Pipeline Embolization Device for the Treatment of Intracranial Pseudoaneurysms

Stephanie H. Chen[1], David J. McCarthy[1], Dallas Sheinberg[1], Ricardo Hanel[1,2], Samir Sur[1], Pascal Jabbour[3], Elias Atallah[3], Nohra Chalouhi[3], Aaron Dumont[4], Peter Amenta[4], David Hasan[5], Daniel Raper[6], Kenneth Liu[6], John A. Jane Jr[6], R. Webster Crowley[7], Pedro Aguilar-Salinas[2], Josh Bentley[8], Stephen Monteith[8], Bartley D. Mitchell[9], Dileep R. Yavagal[1], Eric C. Peterson[1], Robert M. Starke[1]

■ BACKGROUND: **Intracranial pseudoaneurysms (PSAs) are associated with high rupture and mortality rates and have traditionally been treated by parent vessel sacrifice. There has been recent interest in using flow-diverting devices for treatment of these complex lesions while preserving flow through the parent artery. The objective of this study is to examine the safety and efficacy of these devices in the treatment of intracranial PSA.**

■ METHODS: **We performed a multi-institutional retrospective study of intracranial PSAs treated with the Pipeline Embolization Device (PED) between 2014 and 2017 at 7 institutions. Complications and clinical and radiographic outcomes were reviewed.**

■ RESULTS: **A total of 19 patients underwent PED placement for intracranial PSA. Iatrogenic injury and trauma comprised most etiologies in our series. The mean pseudoaneurysm diameter was 8.8 mm, and 18 of 19 PSAs (95%) involved the internal carotid artery (ICA). Multiple PEDs were deployed in a telescoping fashion in 7 patients (37%). Of the 18 patients with follow up imaging, 14 (78%) achieved complete pseudoaneurysm obliteration and 2 achieved near-complete obliteration (11%). Two patients (11%) were found to have significant pseudoaneurysm progression on short-term follow-up and required ICA sacrifice. No patients experienced new neurologic deficits or deterioration secondary to PED placement. No patients experienced bleeding or rebleeding from PSA.**

■ CONCLUSIONS: **In well-selected patients, the use of flow-diverting stents may be a feasible alternative to parent vessel sacrifice. Given the high morbidity and mortality associated with PSA, we recommend short- and long-term radiographic follow-up for patients treated with flow-diverting stents.**

INTRODUCTION

Intracranial pseudoaneurysms (PSAs) are rare, accounting for 1% of intracranial aneurysms. Pseudoaneurysms are defined by injury to the vessel wall resulting in bleeding confined by only the adventitia or surrounding tissue.[1,2] They are associated with high rupture rates of up to 60% prior to definitive treatment, which can result in significant mortality (31%–54%).[3] Blunt and penetrating trauma, infection, or iatrogenic injuries are among the most frequently encountered etiologies. Historically, treatment consists of sacrifice of the parent vessel. In patients that fail a balloon occlusion test, cerebral bypass is often performed for cerebrovascular flow augmentation. This may be particularly challenging in emergent, acutely bleeding patients,

Key words
- Aneurysm
- Bypass
- Clipping
- Endovascular
- Flow diversion
- Iatrogenic
- Infection
- Pipeline
- Pseudoaneurysm
- Sacrifice
- Subarachnoid hemorrhage
- Trauma

Abbreviations and Acronyms
ICA: Internal carotid artery
PED: Pipeline Embolization Device
PSA: Intracranial pseudoaneurysm

From the [1]Department of Neurological Surgery, University of Miami, Miami, Florida; [2]Department of Neurological Surgery, Baptist Health, Miami, Florida; [3]Department of Neurological Surgery, Jefferson University, Philadelphia, Pennsylvania; [4]Department of Neurological Surgery, Tulane Medical Center, New Orleans, Louisiana; [5]Department of Neurological Surgery, University of Iowa, Iowa City, Iowa; [6]Department of Neurological Surgery, University of Virginia, Charlottesville, Virginia; [7]Department of Neurological Surgery, Rush University Medical Center, Chicago, Illinois; [8]Department of Neurological Surgery, Swedish Health, Seattle, Washington; and [9]Department of Neurological Surgery, Methodist Institute, Houston, Texas, USA

To whom correspondence should be addressed: David J. McCarthy, B.S. [E-mail: djm77@med.miami.edu]

*Citation: World Neurosurg. (2019) 127:e86-e93.
https://doi.org/10.1016/j.wneu.2019.02.135*

