Intracranial pseudoaneurysms are a known complication of blunt and penetrating head injuries, brain surgery, and intracranial infection. The natural history of intracranial pseudoaneurysms remains poorly described; however, they have often been associated with delayed hemorrhage and neurological deterioration after trauma and/or brain surgery.1,2 Because of the rarity of congenital vascular malformations in children, traumatic pseudoaneurysms have been reported to comprise as many as one-third of all intracranial aneurysms seen in this population.3–7

Both endovascular and surgical treatment are challenging because these lesions involve a defective vessel wall. Direct clipping and clip-wrapping techniques, parent vessel sacrifice, and bypass have been described.1,2,4 More recently, endovascular techniques are being explored.5,6,8,9

The Pipeline embolization device (PED, Medtronic Neurovascular) has gained regulatory approval for treatment of unruptured, wide-necked aneurysms in the anterior circulation in adults.10–12 Since the publication of the PUFs (Pipeline Embolization Device for Uncoilable or Failed Aneurysms) and PREMIER (Prospective Study on Embolization of Intracranial Aneurysms With the Pipeline Device) trial results, the use of PEDs has been expanding to include aneurysms of the posterior circulation, dissecting aneurysms, and, in some cases, ruptured aneurysms in adults.13–16 However, because of the need for dual antiplatelet treatment, the use of PEDs has been limited in patients who present with hemorrhage from blister aneurysms or pseudoaneurysm given the significant instability of these lesions and the propensity for rebleeding. In children, these limitations are amplified by the overall small size of the patients’ vasculature, possible growth of the

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**ABBREVIATIONS:**

ACA = anterior cerebral artery; DSA = digital subtraction angiography; EVD = external ventricular drain; ICA = internal carotid artery; PED = Pipeline embolization device; SAH = subarachnoid hemorrhage.

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vessels, and limited data on the rate of endothelization and therefore the duration and specific dosage of antiplatelet medications. Thus, use of PEDs in the pediatric population is considered off label.

Here, we describe our experience with the PED in the treatment of traumatic and iatrogenic pseudoaneurysms in pediatric patients who presented with hemorrhage or stroke. We hypothesized that flow diversion in young patients is safe and effective, even in the setting of hemorrhage.

Methods

Study Design

This was a single-center retrospective cohort study of patients treated at Primary Children’s Hospital in Salt Lake City, Utah. Institutional ethics committee approval with a waiver of informed consent was obtained before starting data collection.

Procedural logs were screened for the use of PEDs in the treatment of iatrogenic and/or traumatic intracranial vascular injuries between 2015 and 2021. Data regarding patient demographics, indications for treatment, operative reports, radiological images, endovascular procedure notes, and the patients’ postprocedure hospital course were collected. Procedural data evaluated included the number of procedures, number of PED(s) used, size of PED(s) used, procedural complications, and immediate postprocedural angiographic outcome. Postprocedural data evaluated included postoperative hospital course, any significant neurological events, requirement for further treatment, and modified Rankin scale score at last follow-up.

Endovascular Treatment

The PED is a flow-diverting stent composed of 75% cobalt chromium/25% platinum tungsten with a 48-strand braided mesh design giving 30%–35% surface coverage. It is delivered using specially designed access catheters through the common femoral or radial artery. It is designed to provide sufficient flow diversion to induce stasis within the aneurysm while preserving patency of branch-

Results

Six patients underwent PED treatment for traumatic pseudoaneurysms during the study period. The median patient age was 12 years (range 7–16 years). There were 3 patients with traumatic pseudoaneurysms (1 penetrating brain injury, 1 fall from height, and 1 motor vehicle accident) and 3 patients with iatrogenic pseudoaneurysms (2 direct vessel injuries during craniopharyngioma resection and 1 injury of the anterior cerebral artery [ACA] during external ventricular drain [EVD] placement). There were 2 cases of extradural internal carotid artery (ICA) injury (1 cervical segment and 1 cavernous segment), 2 cases of intradural ICA injury, and 2 cases of ACA injury. Table 1 summarizes the baseline demographics.

