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RESEARCH

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Second-stage pipeline embolization device treatment with coil embolization for large cerebral aneurysm prevents silent diffusion-weighted image ischemic infarction: a retrospective study

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Abstract

Background Second-stage flow diversion with coil embolization may improve occlusion outcomes and reduce periprocedural complications in patients with cerebral aneurysm. However, the actual cause behind this is unclear. In this study, we aimed to compare the efficacy and safety of second-stage pipeline embolization device (PED) and single-stage PED with coil embolization.

Results Of the 22 treated patients with aneurysm, 10 and 12 were treated with second-stage PED and single-stage PED with coil embolization, respectively. The mean follow-up duration was 29.6 months. The mean numbers of diffusion-weighted image (DWI)-positive spots on day 1 post-procedure were 4.9 and 10.8 in the second-stage and single-stage PED with coil embolization groups, respectively ($P=0.01$). Deterioration of the modified Rankin scale score was not ≥ 2 in any patient during follow-up in the second-stage PED group but was observed in 16.7% of cases (2/12) in the single-stage PED with coil embolization group ($P=0.48$). On follow-up angiography, complete occlusion was observed in all patients (10/10) in the second-stage PED group and 66.7% (8/12) in the single-stage PED with coil embolization group ($P=0.09$).

Conclusions The second-stage PED strategy significantly reduces the number of DWI high-intensity spots, leading to the prevention of ischemic complications. This strategy may help to prevent complications and reduce morbidity.

Keywords Aneurysms, Coiling, Flow diversion, Stenting

Background

Flow diverters are a breakthrough treatment option for large or giant intracranial aneurysms. Treating unruptured intracranial aneurysms using the flow diverter imparts a low risk of both mortality (0.8%) and major complications (1.8%) [1]. Although flow-diverting stents are designed as stand-alone constructs, many practitioners recommend augmenting the construct with concurrent coil embolization of the aneurysm [2–4]. Combining coils with flow diverters helps in lowering the risk of delayed aneurysmal rupture in patients with

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large or giant aneurysms. In a meta-analysis of 1654 aneurysms, the rate of delayed rupture resulting in subarachnoid hemorrhage (SAH) following flow diversion for cerebral aneurysm (CA) was 4% [5]. Proposed mechanisms for delayed rupture after flow diversion include hemodynamic shifts with inflow/outflow mismatch and intrathrombus enzymatic proteolysis of the aneurysm wall; however, the exact etiology is unknown. Several reports have recommended combining coils with flow diversion for large and giant aneurysms to stabilize the thrombus and equilibrate hemodynamic stress within the dome of the aneurysm [6]. In Japan, single-stage flow-diverting stents with concurrent coil embolization for aneurysms are not accepted due to insurance calculation issues. Each Japanese hospital bears the cost of the coils. The intentional division of flow-diverting stents from coil embolization as a second-stage procedure is necessary for resolving insurance issues. The literature provides brief information about the pipeline embolization device (PED) as a second-line treatment in patients with recurrent or residual CA [7]. In this study, we aimed to compare the efficacy and safety of second-stage PED and single-stage PED with coil embolization.

Methods

We explored our retrospectively maintained database for screening all patients with an intracranial unruptured large saccular aneurysm treated with PED between November 2015 and July 2022. The patients treated with PED only and with an aneurysm size $\leq$10 mm were excluded. Information on patient demographics, including age and sex, dual antiplatelet therapy, location of the aneurysm, symptom status, and size of the aneurysm and neck, was collected. Symptomatic aneurysm refers to an aneurysm causing a mass effect without rupturing. We also documented whether adjunctive coil embolization was performed simultaneously and obtained all follow-up imaging data.

Patients were pretreated with aspirin (100 mg/day) orally and clopidogrel (75 mg/day) orally for 2 weeks. Aspirin and P2Y12 reaction units were measured using a rapid platelet function assay (Verify Now; Accumetrics, Inc., San Diego, CA, USA) to assess resistance to aspirin or clopidogrel. When resistance was detected, the aspirin or clopidogrel dose was increased; alternatively, cilostazol (200 mg/day) or prasugrel (20 mg/day) was prescribed. Patients continued to receive clopidogrel for a minimum of 6 months and aspirin for a minimum of 2 years after treatment. Prasugrel administration was continued at 3.75 mg/day for a minimum of 6 months.