*Journal homepage: **www.journals.elsevier.com/world-neurosurgery***

*Available online: **www.sciencedirect.com***

patients with active infection, and those with significant comorbidities. Covered stents provide an alternative therapeutic option in large vessels, but cannot usually be navigated into the smaller and more tortuous intracranial vessels. In addition, for those cases where navigation to the target vessel may be feasible, covered stents may unavoidably cover critical vessels such as the anterior choroidal artery. Although there have been several case reports of successful use of flow-diverting stents for treatment of iatrogenic intracranial vascular injuries, the safety and efficacy of this strategy remains unclear.[4,5]

The Pipeline Embolization Device (PED [Medtronic, Minneapolis, Minnesota, USA]) is a flow-diversion device that consists of 25% platinum tungsten and 75% cobalt chromium and provides 30%–35% metal surface area coverage when fully deployed.[6] It is a Food and Drug Administration–approved stand-alone endoluminal device that can achieve circumferential parent vessel reconstruction in intracranial arteries. Although it is considered off-label for PSAs, a number of case reports and small series have described the use of PED for pseudoaneurysms.[7] In the largest case series to date, we present our multi-institutional experience with endoluminal reconstruction of intracranial PSAs using the PED and review the existing literature.

METHODS

From 2014 to 2017, a multi-institutional retrospective study was conducted of intracranial PSAs treated with the PED at 7 institutions. The diagnosis of PSA was made by the treating physician at each contributing center based on clinical presentation and angiographic imaging. Patient demographic data, presenting symptoms, indication for treatment, operative reports, radiologic images, endovascular procedure reports, postprocedural angiographic outcomes, postprocedural complications, and follow-up procedures, angiography, and neurologic images were reviewed by the contributing institution and communicated to the parent institution. Local institutional review board approval was obtained at each participating center.

Endovascular Technique

Informed consent was obtained from the patient or legal representative for the use of the PED for the treatment of PSA, which is an off-label treatment. All procedures were performed under general anesthesia. Vascular access was obtained in the standard fashion. A transradial or transfemoral approach was chosen based on surgeon preference and patient-specific considerations.

To ensure appropriate selection of device size, diagnostic angiograms were performed to obtain measurements of the parent vessels and pseudoaneurysm neck. The device was delivered in the standard fashion, through a microcatheter, having been navigated distally over a shaped microwire, often with the addition of an intermediate support catheter. The PED was then deployed across the neck of the pseudoaneurysm by a combination of unsheathing and pushing the device out of the microcatheter under fluoroscopy. If necessary, the device was recaptured and redeployed to achieve optimal positioning. The decision to deploy multiple devices was based on postdeployment follow-up angiography and surgeon discretion. Procedures were performed after the patient received aspirin, clopidogrel, and heparin.

Statistical Analysis

Data are presented as median or mean and range for continuous variables, and as frequency and percent for categorical variables. Calculations of normality were assessed graphically and statistically. Statistical analyses of categorical variables were carried out using χ^2 and Fisher exact test association as appropriate. Complete PSA obliteration was defined as no evidence of contrast filling the PSA lumen after initial PED placement and excluded PSAs requiring additional procedural treatment or demonstrating residual filling on follow-up. $P \leq 0.05$ was considered statistically significant. Statistical analysis was carried out with Python 3.7 and SAS 9.4 (SAS Institute, Cary, North Carolina, USA).

RESULTS

A total of 19 patients with a mean age of 50 years (range, 16–74 years) underwent PED placement for intracranial PSA. Patient and pseudoaneurysm characteristics are shown in Table 1. Most patients were men (58%). Eighteen of the PSAs (95%) were located in the internal carotid artery (ICA), most commonly in the petrous segment. The mean pseudoaneurysm diameter was 8.8 ± 6.7 mm (range, 1.5–21 mm). Eight of the PSAs (42%) were larger than 1 cm.

Iatrogenic vascular injuries during surgery causing PSA occurred in 11 patients (5 transsphenoidal tumor resections, 4 invasive infection procedures, 1 nasal polyp resection, and 1 craniotomy for craniopharyngioma resection). Three patients presented with traumatic PSA related to blunt trauma, 1 patient presented with pseudoaneurysm from tumor invasion, and 4 patients had undetermined etiologies. A total of 7 patients presented with acute hemorrhage. Multiple PEDs were deployed in an overlapping fashion in 7 patients (37%). Hemorrhagic presentation was not associated with a significant difference in the decision to treat multiple PSAs (3/7 hemorrhagic PSAs, 4/12 nonhemorrhagic PSAs; $P > 0.99$).