All patients were treated in the acute setting, and therefore pretreatment with antiplatelet medications was not possible. The standard antiplatelet regimen consisted of an intraoperative, weight-adjusted loading dose of eptifibatide (90 μg/kg), followed by a dual antiplatelet regimen consisting of aspirin (81 mg) and clopidogrel (0.2 mg/kg/day) starting the next day, which was continued for 3 months, after which only aspirin (81 mg) was continued.

All 6 patients underwent primary PED treatment without any adjuncts. The median follow-up imaging was 135 days (range 90–180 days). All patients underwent follow-up angiography within 7–14 days after treatment. Subsequent follow-up was with CTA in 1 patient, MRA in 2 patients, and DSA in 3 patients. A single PED was used in 5 patients, with follow-up imaging demonstrating complete occlusion of the aneurysm. In 1 patient with an iatrogenic supraclinoid ICA pseudoaneurysm, an early follow-up angiogram demonstrated growth of the aneurysm, necessitating a second PED placement. One patient had a postoperative hemorrhage that resulted in a neurological decline; however, on careful imaging review, the bleeding was remote from the treated aneurysm and was most likely hemorrhage into an area of preexisting encephalomalacia. Parent vessel patency was preserved in 5 of 6 patients. In 1 patient, who presented after a motor vehicle accident with a resultant long-segment cervical ICA dis-

FIG. 1. Photograph showing a flow-diverting stent (PED). The device is composed of 75% cobalt chromium/25% platinum tungsten with a 48-strand braided mesh design giving 30%–35% surface coverage. The length and diameter of the stent vary depending on the size of the injured vessel. The stent fits through a 0.027-inch microcatheter. Figure is available in color online only.
section and a growing pseudoaneurysm in the cavernous segment, the rationale for treatment with a PED was continued growth of the aneurysm despite near occlusion of the parent vessel and suspicion of retrograde filling of the aneurysm. This patient had excellent collateral flow from the anterior communicating artery, which was also contributing to retrograde filling of the aneurysm. The significance of the retrograde filling argued against a parent vessel sacrifice as the only treatment because of the risk of the aneurysm continuing to fill from the distal ICA. After successful PED placement, however, follow-up imaging demonstrated occlusion of the parent vessel proximal and distal to the cavernous segment, including occlusion of the aneurysm. The patient did not experience any neurological sequelae (Table 2).

**Illustrative Cases**

**Case 1**

A 13-year-old boy with a large craniopharyngioma resulting in optic nerve compression and visual deterioration underwent a pterional craniotomy and resection of the tumor. Surgery was complicated by perforator vessel avulsion from the supraclinoid ICA. The injury was managed intraoperatively with pressure followed by application of a muscle plug, and the remainder of the case was uncomplicated. The patient recovered to his baseline postoperatively; however, on day 9, he experienced a neurological decline and required intubation and ventilation. Imaging revealed new subarachnoid hemorrhage (SAH) within the basal cisterns and acute hydrocephalus. An EVD was placed in an emergency fashion. CTA did not reveal any underlying vascular pathology, but because of a high index of suspicion, the patient was taken for DSA. DSA confirmed a $1 \times 2$–mm pseudoaneurysm off the left supraclinoid ICA projecting posterolaterally. The decision was made to treat the pseudoaneurysm with a PED. The patient received a bolus of eptifibatide ($90 \mu g/kg$) intraoperatively. A single PED measuring $4.5 \times 16$ mm was placed, spanning from the distal communicating segment to the cavernous segment of the ICA, without complication. Postoperatively, the patient was placed on

**TABLE 1. Baseline characteristics**

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>Mechanism</th>
<th>Presentation</th>
<th>Hemorrhagic GCS Score on Initial Imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>13, M</td>
<td>Iatrogenic during craniopharyngioma resection</td>
<td>Delayed SAH</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>11, M</td>
<td>VPS blockage treated w/ EVD; injury to ACA during EVD replacement</td>
<td>SAH &amp; ICH</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>16, M</td>
<td>Iatrogenic during craniopharyngioma resection</td>
<td>Immediate postop DSA</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>7, M</td>
<td>Penetrating brain injury from fall onto pencil</td>
<td>SAH &amp; ICH</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>7, F</td>
<td>MVA, struck by jet ski</td>
<td>Multifocal infarctions on delayed imaging</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>14, M</td>
<td>Fall from 30 ft</td>
<td>Hemiparesis, infarction on imaging</td>
<td>No</td>
</tr>
</tbody>
</table>

GCS = Glasgow Coma Scale; ICH = intracerebral hematoma; MVA = motor vehicle accident; VPS = ventriculoperitoneal shunt.