The procedures were performed on a biplane angiographic system with the patient under general anesthesia. Intravenous heparin was usually administered following arterial access to achieve an activated clotting time of 250 s.

We compared the treatment strategy with the timing of PED placement. The patients were divided into two groups (second-stage PED versus single-stage PED with coil embolization).

In the single-stage PED with coil embolization group, coiling was performed in conjunction with PED treatment. During adjunctive coil embolization, the aneurysm was either coiled by a jailed microcatheter after deployment of the PED or initially coiled with balloon remodeling, followed immediately by the deployment of the PED. Coil embolization was performed to promote earlier thrombosis of the aneurysm.

In the second-stage PED with coil embolization group, no attempt was made to perform complete occlusion of the aneurysm with coils. The second-stage PED group included a residual CA that underwent planned coiled embolization followed by a PED. PED was scheduled after a variable period and was usually performed within 1 month for a large aneurysm that contained a paraclinoid portion with jet flow because of the increased risk of rupture.

All patients were examined at our hospital by an independent neurosurgeon who measured the neurological outcomes using the modified Rankin scale (mRS) at the final follow-up visit. Magnetic resonance imaging (MRI) scans were routinely obtained 24–36 h after treatment. In the second-stage PED with coil embolization group, MRI scans were performed for the first time after coil embolization and the second time after PED insertion. The mean numbers of the diffusion-weighted image (DWI)-positive spots were compared between the second-stage PED and single-stage PED with coil embolization groups. The second-stage PED with coil embolization group presented the numbers that were the sum of DWI-positive spots after coil embolization and after PED deployment. Four-vessel digital subtraction angiography (DSA) was performed before and immediately after embolization and at the 6-month or 12-month follow-up visit. Some patients underwent DSA at the 24-month follow-up visit if the aneurysm was not occluded at the 12-month visit. Occlusion on follow-up DSA was graded according to the O'Kelly–Marotta scale for flow diversion as follows: A, complete; B, incomplete; C, neck remnant; or D, no filling [8].

Our dataset consisted of both continuous and categorical variables. When comparing the differences between groups, a t-test was used for continuous variables, and Fisher's exact test was used for categorical variables. All statistical analyses were performed with standard statistical software (JMP® 10; SAS Institute Inc., Cary, NC, USA). A P value < 0.05 was considered significant.

Results

Of the 99 aneurysms treated using PED between November 2015 and July 2022 at our institution, those treated with PED only and with an aneurysm size of ≤10 mm were excluded. Ten patients were treated with a second-stage PED and twelve with a single-stage PED with coil embolization. Twenty-two patients were compared according to the method used (second-stage PED versus single-stage PED with coil embolization) (Figs. 1, 2).

The mean patient age (± standard deviation) was 61.0 ± 10.9 (range, 42–83) years. The study group included 18 females (81.8%). Dual antiplatelet therapy was administered as pretreatment for the patients [aspirin + clopidogrel, 19 (86.4%) patients; aspirin + cilostazol, 1 (4.5%); and aspirin + prasugrel, 2 (9.1%)]. The mean aneurysm size was 18.4 ± 6.7 mm, and the mean aneurysm neck size was 7.1 ± 3.0 mm. Two aneurysms (9.1%) were located in the internal carotid-posterior communicating artery, five (22.7%) were located in the cavernous portion of the internal carotid artery, and 15 (68.2%) were located in the paraclinoid portion of the internal carotid artery. Eight aneurysms (36.4%) were symptomatic. The mean time to final follow-up was 29.6 ± 15.9 (range 12–74) months. In the second-stage PED group, the median time from the first coil embolization to the placement of a PED was 1 (interquartile range 1–3) month. There was a significant difference in the frequency of a symptomatic aneurysm between the second-stage PED and single-stage PED with coil embolization groups ($P < 0.05$). Aneurysm size was not significantly different between the two groups, but the size of the second-stage PED group tended to be smaller than that of the single-stage PED with coil embolization group ($P = 0.05$). No significant difference between the groups was found for any other characteristic (Table 1).