Average length of radiographic follow-up was 6 months (median, 4 months). Of the 18 patients with follow-up imaging, 14 (78%) achieved complete pseudoaneurysm obliteration. Of these, 1 patient had an additional PED deployed 1 week after the initial procedure. Two patients (11%) had near-complete occlusion of the pseudoaneurysm on follow-up at 7 and 8 months and no further treatments were performed. Two patients (11%) subsequently underwent sacrifice of the parent ICA because of persistent filling and progression of the PSA on short-term follow-up within 1 month. Persistent filling was defined as incomplete aneurysm occlusion on follow-up imaging after the initial PED intervention. There was no statistically significant difference in vessel sacrifice rates between PSAs treated with multiple PEDs (0/7) and PSAs treated with a single PED (2/14; $P = 0.51$). Furthermore, no difference was found in complete obliteration rates between patients treated with multiple versus single PEDs (6/7 multiple PEDs, 8/12 single PED; $P = 0.298$).

Average clinical follow-up time was 7 months (median, 4 months). No patients experienced new neurologic deficits or deterioration secondary to PED placement. Adequate documentation of the modified Rankin Scale score at last follow-up was available for 11 patients; 10 patients had a modified Rankin Scale score of 2 or less, indicative of a favorable outcome. One death

Table 1. Patient, Pseudoaneurysm, and Procedure Characteristics

Characteristic	Value
Age (years)	50 ± 17
Female	8 (42)
Etiology	
Iatrogenic trauma	11 (58)
Trauma	3 (16)
Other	5 (26)
Presentation	
Urgent because of hemorrhage	8 (42)
Urgent because of ischemia	1 (5)
Nonurgent	10 (52)
PSA maximum diameter*	8.8 ± 6.7
Left-sided PSA	12 (63)
PSA location	
Petrous ICA	8 (42)
Cavernous ICA	5 (26)
Clinoidal ICA	3 (16)
ICA terminus/bifurcation	2 (11)
MCA	1 (5)
Multiple PEDs placed	7 (37)
PED PSA obliteration achieved	14 (73)

Values are mean ± SD or number of patients (%).
PSA, pseudoaneurysm; ICA, internal carotid artery; MCA, middle cerebral artery; PED, Pipeline Embolization Device.
*Size missing for 1 lesion.

occurred during follow-up, unrelated to the pseudoaneurysm or PED placement, resulting from progression of systemic melanoma. No patients experienced bleeding events after treatment with the PED for PSA.

Illustrative Case 1

A young adult presented with vision loss and difficulties in work was diagnosed with a craniopharyngioma and underwent a right orbitofrontal craniotomy for tumor resection in 2012. There were no intraoperative complications. On routine follow-up magnetic resonance imaging, a right supraclinoid ICA abnormality was noticed (Figure 1A). This was found to be enlarging on subsequent imaging. On diagnostic angiography, a 10-mm fusiform right supraclinoid ICA pseudoaneurysm involving the posterior communicating artery origin and ICA terminus was discovered (Figures 1B and C). A PED (size 3.75 × 25 mm) was deployed from the M1 segment of the middle cerebral artery into the cavernous ICA with subsequent contrast stagnation in the aneurysm. On follow-up angiography 1 year later, there was no residual or recurrent aneurysm filling (Figure 1C).

Illustrative Case 2

A patient in their 40s presented with complaints of headaches, facial pain, dizziness, and left ear fullness (Figure 2). Preoperative magnetic resonance imaging, magnetic resonance angiography, and computed tomography angiography were performed, which were suggestive of a left petrous bone lesion. However, intraoperatively, brisk high flow arterial bleeding was encountered consistent with a thrombosed aneurysm. The bleeding was tamponaded with cottonoid patties, and a Foley catheter was placed within the sphenoid sinus to hold the patties. The patient was then taken emergently for digital subtraction angiography. The cerebral angiogram demonstrated an ICA pseudoaneurysm. The patient had significant venous delay on balloon occlusion test. The petrous carotid was stented

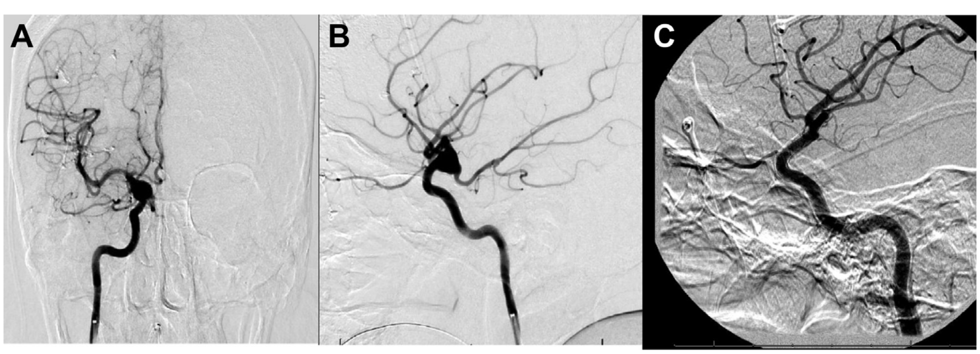

Figure 1. (**A**) Anterior-posterior and (**B**) lateral projections on digital subtraction angiography (DSA) of 10-mm fusiform right supraclinoid internal carotid artery (ICA) aneurysm involving posterior communicating artery origin and ICA terminus. (**C**) Follow-up DSA 1 year after placement of the Pipeline Embolization Device demonstrating complete resolution of the pseudoaneurysm and reconstruction of the ICA.