**TABLE 2. Procedure and outcome details**

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Vessel Injury</th>
<th>Aneurysm Size (mm)</th>
<th>Initial Treatment &amp; Device Size (mm)</th>
<th>Initial Outcome</th>
<th>FU Treatment</th>
<th>PED Successful</th>
<th>Time to Last FU, days</th>
<th>Imaging FU</th>
<th>mRS Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Supraclinoid ICA</td>
<td>$1 \times 2$</td>
<td>PED, $4.5 \times 16$</td>
<td>No residual</td>
<td>NA</td>
<td>Yes</td>
<td>90</td>
<td>Day 14 DSA showed no residual; 3-mo MRA showed no recurrence &amp; patent parent vessel</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>A2 ACA</td>
<td>$3 \times 2$</td>
<td>PED, $2.5 \times 10$</td>
<td>No residual</td>
<td>NA</td>
<td>Yes</td>
<td>300</td>
<td>Day 5 DSA showed no residual; 10-mo MRA showed no recurrence &amp; patent parent vessel</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>Supraclinoid ICA</td>
<td>$5 \times 5$</td>
<td>PED, $4.5 \times 14$</td>
<td>Aneurysm growth on POD 4</td>
<td>PED, $4.5 \times 18$ mm</td>
<td>Yes</td>
<td>180</td>
<td>9-mo DSA showed no recurrence but evidence of intimal hyperplasia</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>A2 ACA</td>
<td>$3 \times 4$</td>
<td>PED, $2.5 \times 14$</td>
<td>No residual</td>
<td>NA</td>
<td>Yes</td>
<td>180</td>
<td>6-mo DSA showed no recurrence</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Cavernous ICA</td>
<td>$18 \times 10$</td>
<td>PED, $3 \times 30$</td>
<td>Proximal vessel occlusion</td>
<td>NA</td>
<td>Yes</td>
<td>90</td>
<td>3-mo DSA showed complete vessel occlusion w/ retrograde filling of aneurysm</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>Cervical ICA</td>
<td>$11 \times 6$</td>
<td>PED, $3.5 \times 18$</td>
<td>No residual</td>
<td>NA</td>
<td>Yes</td>
<td>90</td>
<td>6-mo CTA showed no residual aneurysm</td>
<td>2</td>
</tr>
</tbody>
</table>

FU = follow-up; mRS = modified Rankin Scale; NA = not applicable; POD = postoperative day.
a regimen of weight-adjusted dual antiplatelet therapy. Follow-up DSA on day 14 after treatment demonstrated no residual aneurysm, and 3-month MRA confirmed a patent left ICA without evidence of pseudoaneurysm (Fig. 2). The patient required placement of a ventriculoperitoneal shunt because of hydrocephalus. He continues to recover but is independently mobile at the 3-month follow-up.

Case 3

A 16-year-old boy developed a midline suprasellar recurrence of a craniopharyngioma that had been treated with a resection and radiotherapy 9 years earlier. A transsphenoidal approach was chosen. Surgery was complicated by injury to the left supraclinoid ICA during tumor dissection. Bleeding was controlled intraoperatively with irrigation and packing. Immediate postoperative angiography demonstrated vessel wall injury with a small intraluminal thrombus but no definite pseudoaneurysm. The patient was initially managed expectantly and underwent follow-up DSA on postoperative day 5. DSA findings confirmed the presence of an enlarging 5 × 5-mm pseudoaneurysm arising from the medial wall of the supraclinoid ICA. The decision was made to treat the pseudoaneurysm with a PED. The patient received a bolus of eptifibatide (90 μg/kg) intraoperatively. A single PED measuring 4.5 × 14 mm was placed, spanning from the distal communicating segment to the cavernous segment of the ICA, without complications. Follow-up DSA on day 4 posttreatment demonstrated further growth of the aneurysm, and a decision was made to treat with a second PED. Because the patient was on a regimen of antiplatelet medication, he did not require intraoperative eptifibatide. The second, longer PED, measuring 4.5 × 18 mm, was placed to allow landing both proximally and distally to the first device. DSA at 9 months confirmed no recurrence of the aneurysm, with mild intimal hyperplasia and in-stent stenosis but no flow limitation (Fig. 3).