Deterioration of the mRS score ≥ 2 was not found in any patient in the second-stage PED group at any follow-up visit but was found in 16.7% of the patients (2/12) in the single-stage PED with coil embolization group ($P = 0.48$). During the perioperative phase, two patients in the single-stage PED with coil embolization group developed permanent morbidity due to brain edema and remote intracranial hemorrhage. Symptomatic ischemic complication was not found in any patient in the second-stage PED group; however, it was found in 8.3% of the patients (1/12) in the single-stage PED with

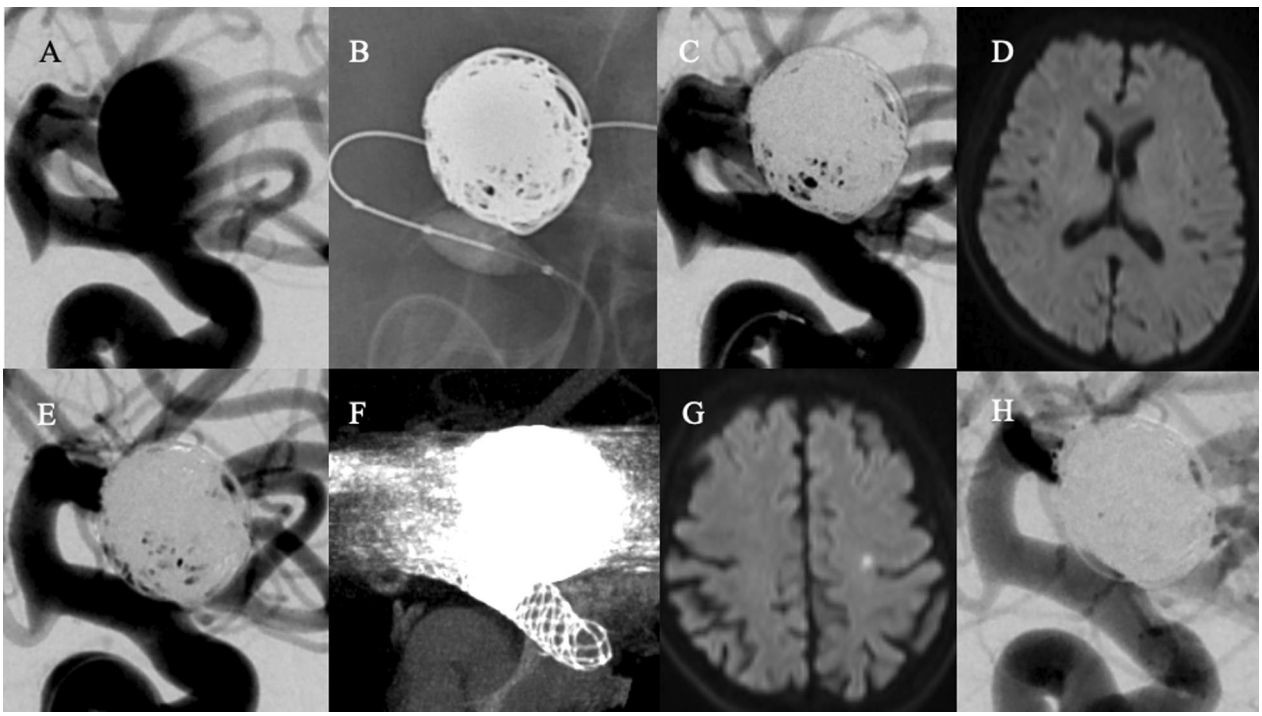

Fig. 1 Illustrative case of second-stage PED with coil embolization. **A** Lateral angiogram revealing a large intracranial aneurysm measuring 14.0 mm located in the paraclinoid portion of the left internal carotid artery. **B** Digital angiogram of coil embolization using microballoon. **C** Residual cerebral aneurysm state after coil embolization. **D** DWI study obtained 1 day post-coil embolization, revealing no hyperintense lesions. **E** Pre-pipeline embolization revealing residual cerebral aneurysm 1 month after coil embolization. **F** Multiplanar reconstructed dynamic CT scan obtained after dilute contrast injection, showing the deployed PED and coils. **G** DWI study obtained 1 day post-pipeline embolization, revealing a hyperintense lesion in the frontal lobe. **H** 6 months after second-stage PED deployment with coil embolization, revealing complete occlusion, OKM D. *CT, computed tomography; DWI, diffusion-weighted image; OKMD, OKM, O'Kelly–Marotta grade D; PED, pipeline embolization device*