Figure 2. (**A**) Axial T2-weighted magnetic resonance image demonstrating hyperintense lesion of the left petrous bone. (**B**) Lateral digital subtraction angiography (DSA) prior to Pipeline Embolization Device (PED) placement after patient radiographically failed balloon occlusion test. Anterior-posterior projection on DSA after PED placement. (**C**) Axial computed tomography image demonstrating PED in the petrous carotid.

with 2 overlapping PEDs. The patient was discharged neurologically intact on physical examination. On follow-up angiography 3 months later, there was complete resolution of the pseudoaneurysm.

Illustrative Case 3

A 51-year-old patient presented with headaches and visual changes and was diagnosed with a pituitary macroadenoma. During endoscopic transsphenoidal resection, brisk arterial bleeding was encountered and continued despite packing and inflation of a Fogarty balloon within the resection cavity (Figure 3). Blood pressure dropped to 40/20 mm Hg, and massive transfusion protocol was initiated with subsequent emergent transfer to angiography suite. The cerebral angiogram demonstrated a focal injury to the cavernous ICA. A 5-mm-diameter PED was deployed across the site of injury despite angiographic measurement of a smaller diameter ICA. Angiography 36 hours later showed poor wall apposition of the PED and active extravasation with persistent filling of the pseudoaneurysm. Parent vessel occlusion of the ICA using coils and liquid embolic agents was undertaken after confirming angiographic criteria was met for passing a balloon test occlusion.

The patient recovered well and was discharged neurologically intact but was lost to follow-up.

DISCUSSION

Pseudoaneurysms, or false aneurysms, lack a true wall and are created by injury to all 3 layers of the arterial wall (intima, media, and adventitia).[1] Blood flow egress is typically prevented by only a friable layer of connective tissue. Therefore, manipulation of PSAs is associated with a high risk of intraoperative rupture. Because of the nature of the vessel injury, PSAs often lack a true neck precluding durable clip placement, and they often possess a fusiform morphology. As a result, PSAs remain one of the most difficult vascular lesions to treat.

Historically, parent vessel sacrifice with or without bypass has been considered the treatment of choice. However, cerebral bypass surgery is particularly challenging in patients with emergent acute bleeding and in patients with active infection or significant comorbidities. With the advent of endovascular techniques, percutaneous, endoluminal sacrifice using detachable coils or liquid embolic agents has become a preferred option in select patients. Further development of endovascular devices and techniques has resulted in therapeutic options that enable preservation of the parent vessel. Patients are often selected after failing carotid artery balloon test occlusion. In the present study, there was no specific pattern seen in patients that failed treatment and patients in whom treatment was successful. Covered stents can be deployed in larger extracranial vessels, but typically cannot be navigated into the smaller more torturous intracranial vessels, and would occlude any adjacent branch vessels.[8]

Literature Review

Recent expanded use of the PED has provided one potential solution. The PED is a flow-diverting device that was initially Food and Drug Administration approved in the United States for treatment of large or fusiform unruptured intracranial aneurysms from the petrous to the superior hypophyseal segment of the ICA. Since its introduction, the PED has been increasingly used off-label to treat a number of vascular lesions. Amenta et al.[9] reported the first case of successful PED placement for treatment of a petrous ICA pseudoaneurysm after iatrogenic injury during endoscopic sinus surgery. Subsequently, several case reports and case series have been published describing the use of flow-diverting stents for the treatment of pseudoaneurysms of various etiologies (Table 2). Giorgianni et al.[14] describe a case of 2 pseudoaneurysms from the A1 segment of the right anterior cerebral artery and from the A2 segment of the left anterior cerebral artery in a young patient after major head trauma causing multiple skull fractures. Both PSAs were treated with the PED after the acute posttraumatic period (1–3 months) and demonstrated complete angiographic resolution at 6 months.