FIG. 2. Case 1. A: Preoperative axial MR image demonstrating a large, multilobulated, partially cystic suprasellar tumor most consistent with a craniopharyngioma. The tumor is eccentric to the left and involves the supraclinoid ICA. B: CT scan obtained on day 9 after an unexpected neurological decline demonstrating SAH located within the interpeduncular fossa with acute hydrocephalus. C: Initial angiogram demonstrating a supraclinoid ICA pseudoaneurysm (arrow). D: Intraoperative fluoroscopic image showing the locations of the PED before deployment. E: Intraoperative fluoroscopic image showing the deployed PED spanning from the communicating to the cavernous segment. F: Follow-up angiogram obtained at 1 week, demonstrating complete resolution of aneurysm. The arrow indicates the previous location of the aneurysm. G: Follow-up coronal MR image obtained at 3 months, demonstrating a patent ICA and no evidence of aneurysm (arrow).
FIG. 3. Case 3. A: Coronal MR image demonstrating a suprasellar lesion (arrow) located mostly in the midline with mild compression of the optic chiasm. B: Immediate postoperative DSA demonstrating an irregularity in the communicating segment of the left supraclinoid ICA. There is evidence of wall disruption and intraluminal thrombus (arrow). Given the lack of active extravasation and patient stability, conservative management was initially pursued. C: Follow-up angiogram obtained on postoperative day 5, demonstrating an enlarging pseudoaneurysm at the supraclinoid ICA (arrow). Treatment with a PED was recommended. D: Follow-up angiogram obtained on day 4 after placement of the first PED, demonstrating good position of the stent (arrowheads) but enlargement of the aneurysm. A second PED was placed at this time. E and F: Follow-up angiograms obtained at 9 months, demonstrating complete resolution of the aneurysm. There is, however, non-flow-limiting in-stent stenosis (arrowheads) that requires ongoing surveillance. G: Surveillance coronal MR image demonstrating no evidence of recurrent craniopharyngioma.
Case 4

A 7-year-old boy presented after sustaining a penetrating brain injury from a fall onto a pencil. The patient was confused on admission but without focal neurological deficits. The pencil had been removed by the emergency medical services team before transfer, and the superficial wounds were irrigated. Imaging demonstrated a fracture through the roof of the right orbit and hemorrhage through the inferior right frontal lobe coursing toward midline. There was interhemispheric SAH and intraventricular hemorrhage suspicious for vascular injury. CTA confirmed an irregularity at the left A2 segment of the ACA. DSA confirmed a 3 × 4–mm traumatic pseudoaneurysm located at the left ACA. The patient received a bolus of eptifibatide (90 μg/kg) followed by an infusion of 1 μg/kg/min for 24 hours. The aneurysm was treated with a 2.5 × 14–mm PED spanning the A2 segment and covering the aneurysm. Postoperatively, the patient was started on a weight-adjusted dual antiplatelet regimen and made a full recovery. DSA at 6 months demonstrated no evidence of residual aneurysm or parent vessel stenosis (Fig. 4).