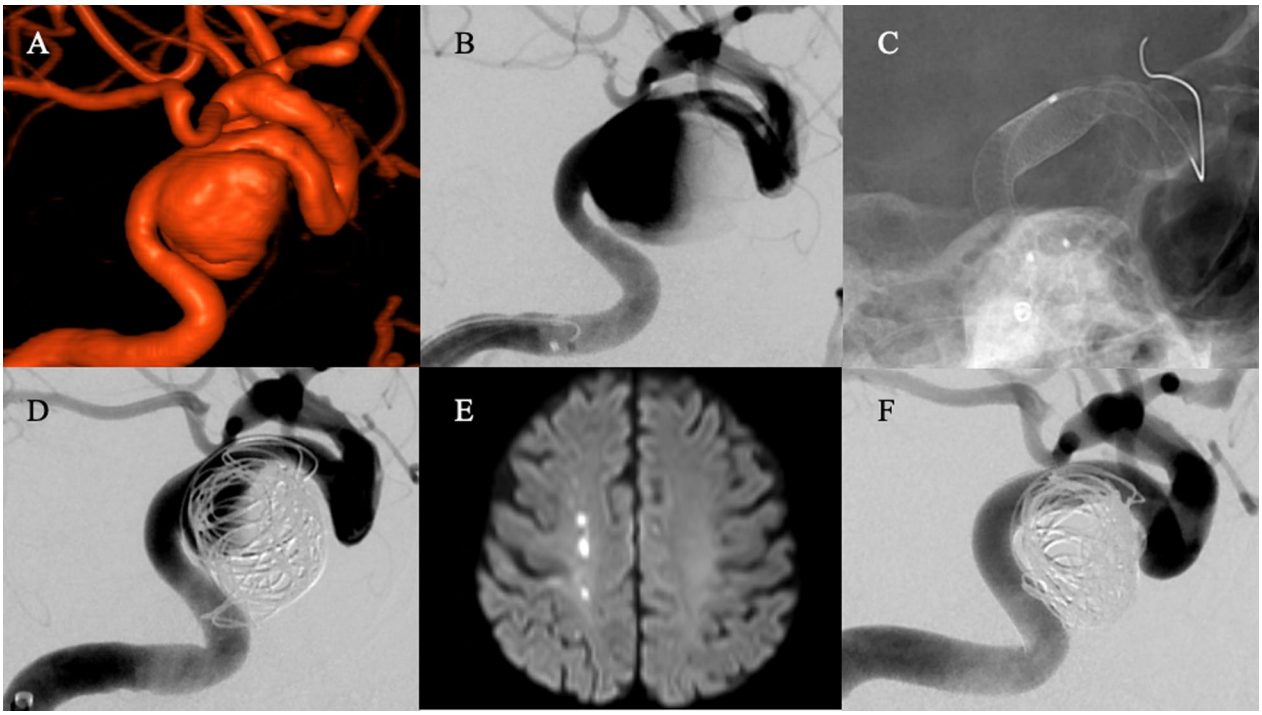

Fig. 2 Illustrative case of single-stage PED with coil embolization. **A** Lateral angiogram revealing a large internal aneurysm measuring 16.0 mm located in the cavernous portion of the right internal carotid artery. **B** Pre-pipeline embolization with coil embolization. **C** Post-deployment of PED transversing the neck of the aneurysm. **D** Coil embolization after the deployment of PED. **E** DWI study obtained 1 day post-pipeline embolization, revealing hyperintense lesions in the right centrum semiovale. **F** 6 months post-deployment of single-stage PED with coil embolization, revealing complete occlusion, OKM D. *DWI, diffusion-weighted image; OKMD, OKM, O'Kelly–Marotta grade D; PED, pipeline embolization device*

Table 1 Summary of clinical and demographic characteristics of the study population