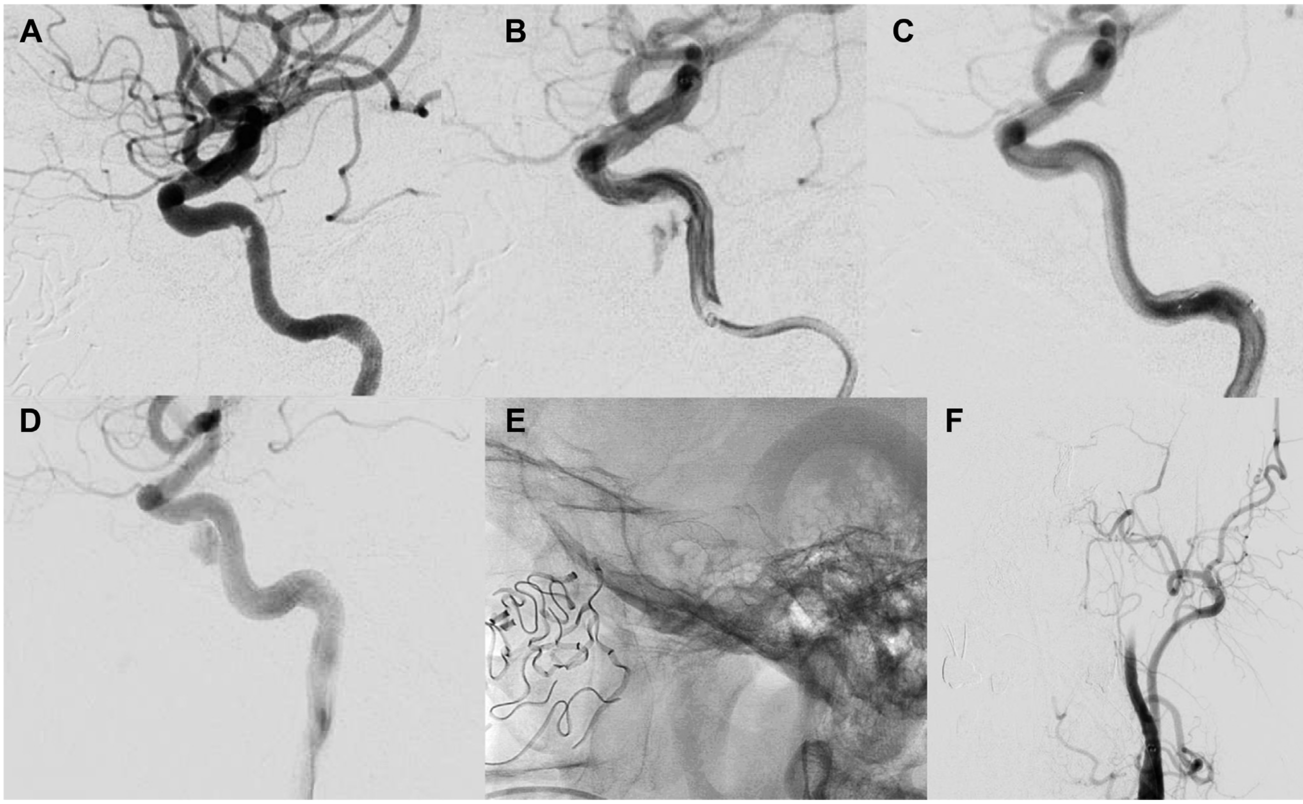

Figure 3. (**A**) Area of injury on initial angiography. (**B**) Area of injury after Eptifibatide drip and heparinization, now demonstrating active extravasation. (**C**) Immediately after Pipeline Embolization Device (PED) placement. (**D**) Thirty-six hours later, active extravasation and pseudoaneurysm noted and now PED no longer opposed to vessel wall (**E**). (**F**) Angiogram after vessel sacrifice.

Kadkhodayan et al.[13] used the PED to treat a petrous ICA pseudoaneurysm associated with chronic otitis media and temporal bone osteomyelitis. Although postembolization angiography demonstrated a widely patent ICA, slowed flow within the pseudoaneurysm, and no extravasation, the patient returned with brisk bleeding 12 days later requiring endovascular vessel sacrifice. Tsang et al.[4] reported the use of the PED for pseudoaneurysm occlusion at the skull base in 7 patients with postirradiated carotid PSA. PED treatment was effective in excluding the pseudoaneurysm and preventing recurrent blowout. However, one patient had a periprocedural cerebral infarction and 3 patients developed delayed ICA occlusion secondary to in-stent thrombosis. Important to note is that the authors used a conservative, abridged antiplatelet regimen in this population because of a concern for hemorrhage from the nasopharyngeal tumors. They concluded that this inadequate antiplatelet treatment may be partially responsible for the high rate of ischemic complications after PED treatment in their series.

Recently, Sami et al.[17] described their series of 7 patients with 8 total traumatic intracranial PSAs treated with PED alone. Seven of 8 PSAs demonstrated immediate stagnation of flow or decreased filling of PSA after PED placement. On long-term follow-up, 5 of the 6 PSAs (83.3%) demonstrated complete occlusion, whereas 1 of 6 demonstrated near-complete occlusion. There were 2 mortalities in their case series: one associated with microcatheter perforation and the other associated with intracranial hemorrhage after a fall several weeks after discharge from the hospital. Both deaths highlight the life-threatening risks of hemorrhagic complications in the setting of dual antiplatelet therapy.

