well in the short and long term, with no technical complications or patency difficulties.

Despite the dramatic differences in size compared with adults, these pediatric patients exhibited donor and



TABLE 2: Outcome of bypasses\*

Parameter	Value†	Comment
<b>radiographic outcome</b>		
overall		
short-term patency (0–3 mos)	18 of 18 (100)	
stenosis (non–flow limiting)	2 of 18 (11.1)	
mean/median/range long-term FU duration	40/15/9–197 mos	
long-term graft patency	16 of 16 (100)	1 graft was replaced; 1 patient did not undergo FU imaging
aneurysm group		
complete occlusion	9 of 10 (90)	
new aneurysm formation	2 of 10 (20)	
aneurysm recurrence	0 of 9 (0)	
tumor group		
gross-total resection	7 of 8 (87)	
tumor recurrence	2 of 7 (28.5)	1 osteogenic sarcoma; 1 chondrosarcoma; 1 patient did not undergo FU imaging
<b>clinical outcome</b>		
overall mean/median/range FU duration	40.5/24/3–197 mos	
mRS score‡		
aneurysm group		
0–2	9 of 9	
3–4	0	
5–6	0	
tumor group		
0–2	5	1 osteosarcoma; 1 chondrosarcoma; 1 giant cell tumor; 2 chordomas
3–4	0	
5–6	3	1 osteosarcoma; 1 chondrosarcoma; 1 patient w/ NF2 discharged to skilled nursing facility
complications		
infection	0	
major stroke	1 of 18 (5.5)	anterior parietal branch of the MCA
surgical morbidity	1 of 18 (5.5)	vocal chord injury requiring op
graft stenosis	2	1 detected intraop; 1 detected postop

\* FU = follow-up.

† Values are the number of cases (%) unless noted otherwise.

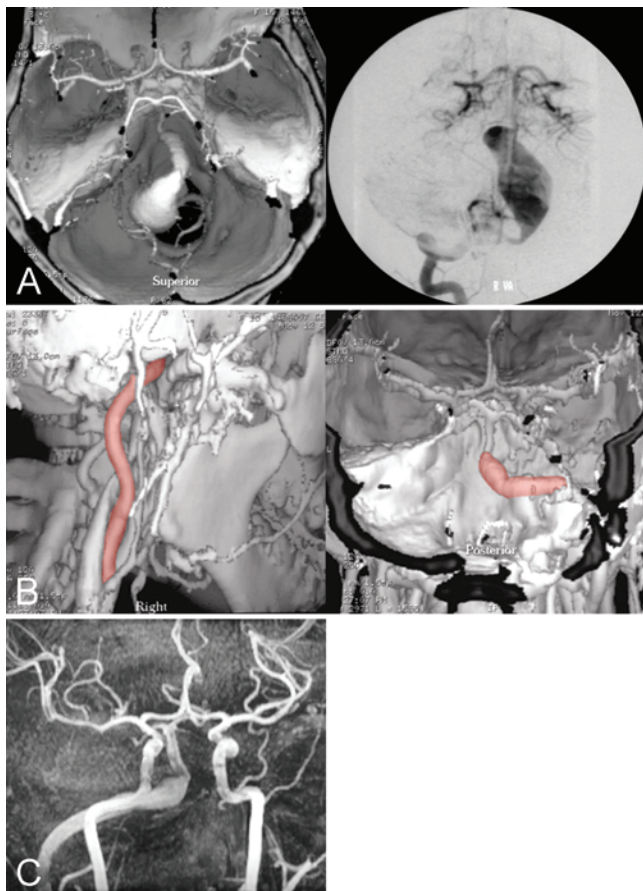
‡ Values represent the number of patients.

recipient vessel diameters quite similar to those reported for bypass in adults.<sup>23,29,31</sup> Because the scale of size was similar to adults, the microsurgical technique remained familiar to surgeons accustomed to adult anatomy. Given the reasonable long-term results in this series, we recommend careful preoperative donor/recipient vessel and anastomosis site selection that maintains a minimum diameter vessel size as discussed in *Results*. Based on our experience, as a guideline we recommend minimum RAG diameter  $\geq 2$  mm, SVG  $\geq 2.5$  mm, and in situ or side-to-side bypass vessels  $\geq 1.0$  mm. Certainly smaller vessels can be used, as has been reported by others;<sup>47</sup> this is merely a guide. Hence, we prefer size-based selection of vessels for bypass suitability rather than using the age of patient.

At our institution, we approach all complex vascular

and skull base lesions with a multimodality team approach. Hence, in addition to microsurgery, complex aneurysms are evaluated for possible endovascular therapy, and complex skull base tumors are considered for endoscopic and radiosurgical treatment. The vascular cases presented in this series either predate modern neuroendovascular techniques or represent cases in which stent-assisted coiling or flow diversion was not considered suitable by the treatment team. Undoubtedly, endovascular therapies have revolutionized the treatment of complex vascular disease. However, we believe that there exists a highly selected population of lesions that require cerebral bypass for definitive treatment. Although these technical skills are still widely present in neurosurgical centers worldwide, the diminishing indications for cerebrovascular bypass will make training future surgeons problematic.





**Fig. 4.** Case 4. **A:** Preoperative angiograms obtained in a 15-year-old girl with a giant basilar artery aneurysm. **B:** Postoperative angiograms showing complete exclusion of the aneurysm from the circulation and a patent bypass graft. **C:** Magnetic resonance angiogram obtained at the 16.4-year follow-up, showing complete obliteration of the aneurysm and a patent bypass graft with a mild dilation before the anastomotic site in the SVG that has been unchanged for the last several years. Images in Panels A and B are reprinted with permission from Sekhar LN, Chandler JP, Alyono D: Saphenous vein graft reconstruction of an unclippable giant basilar artery aneurysm performed with the patient under deep hypothermic circulatory arrest: technical case report. *Neurosurgery* 42(3):667–673, 1998.

### Conclusions

While our pediatric bypass experience was garnered over a long treatment period, it has provided us long-term follow-up that confirms extended bypass patency in pediatric patients in complex aneurysms and tumors. Even in the modern endovascular era, these techniques remain as important as ever in the treatment algorithm for these diseases.

### Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: all authors. Acquisition of data: Tariq. Analysis and interpretation of data: Kim, Tariq. Drafting the article: all authors. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors.

Approved the final version of the manuscript on behalf of all authors: Kim. Administrative/technical/material support: Kim, Sekhar. Study supervision: Kim, Sekhar.

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