Discussion

Intracranial pseudoaneurysms, although rare in the adult population, constitute a large proportion of all intracranial aneurysms in children.3–5,7 Surgery remains challenging, and options include clipping, clip wrapping, and revascularization techniques.4,7 Recently, the use of flow-diverting stents has been reported in the treatment of pseudoaneurysms in the adult population with favorable results;16–19 however, there remains a paucity of data on the use of flow diversion in children,20,21 more specifically, in children presenting with hemorrhage or stroke. The challenges to treating pediatric patients with flow-diverting

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**TABLE 3. Previous studies of PED use in patients with pseudoaneurysms**

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>No. of Pts</th>
<th>Age*</th>
<th>Presentation</th>
<th>Procedure (no. of devices/pt)</th>
<th>Complications</th>
<th>FU Duration &amp; Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Szikora et al., 201022</td>
<td>1</td>
<td>16</td>
<td>Mass effect</td>
<td>PED (5)</td>
<td>None</td>
<td>6 mos; complete occlusion</td>
</tr>
<tr>
<td>de Barros Faria et al., 201123</td>
<td>3</td>
<td>5–12</td>
<td>1 mass effect, 2 hemorrhage</td>
<td>PED (2–4)</td>
<td>None</td>
<td>3–6 mos; 2 complete occlusion, 1 incomplete occlusion</td>
</tr>
<tr>
<td>Lin et al., 201624</td>
<td>1</td>
<td>13</td>
<td>Hemorrhage</td>
<td>PED (1)</td>
<td>None</td>
<td>3 mos; complete occlusion</td>
</tr>
<tr>
<td>Cobb et al., 201725</td>
<td>1</td>
<td>13</td>
<td>Iatrogenic</td>
<td>PED (1)</td>
<td>None</td>
<td>4 mos; complete occlusion</td>
</tr>
<tr>
<td>Trivelato et al., 201726</td>
<td>1</td>
<td>9</td>
<td>Trauma</td>
<td>PED (1)</td>
<td>None</td>
<td>6 mos; complete occlusion</td>
</tr>
<tr>
<td>Lozupone et al., 201827</td>
<td>2</td>
<td>6, 12</td>
<td>2 hemorrhage</td>
<td>PED (1)</td>
<td>None</td>
<td>6–12 mos; complete occlusion</td>
</tr>
<tr>
<td>Colby et al., 20189</td>
<td>1</td>
<td>9 mos</td>
<td>Iatrogenic/hemorrhage</td>
<td>PED (1) w/ adjunct coiling</td>
<td>None</td>
<td>7 mos; complete occlusion</td>
</tr>
<tr>
<td>Cunegatto-Braga et al., 201818</td>
<td>1</td>
<td>4</td>
<td>Hemorrhage</td>
<td>PED (1)</td>
<td>None</td>
<td>6 mos; complete occlusion</td>
</tr>
<tr>
<td>Sami et al., 201819</td>
<td>1</td>
<td>6</td>
<td>Mass effect</td>
<td>PED (1)</td>
<td>None</td>
<td>21 mos; complete occlusion</td>
</tr>
<tr>
<td>Sastry et al., 201820</td>
<td>1</td>
<td>13</td>
<td>Hemorrhage</td>
<td>PED (1)</td>
<td>None</td>
<td>7 mos; complete occlusion</td>
</tr>
<tr>
<td>Wang et al., 201921</td>
<td>4</td>
<td>8–12</td>
<td>4 headache, 2 mass effect</td>
<td>PED (1–4)</td>
<td>1 patient died</td>
<td>6 mos; complete occlusion</td>
</tr>
<tr>
<td>Shlobin et al., 202120</td>
<td>2</td>
<td>9, 12</td>
<td>1 stroke, 1 incidental</td>
<td>PED (1–3)</td>
<td>1 parent vessel occlusion, asymptomatic</td>
<td>19–40 mos; complete occlusion</td>
</tr>
</tbody>
</table>

Pt = patient.

* Age is in years unless specified otherwise.
stents are related to the small size of access vessels, which limits the size of supporting catheters that can be used, the difficulties in perioperative and long-term antiplatelet medication management, the lack of consensus on best strategies of follow-up given the exposure to radiation, and the lack of regulatory approval. We report 6 cases of pediatric pseudoaneurysms treated with PED. Our data support the use of PED in children and provide rationale for further prospective studies that will establish the role of flow diversion for pediatric vascular pathology, including those with hemorrhagic presentation.