Characteristic	All patients	Second-stage PED/coils	Single-stage PED/coils	*P* value
Aneurysms treated, *n*	22	10	12	
Age, years, mean (SD)	62.6 (10.3)	59.1 (9.4)	65.6 (10.2)	0.16
Female sex, *n*	18 (81.8%)	7 (70%)	11 (91.7%)	0.29
Dual antiplatelet therapy				
ASA + Clopidogrel, *n*	19 (86.4%)	10 (100%)	9 (75.0%)	0.2
ASA + Cilostazol, *n*	1 (4.5%)	0 (0%)	1 (8.3%)	1.0
ASA + Prasugrel, *n*	2 (9.1%)	0 (0%)	2 (16.7)	0.48
Aneurysm size, mm, mean (SD)	18.4 (6.7)	15.4 (4.2)	20.9 (7.3)	0.05
Neck size, mm, mean (SD)	7.1 (3.0)	6.0 (1.9)	8.2 (3.4)	0.10
Symptomatic aneurysm, n	8 (36.4%)	1 (10%)	7 (58.3%)	0.03
Follow-up, months, mean (SD)	29.6 (15.9)	24.8 (14.1)	33.7 (16.2)	0.21

PED pipeline embolization device, *SD* standard deviation, *ASA* acetylsalicylic acid

coil embolization group, with no significant difference between the groups ($P=0.35$). MRI scans were routinely obtained 24–36 h after treatment. In the second-stage PED group, the mean number of DWI-positive spots was 1.1 after coil embolization, and it was 3.8 after PED embolization. The mean number of the DWI-positive spots was 8.1 in all aneurysms, 4.9 in the second-stage PED group, and 10.8 in the single-stage PED with coil embolization group ($P=0.01$). Retreatment was required in two patients (16.7%, 2/12) in the single-stage PED with coil embolization group ($P=0.48$). The mRS score was 0–1 in 10 patients (100%, 10/10) in the second-stage PED group and 10 (83.3%, 10/12) in the single-stage PED with coil embolization group ($P=0.48$; Table 2). On

Table 2 Clinical and image outcomes post-embolization

Characteristic	All patients	Second-stage PED/coils	Single-stage PED/coils	*P* value
Aneurysms treated, *n*	22	10	12	
mRS 0–1, *n*	20 (90.9%)	10 (100%)	10 (83.3%)	0.48
Deterioration of mRS (≥ 2 points), *n*	2 (9.1%)	0 (0%)	2 (16.7%)	0.48
Symptomatic ischemic complication, *n*	1 (4.5%)	0 (0%)	1 (8.3%)	1.0
DWI-high spots, mean (SD)	8.1 (5.7)	4.9 (3.8)	10.8 (5.7)	0.01
Retreatment, *n*	2 (9.1%)	0 (0%)	2 (16.7%)	0.48

PED pipeline embolization device, *mRS* modified Rankin scale, *SD* standard deviation

Table 3 Angiographic outcomes post-embolization

Characteristic	All aneurysms	Second-stage PED/coils	Single-stage PED/coils	*P* value
Follow-up angiogram, *n*	22	10	12	
OKM C and D, *n*	21 (95.5%)	10 (100%)	11 (91.7%)	1.0
OKM D, *n*	18 (73.3%)	10 (100%)	8 (66.7%)	0.09

OKM O'Kelly–Marotta grade, *PED* pipeline embolization device

follow-up angiography, complete occlusion was observed in all patients (10/10) in the second-stage PED group and 66.7% (8/12) in the single-stage PED with coil embolization group ($P=0.09$; Table 3).

Discussion

From this study, we found that the intentional second-stage PED strategy significantly reduced the number of DWI high-intensity spots. Thus, deterioration of the mRS score ≥ 2 was not found in any patient in the second-stage PED group at any follow-up visit. However, limited information is available on the use of PED as a second-line treatment for recurrent or residual aneurysms [3, 7, 9].