Flow-Diverter Limitations

The success of flow-diversion technology for aneurysm occlusion is derived from the lack of a significant pressure gradient across the device wall; therefore, flow diminishes while endothelialization across the stent braids commences. An actively bleeding pseudoaneurysm could continue to bleed if a pressure gradient (and therefore blood flow) is maintained across the device. Therefore, an important limitation of the PED is that it does not provide immediate thrombosis of the pseudoaneurysm or exclusion from circulation, and complete occlusion may take weeks to occur. During this time, the patient remains at risk for rerupture.

The requirement for dual antiplatelet therapy remains one of the major limitations of PED use in the treatment of PSAs. Although dual antiplatelet therapy in the setting of recent

Table 2. Literature Review of Pipeline Embolization Device—Treated Pseudoaneurysms

Study	Number and Etiology	PSA Locations	Treatment	PSA Outcome	Date After PED; Neurologic Mortalities
Nerva et al., 2015[10]	2 TSS	2 cavernous ICA	1 PED + coils 1 PED alone	2 CR	3 months; death from sepsis
Amenta et al., 2012[9]	1 Endovascular procedure	ICA PSA	1 PED alone	CR	None
Sylvester et al., 2016[11]	2 TSS	2 ICA	2 PED alone	2 CR	None
Griauzde et al., 2017[12]	3 TSS 1 ETV	3 ICA 1 Basilar	3 PED alone 1 PED + coils	3 CR 1 VS	None
Kadkhodayan et al., 2013[13]	1 Mycotic	1 Petrous ICA	PED	Rebleed and VS	Lost to follow-up
Giorgianni et al., 2015[14]	1 Trauma	B/L ACA	1 PED alone	CR	None
Lerat et al., 2011[15]	2 Unknown	2 Petrous ICA	PED	1 CR 1 STO	None
Kim et al., 2013[16]	1 Trauma	1 Ophthalmic ICA	PED alone	NA	Lost to follow-up
Sami et al., 2018[17]	2 TSS 5 Trauma	3 Cavernous ICA 1 Paraclinoid ICA 1 Petrous ICA 1 PCA 1 ACA	7 PED alone	1 STO 4 CR	3 months; perforation with SAH resulting in death 6 weeks; death from traumatic SAH after fall
Tsang et al., 2015[4]	7 Postradiation	5 Petrous ICA 2 Laceral ICA	5 PED alone 2 PED + coils	2 CR 3 VS 2 NA	18 months; death from brainstem hemorrhage
Prasad et al., 2014[7]	2 Trauma	2 Cavernous ICA	1 PED + coils	2 CR	None

PSA, pseudoaneurysm; PED, Pipeline Embolization Device; TSS, transsphenoidal surgery; ICA, internal carotid artery; CR, complete resolution; ETV, endoscopic third ventriculostomy; VS, vessel sacrifice; ACA, anterior communicating artery; STO, subtotal occlusion; NA, not available; B/L, bilateral; SAH, subarachnoid hemorrhage.

subarachnoid hemorrhage or intracranial hemorrhage has been reported, the mechanisms for pseudoaneurysm formation have significant implications for determining safety of administering dual antiplatelet therapy.[18,19]

Although this is perhaps a minor concern in treating incidentally found pseudoaneurysms, it is a significant issue for patients who present with acute hemorrhage. Nonetheless, in our series, the 7 patients that were treated in the acute phase had an average of 1.4 PEDs placed, with no subsequent hemorrhage or thrombotic complications.

Certainly, balancing the risks of hemorrhage with that of thrombosis and ischemia is of paramount importance in determining the optimal treatment strategy. In our series, no patients experienced clinically significant ischemic complications. The mixed results described in the literature may be partially attributed to the heterogenous regimens of dual antiplatelet therapy.[18] There are no data-driven guidelines on optimal antiplatelet therapy. In our study, all institutions used a protocol wherein clopidogrel and aspirin were administered for 4–6 months after PED placement until a follow-up angiogram was performed, and all patients were then treated with aspirin thereafter.

Treatment Failures

Although most cases presented in this series resulted in angiographic and clinical success (albeit with limited follow-up), 2 cases demonstrated failure of the PED to achieve aneurysm obliteration, and parent vessel sacrifice was undertaken in both cases.

In one case (case 3), nonapposition of the PED on the cavernous carotid wall was observed in short-term follow-up, associated with progression of the pseudoaneurysm. This treatment was performed in the setting of an acute iatrogenic injury and highlights the potential for vessel spasm or narrowing by packing to decrease the apparent vessel diameter. Despite relative oversizing of the PED (using the largest, 5-mm-diameter device available), poor apposition was seen on follow-up; ultimately, sacrifice of the parent vessel was performed.