To date, there have been only 52 reported cases of pediatric aneurysms treated with PEDs.20,21 Of those, only 19 cases described treatment of pediatric pseudoaneurysms,9,20,22–31 with only 7 describing treatment of pseudoaneurysms presenting with hemorrhage (Table 3).23,24,27,28,30 Colby et al.9 described treatment of a 9-month-old patient with a large middle cerebral artery pseudoaneurysm secondary to resection of an intrinsic brain tumor. They reported complete resolution of the aneurysm on 7-month follow-up imaging. Importantly, the authors used PED-assisted coiling, using a 2.5 × 16–mm PED, which is the smallest diameter available. Lubicz et al.32 reported the use of a PED in a 17-year-old patient with a dissecting fusiform aneurysm of the distal basilar artery, who presented with SAH. They successfully deployed a 3 × 40–mm Silk flow diverting stent (SFD, Balt Extrusion). However, they noted incomplete resolution of the aneurysm at 6 months. Lin et al.24 reported the successful treatment of a 13-year-old patient with a pseudoaneurysm of the A2 segment of the ACA with a single PED device. De Barros Faria et al.23 described 3 cases of pediatric dissecting pseudoaneurysms treated with flow diversion. In that series, all patients required more than one PED, and one patient had incomplete occlusion of the aneurysm at last follow-up.

We report on 6 pediatric patients, including 3 patients with hemorrhagic presentation, who underwent PED treatment for pseudoaneurysms. In all cases, we observed complete resolution of the aneurysms on last follow-up. One patient (case 3) required re-treatment because of a growing aneurysm despite PED placement. This patient had frank vessel injury during surgery and a likely large arterial wall defect. We believe that a single PED may be insufficient for the treatment of pseudoaneurysms that are accompanied by large vessel-wall defects because of the large area of endothelialization required. Although large and wide-necked aneurysms are commonly treated with PEDs, the prolonged time required for PEDs to lead to complete occlusion (6–12 months) may be too long in the setting of a pseudoaneurysm with a known vessel-wall injury. Previous reports have described the use of PED-assisted coiling to treat large pseudoaneurysms.9 Although we believe that this is a useful technique, it is risky in the setting of a recent hemorrhage and unstable aneurysm capsule. In our case 3, early follow-up imaging identified the growing aneurysm, and successful treatment was undertaken with a second PED placement. It remains unknown whether, in cases of large pseudoaneurysms with hemorrhagic presentation, two PEDs provide better coverage and a reduced risk of early rehemorrhage. Although increasing coverage is typically thought to reduce the inflow to the aneurysm, placement of two PEDs significantly increases the complexity of the procedure and places branching vessels at higher risk of occlusion.33 The timing of second PED placement in such high-risk cases is also an ongoing question, as it is unknown whether it is better to place a second PED initially or only if follow-up imaging demonstrates persistent aneurysm filling or progression.

The size of the access vessel, typically the common femoral artery, is an additional limiting factor for PED treatment in the pediatric population. Although small guide catheters and biaxial systems are frequently used for coiling procedures in children without sacrificing support and stability, the delivery of PEDs typically involves a triaxial system (including a large 0.027-inch microcatheter). Limiting the size of the guide catheter and reducing the system to a biaxial system can hamper safe delivery of the PED because of increased resistance and reduced stability. In our case series, all PEDs were safely deployed in the target locations using a biaxial 5-Fr guide system and microcatheter, without an intermediate catheter. The size of the parent vessel has also been shown to be related to the risk of parent vessel occlusion and stroke after PED treatment.30,31 Interestingly, the sizes of PEDs used in this series were not significantly different from what would have been expected in the adult population: 3.5- to 4.5-mm-diameter PEDs were used in the ICA, with 2.5-mm-diameter PEDs used in the distal anterior circulation. We did not encounter significant difficulties sizing the PEDs. Accordingly, the only patient who developed a parent vessel occlusion had a cavernous segment ICA aneurysm with a long-segment dissection extending into the cervical ICA, with stagnant flow on preoperative imaging. The rationale for treatment with a PED in this patient was the presence of retrograde filling of the aneurysm with visible growth on serial imaging. Because of excellent cross-flow, the alternative treatment for this patient would have been endovascular parent vessel occlusion.