The most common reason for combining coils with flow diversion is that it reduces the risk of delayed aneurysmal rupture in patients with large or giant aneurysms. In a meta-analysis of 1654 aneurysms, the rate of delayed rupture resulting in SAH following flow diversion for CA was 4%. Large and giant aneurysms were more susceptible to this phenomenon. The odds ratio for delayed SAH associated with a small or large aneurysm compared with a giant aneurysm was 0.10 [5]. Bender et al. recommended combining coils with flow diversion for large and giant aneurysms to stabilize the thrombus and equilibrate hemodynamic stress within the dome of the aneurysm. They also mentioned that combining coils with flow diversion expedites the occlusion of morphologically irregular aneurysms and provides scaffolding support for the stent in giant aneurysms [6]. No study has shown a statistically significant increase in morbidity compared with single-modality flow diversion combining coils with flow diversion [10]. However, a study demonstrated combining coils with flow diversion with a significantly increased rate of intra-procedural stent thrombosis, progressing to symptomatic ischemia without timely recognition and treatment [11]. Previous reports have recommended the use of a light coil pack (14% packing density overall) and systemic heparinization in these patients overnight following their procedure to limit the risk of acute stent thrombosis [6]. In a systematic review and meta-analysis, dual antiplatelet regimens, including ticagrelor or prasugrel, were safe for patients undergoing flow diversion procedures. Compared with clopidogrel, the use of ticagrelor or prasugrel was significantly associated with a low risk of mortality [3]. A potent antiplatelet therapy like ticagrelor or prasugrel might mitigate the complications.

In our study, 15 asymptomatic DWI-positive spots were detected 24 h after treatment in one patient in the single-stage PED with coil embolization group. The patient developed symptomatic cerebral infarction after the procedure on postoperative day 14. When the patient developed symptomatic cerebral infarction, new DWI-positive areas were detected. After 24 h, the patient developed intracranial hemorrhage in the same infarcted area. The incidence of DWI positivity following flow diversion was 51–67% [12–14]. In a meta-analysis, which included > 2000 patients undergoing endovascular treatment of intracranial aneurysms, there was a trend toward a higher rate of thromboembolic complications among those treated with flow diverters compared with those treated with coiling alone. Compared with stent-assisted coiling, the use of flow-diverting stents showed a statistically significant correlation with silent DWI findings postintervention. Because flow diverters are high-density metal constructs with large endoluminal surface areas, these devices pose a higher risk of thrombosis in the lumen of the parent artery. Shearing stress from blood flow through the device can cause these thrombi to embolize [12]. Most thromboembolic events likely do not present as focal neurologic deficits simply because they occur in non-eloquent locations. Studies have

prospectively explored the relationship between DWI positivity for lesions and neuropsychological examination performance and have yielded variable results. Patients with intracranial DWI lesions post-cardiac endovascular and surgical procedures have reduced cognitive function on neuropsychological examinations [15, 16]. However, studies on coiling and flow diversion have demonstrated no association between the presence of DWI lesions and neuropsychological examination performance [11, 17]. In our study, the second-stage PED strategy significantly reduced the number of DWI-positive spots. Unlike second-stage PED, using multiple devices is necessary for the single-stage PED with coil embolization, which might have been associated with a significant increase in the number of DWI-positive spots in our study.

Kühn et al. evaluated 24 patients treated with a second-line PED for recurrent or residual intracranial aneurysms in a single-center analysis and did not observe any treatment-related complications that resulted in a worsening mRS score and attributed their favorable results to the fact that none of their cases had previously been treated with stent-assisted coiling [7]. In our study, patients who underwent second-stage PED did not experience more morbidity than those who underwent single-stage PED with coil embolization. The use of second-stage PED might help to reduce post-procedural morbidity, especially stroke complications. The risk of embolic stroke may be lower with second-stage PED after coil embolization because it is a divided procedure. Chiu et al. [18] reported cerebral hyperperfusion syndrome after endovascular flow diversion. This change has been hypothesized to be the cause of intraparenchymal hemorrhage after flow diversion. We believe that second-stage PED might have led to mildly reduced vessel flow distal to the aneurysm due to the divided procedure. This procedure might be associated with less risk of remote intracranial hemorrhage.

In our study, all patients in the second-stage PED group showed complete occlusion on the final follow-up angiogram. Our result is consistent with the occlusion rates of 85.7–94.4% reported in previous literature mentioning PED in patients with recurrent or residual CAs [7, 9]. In our study, the occlusion rate of angiographical outcomes was not significantly different in the single-stage PED group; however, the second-stage PED group showed a better tendency of complete occlusion rate than the single-stage PED group ($P=0.09$). Among baseline characteristics, aneurysm size was not significantly different between the two groups; however, it tended to be smaller in the second-stage PED group than in the single-stage PED with coil embolization group ($P=0.05$). Ogilvy et al. reported that aneurysm size (>10 mm), neck size (>4 mm), rupture, and stent assistance were independent predictors of retreatment in patients treated with coiling, stent-assisted coiling, and flow diverter [19]. In our study, larger aneurysms were included in the single-stage PED group, which might have influenced the complete occlusion rate in the two groups.