Considerations that may prevent this type of failure include postdeployment balloon angioplasty, deployment of multiple PED devices, or coil embolization of the pseudoaneurysm at the time of deployment. Although these adjuncts to standard PED deployment have been well described, their specific utility in treating pseudoaneurysm may deserve more attention.[7,20-22]

The second failure in this series involved a large pseudoaneurysm of the cavernous ICA, which was initially treated by coil embolization in addition to PED placement. The base of this pseudoaneurysm measured 20 mm, and on short-term follow-up angiography, progression of the pseudoaneurysm was noted with increased contrast flow into the aneurysm compared with post-treatment appearance. Perhaps in such cases, an increased attention to wall apposition proximal and distal to the aneurysm neck is warranted. Although specific details from this case are not available, persistent filling of the aneurysm may have been preventable with multiple PEDs deployed, or balloon angioplasty to improve apposition.

In summary, these adjunct strategies may be of benefit in treating these often complex lesions. Further investigation into these treatment decisions is certainly warranted.

Future Directions

An emerging technology that may offer additional benefit in this regard is the PED with Shield Technology (PED + Shield [Medtronic]). It is a phosphorylcholine surface modification of the PED flow diverter that has been shown to have decreased thrombogenicity in animal studies and is currently approved for clinical use in Europe, but not in the United States.[23] There have been recent case reports detailing use of this device with aspirin as the sole oral antiplatelet agent.[24] Further development or rigorous validation of this technology may broaden the use of flow diversion in the setting of acute pseudoaneurysm formation.

In summary, our experience and the review of the literature demonstrate the feasibility of the PED for treatment of well-selected intracranial PSAs. The PED confers the advantage of endoluminal reconstruction and preservation of the parent vessel in addition to pseudoaneurysm obliteration. However, further studies are necessary to elucidate the safety and efficacy of flow diversion as a primary treatment for PSAs.

Study Limitations

Although we report the largest cohort of PSAs treated with PEDs to date, this is a retrospective study with a relatively small sample size. Follow-up was limited to a short time frame, and further investigation is needed to assess whether our results persist at longer durations of time. Although we report no ischemic complications from PED placement, patients did not routinely undergo postprocedural magnetic resonance imaging scans to evaluate for clinically silent infarctions. Furthermore, our study population was heterogenous with PSAs of various etiologies, ages, and locations, and decision-making was at the sole discretion of the treating provider. Therefore, our results may not be generalizable to all PSAs, particularly supraclinoid ICA pseudoaneurysms which have a significantly higher morbidity and mortality in the event of rebleeding. Finally, the specific protocol for PED deployment and selection of device size was not prespecified, and variability in angiogram and procedural techniques could be significantly different between institutions and cases.

CONCLUSIONS

Although parent vessel sacrifice has traditionally been the preferred treatment for intracranial PSAs, flow diversion with the PED may be a feasible alternative. This may be of particular importance in patients who cannot tolerate parent vessel sacrifice or open surgical bypass. Given the high morbidity and mortality associated with PSAs, we recommend both short- and long-term clinical and radiographic follow-up for evaluation of pseudoaneurysm progression and device-related events.

REFERENCES

1. Larson PS, Reisner A, Morassutti DJ, Abdulhadi B, Harpring JE. Traumatic intracranial aneurysms. *Neurosurg Focus*. 2000;8:e4.

2. Moon TH, Kim SH, Lee JW, Huh SK. Clinical analysis of traumatic cerebral pseudoaneurysms. *Korean J Neurotrauma*. 2015;11:124-130.

3. Holmes B, Harbaugh RE. Traumatic intracranial aneurysms: a contemporary review. *J Trauma*. 1993;35:855-860.

4. Tsang AC, Leung KM, Lee R, Lui WM, Leung GK. Primary endovascular treatment of post-irradiated carotid pseudoaneurysm at the skull base with the Pipeline embolization device. *J Neurointerv Surg*. 2015;7:603-607.

5. Wan WS, Lai V, Lau HY, Wong YC, Poon WL, Tan CB. Endovascular treatment paradigm of carotid blowout syndrome: review of 8-years experience. *Eur J Radiol*. 2013;82:95-99.

6. Kallmes DF, Ding YH, Dai D, Kadirvel R, Lewis DA, Cloft HJ. A second-generation, endoluminal, flow-disrupting device for treatment of saccular aneurysms. *AJNR Am J Neuroradiol*. 2009;30:1153-1158.

7. Prasad V, Gandhi D, Jindal G. Pipeline endovascular reconstruction of traumatic dissecting aneurysms of the intracranial internal carotid artery. *J Neurointerv Surg*. 2014;6:e48.