Dual antiplatelet therapy is necessary to prevent thromboembolic events related to PEDs, but it is relatively contraindicated in the setting of an intracranial hemorrhage. Furthermore, there is little evidence to guide antiplatelet dosing in the pediatric population. Previous reports have suggested the use of 81 mg of aspirin with 0.2–1 mg/kg/day of clopidogrel for 7 days before treatment.25,34 However, long pretreatment is typically not possible in cases of acute hemorrhage. We therefore prefer intraoperative loading with weight-adjusted eptifibatide (90 μg/kg), followed by oral antiplatelets with 81 mg of aspirin and 0.2 mg/kg/day of clopidogrel starting the next day and continued for 3 months, after which the patients are switched to single antiplatelet with aspirin (81 mg) alone.

In the current series, one patient experienced a new intracerebral hemorrhage in the immediate postoperative period, which was thought to be related to the antiplatelet treatment. Importantly, the hemorrhage was not thought to represent a rebleed from the aneurysm but rather bleeding into an area of prior encephalomalacia. In animal models, complete endothelialization, which can occur within 7 days, is necessary to ensure complete obliteration of the aneurysm and is also necessary to reduce the risk of thromboembolic complications.35 It has been shown that
the lack of sufficient endothelialization is the most common finding in aneurysms that fail to occlude in patients > 60 years old.\textsuperscript{36} Given the above and the higher occlusion rates seen in younger patients,\textsuperscript{37} there is a move toward shortening the duration of dual antiplatelet treatment. In addition, the attention to the inherent thrombogenicity of stents has led to the creation of PEDs with antithrombogenic coating (e.g., Pipeline Flex with Shield technology), which may further shorten or even eliminate the need for dual antiplatelets therapy in the future.\textsuperscript{38} In our practice, therefore, we limit the duration of dual antiplatelet treatment in pediatric patients to 3 months to minimize the risk of adverse events. Although the results underscore the inherent risk of dual antiplatelet treatment, we believe that our data still support the use of flow diversion in ruptured pseudoaneurysms.

Follow-up imaging to assess aneurysm obliteration is required after PED treatment. In adults with unruptured aneurysms, the first imaging studies are typically done at 6 months after treatment and repeated at 1, 3, and 5 years, or until complete obliteration is seen.\textsuperscript{39} However, there are no available data to guide best practice of surveillance imaging for children, in particular, for children with ruptured pseudoaneurysms. Because of the unstable nature of pseudoaneurysms, most practitioners will perform some form of imaging within the first week after treatment, with variable follow-up timing and modalities thereafter. In our practice, patients undergo follow-up angiography 7 days after treatment. If the repeat angiogram does not show residual aneurysm, the next imaging session is scheduled for 3 months. The gold standard for follow-up imaging after PED treatment is DSA; however, to limit radiation exposure and the need for general anesthesia in the pediatric population, a bespoke approach tailored to the patients is often used. In the present series, we used CTA and MRA as well as DSA. All of these modalities provided sufficient detail in our opinion to allow decision-making; however, in cases with incomplete aneurysm occlusion, DSA may be needed, despite the invasive nature and radiation exposure.

Conclusions

In this retrospective series, we have demonstrated the feasibility of treating traumatic and iatrogenic pseudoaneurysms in children using flow diversion. Although the use of flow diversion for pediatric intracranial aneurysms is still in its early stages, our data demonstrate that flow diversion is an important tool that can be safely and effectively used as an alternative to more traditional endovascular and surgical approaches, even in young patients. Furthermore, we have obtained satisfactory results in patients with hemorrhagic presentations despite the requirement for dual antiplatelet treatment. Long-term data specific to the pediatric population will be required to confirm the enduring safety of these devices.

References


**Disclosures**


**Author Contributions**

Conception and design: Taussky. Acquisition of data: Budohoski, Thakrar, Voronovich, Rennert. Analysis and interpretation of data: Budohoski. Drafting the article: Budohoski. 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: Taussky. Administrative/technical/material support: Taussky.

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