The limitations of our study include its single-center, retrospective design, small sample size, and short follow-up duration. Moreover, it is difficult to perform a second-stage PED for aneurysms with a very wide neck and those of the fusiform type. Therefore, there may have been some degree of unmeasured confounding variables in this study as a result of the morphological selection bias. Nevertheless, we believe that this strategy provides valuable reassurance for patients undergoing retreatment of an aneurysm with PED.

Conclusions

Symptomatic ischemic complication was found in one patient in the single-stage PED with coil embolization group and in none of the patients in the second-stage PED group, with no significant difference between the two groups. Notably, the second-stage PED strategy significantly reduced the number of DWI high-intensity spots, thus preventing ischemic complications and the deterioration in morbidity. This strategy allows effective and safe treatment of aneurysms using a PED.

Abbreviations

CA	Cerebral aneurysm
DSA	Digital subtraction angiography
DWI	Diffusion-weighted image
MRI	Magnetic resonance imaging
mRS	Modified Rankin scale
PED	Pipeline embolization device
SAH	Subarachnoid hemorrhage

Acknowledgements

Not applicable.

Author contributions

All authors contributed to the study conception and design. YK involved in conceptualization, data curation, formal analysis, investigation, methodology, software; resources, validation, visualization, roles/writing—original draft. TT took part in supervision, project administration. YN involved in data curation, formal analysis. AH and KS involved in writing—review and editing.

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Availability of data and materials

The data supporting the findings of this study are available on request from the corresponding author, Yosuke Kawamura. The data are not publicly available due to restrictions as they contain information that could compromise the privacy of research participants.

Declarations

Ethics approval and consent to participate

This retrospective single-center study was approved by the institutional review board of the Dokkyo Medical University Saitama Medical Center

(Approval Number: 2062). All procedures performed in studies followed the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Consent for publication

The need to obtain written patient consent was waived because of the retrospective nature of this study. However, we obtained consent using the opt-out method (by placing a poster on our institution's website in which we described the study protocol and offering patients who were eligible for inclusion in the study the opportunity not to be enrolled).

Competing interests

The authors declare that they have no conflict of interest.