8. Maras D, Lioupis C, Magoufis G, Tsamopoulos N, Moulakakis K, Andrikopoulos V. Covered stent-graft treatment of traumatic internal carotid artery pseudoaneurysms: a review. *Cardiovasc Intervent Radiol*. 2006;29:958-968.

9. Amenta PS, Starke RM, Jabbour PM, et al. Successful treatment of a traumatic carotid pseudoaneurysm with the Pipeline stent: case report and review of the literature. *Surg Neurol Int*. 2012;3:160.

10. Nerva JD, Morton RP, Levitt MR, et al. Pipeline Embolization Device as primary treatment for blister aneurysms and iatrogenic pseudoaneurysms of the internal carotid artery. *J Neurointerv Surg*. 2015;7:210-216.

11. Sylvester PT, Moran CJ, Derdeyn CP, et al. Endovascular management of internal carotid artery injuries secondary to endonasal surgery: case series and review of the literature. *J Neurosurg*. 2016;125:1256-1276.

12. Griauzde J, Ravindra VM, Chaudhary N, et al. Use of the Pipeline embolization device in the treatment of iatrogenic intracranial vascular injuries: a bi-institutional experience. *Neurosurg Focus*. 2017;42:E9.

13. Kadkhodayan Y, Shetty VS, Blackburn SL, Reynolds MR, Cross DT 3rd, Moran CJ. Pipeline embolization device and subsequent vessel sacrifice for treatment of a bleeding carotid pseudoaneurysm at the skull base: a case report. *J Neurointerv Surg*. 2013;5:e31.

14. Giorgianni A, Pellegrino C, Minotto R, et al. Flow-diverter stenting of post-traumatic bilateral anterior cerebral artery pseudoaneurysm: a case report. *Interv Neuroradiol*. 2015;21:23-28.

15. Lerat J, Orsel S, Mounayer C, et al. Peripheral facial paralysis and bilateral carotid pseudoaneurysms of petrous localization: a case report. *Skull Base Rep*. 2011;1:133-138.

16. Kim JD, Barber SM, Diaz OM, et al. Post-traumatic amaurosis secondary to paraophthalmic internal carotid artery pseudoaneurysm treated with pipeline embolization device. *J Neuroophthalmol*. 2013;33:359-362.

17. Sami MT, Gattozzi DA, Soliman HM, et al. Use of Pipeline embolization device for the treatment of traumatic intracranial pseudoaneurysms: case series and review of cases from literature. *Clin Neurol Neurosurg*. 2018;169:154-160.

18. Gupta R, Moore JM, Griessenauer CJ, et al. Assessment of dual-antiplatelet regimen for pipeline embolization device placement: a survey of major academic neurovascular centers in the United States. *World Neurosurg*. 2016;96:285-292.

19. Natarajan SK, Shallwani H, Fennell VS, et al. Flow diversion after aneurysmal subarachnoid hemorrhage. *Neurosurg Clin N Am*. 2017;28:375-388.

20. Kabbasch C, Mpotsaris A, Behme D, Dorn F, Stavrinou P, Liebig T. Pipeline Embolization device for treatment of intracranial aneurysms-the more, the better? A single-center retrospective observational study. *J Vasc Interv Neurol*. 2016;9:14-20.

21. Sweid A, Atallah E, Herial N, et al. Pipeline-assisted coiling versus pipeline in flow diversion treatment of intracranial aneurysms. *J Clin Neurosci*. 2018;58:20-24.

22. Caroff J, de Macedo Rodrigues K, Howk M, et al. E-016 angioplasty following pipeline embolization device delivery safely improves the midterm angiographic outcome. *J Neurointerv Surg*. 2018;10(suppl 2):A55.

23. Hagen MW, Girdhar G, Wainwright J, Hinds MT. Thrombogenicity of flow diverters in an ex vivo shunt model: effect of phosphorylcholine surface modification. *J Neurointerv Surg*. 2017;9:1006-1011.

24. Chiu AH, Ramesh R, Wenderoth J, Davies M, Cheung A. Use of aspirin as sole oral antiplatelet therapy in acute flow diversion for ruptured dissecting aneurysms. *J Neurointerv Surg*. 2017;9:e18.

Conflict of interest statement: D. R. Yavagal is a consultant for Neuroanalytics and Medtronic. E. C. Peterson is a consultant for Medtronic, Codman, Stryker, and Penumbra.

Received 19 November 2018; accepted 18 February 2019

Citation: World Neurosurg. (2019) 127:e86-e93.
https://doi.org/10.1016/j.wneu.2019.02.135

Journal homepage: ***www.journals.elsevier.com/world-neurosurgery***

Available online: ***www.sciencedirect.com***