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References

1. Bhatia KD, Kortman H, Orru E, Klostranec JM, Pereira VM, Krings T (2019) Periprocedural complications of second-generation flow diverter treatment using Pipeline Flex for unruptured intracranial aneurysms: a systematic review and meta-analysis. J Neurointerv Surg 11:817–824. https://doi.org/10.1136/neurintsurg-2019-014937
2. Fiorella D, Woo HH, Albuquerque FC, Nelson PK (2008) Definitive reconstruction of circumferential, fusiform intracranial aneurysms with the pipeline embolization device. Neurosurgery 62:1115–1120. https://doi.org/10.1227/01.neu.0000325873.44881.6e
3. McAuliffe W, Wycoco V, Rice H, Phatouros C, Singh TJ, Wenderoth J (2012) Immediate and midterm results following treatment of unruptured intracranial aneurysms with the pipeline embolization device. Am J Neuroradiol 33:164–170. https://doi.org/10.3174/ajnr.A2727
4. Nelson PK, Lylyk P, Szikora I, Wetzel SG, Wanke I, Fiorella D (2011) The pipeline embolization device for the intracranial treatment of aneurysms trial. Am J Neuroradiol 32:34–40. https://doi.org/10.3174/ajnr.A2421
5. Brinjikji W, Murad MH, Lanzino G, Cloft HJ, Kallmes DF (2013) Endovascular treatment of intracranial aneurysms with flow diverters: a meta-analysis. Stroke 44:442–447. https://doi.org/10.1161/STROKEAHA.112.678151
6. Bender MT, Jiang B, Campos JK, Lin LM, Beaty N, Vo CD et al (2018) Single-stage flow diversion with adjunctive coiling for cerebral aneurysm: outcomes and technical considerations in 72 cases. J Neurointerv Surg 10:843–850. https://doi.org/10.1136/neurintsurg-2017-013739
7. Kühn AL, de Macedo RK, Lozano JD, Rex DE, Massari F, Tamura T et al (2017) Use of the pipeline embolization device for recurrent and residual cerebral aneurysms: a safety and efficacy analysis with short-term follow-up. J Neurointerv Surg 9:1208–1213. https://doi.org/10.1136/neurintsurg-2016-012772
8. O'kelly CJ, Krings T, Fiorella D, Marotta TR (2010) A novel grading scale for the angiographic assessment of intracranial aneurysms treated using flow diverting stents. Interv Neuroradiol 16:133–137. https://doi.org/10.1177/159101991001600204
9. Brinjikji W, Piano M, Fang S, Pero G, Kallmes DF, Quilici L et al (2016) Treatment of ruptured complex and large/giant ruptured cerebral aneurysms by acute coiling followed by staged flow diversion. J Neurosurg 125:120–127. https://doi.org/10.3171/2015.6.JNS151038
10. Park MS, Nanaszko M, Sanborn MR, Moon K, Albuquerque FC, McDougall CG (2016) Re-treatment rates after treatment with the pipeline embolization device alone versus pipeline and coil embolization of cerebral aneurysms: a single-center experience. J Neurosurg 125:137–144. https://doi.org/10.3171/2015.7.JNS15582
11. Iosif C, Camilleri Y, Saleme S, Caire F, Yardin C, Ponomarjova S et al (2015) Diffusion-weighted imaging-detected ischemic lesions associated with flow-diverting stents in intracranial aneurysms: safety, potential mechanisms, clinical outcome, and concerns. J Neurosurg 122:627–636. https://doi.org/10.3171/2014.10.JNS132566
12. Bond KM, Brinjikji W, Murad MH, Kallmes DF, Cloft HJ, Lanzino G (2017) Diffusion-weighted imaging-detected ischemic lesions following endovascular treatment of cerebral aneurysms: a systematic review and meta-analysis. Am J Neuroradiol 38:304–309. https://doi.org/10.3174/ajnr.A4989
13. Tan LA, Keigher KM, Munich SA, Moftakhar R, Lopes DK (2015) Thromboembolic complications with pipeline embolization device placement: impact of procedure time, number of stents and pre-procedure P2Y12 reaction unit (PRU) value. J Neurointerv Surg 7:217–221. https://doi.org/10.1136/neurintsurg-2014-011111
14. Brasiliense LB, Stanley MA, Grewal SS, Cloft HJ, Sauvageau E, Lanzino G et al (2016) Silent ischemic events after pipeline embolization device: a prospective evaluation with MR diffusion-weighted imaging. J Neurointerv Surg 8:1136–1139. https://doi.org/10.1136/neurintsurg-2015-012091
15. Lund C, Nes RB, Ugelstad TP, Due-Tønnessen P, Andersen R, Hol PK et al (2005) Cerebral emboli during left heart catheterization may cause acute brain injury. Eur Heart J 26:1269–1275. https://doi.org/10.1093/eurheartj/ehi148
16. Restrepo L, Wityk RJ, Grega MA, Borowicz L Jr, Barker PB, Jacobs MA et al (2002) Diffusion- and perfusion-weighted magnetic resonance imaging of the brain before and after coronary artery bypass grafting surgery. Stroke 33:2909–2915. https://doi.org/10.1161/01.str.0000040408.75704.15
17. Kang DH, Hwang YH, Kim YS, Bae GY, Lee SJ (2013) Cognitive outcome and clinically silent thromboembolic events after coiling of asymptomatic unruptured intracranial aneurysms. Neurosurgery 72:638–645. https://doi.org/10.1227/NEU.0b013e3182846f74
18. Chiu AH, Wenderoth J (2013) Cerebral hyperperfusion after flow diversion of large intracranial aneurysms. J Neurointerv Surg 5:e48. https://doi.org/10.1136/neurintsurg-2012-010479.rep
19. Ogilvy CS, Chua MH, Fusco MR, Reddy AS, Thomas AJ (2015) Stratification of recanalization for patients with endovascular treatment of intracranial aneurysms. Neurosurg 76:390–395. https://doi.org/10.1227/NEU.0000000000000651

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