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Research article

Comparison of pipeline embolization device and tubridge flow diverter for posterior circulation aneurysms: A multicentre propensity score matched study

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ABSTRACT

Rationale and objectives: The off-label use of flow diverters (FDs) has broadened to include treating aneurysms in posterior circulation (PC). A novel flow diverter, the Tubridge flow diverter (TFD), has been created in China specifically for treating PC aneurysms. However, studies comparing between pipeline embolization device (PED) and TFD are rare. Thus, our study aimed to explore the effectiveness of PED and TFD in the treatment of PC aneurysms using a propensity score matched cohort design.

Methods: Retrospective data collection was conducted on patients who underwent treatment with either PED or TFD over the period from 2015 through 2020. Propensity score matching (PSM) was employed to calibrate for patient age; history of ischemic stroke; aneurysm size; morphology; location and neck; number of FDs; parent vessel diameter; and the employment of assisted coiling and balloon techniques. Data on previously ruptured aneurysms was not included in the analysis. A comparison was conducted between the two devices to assess perioperative complications, aneurysm occlusion rates, and functional outcomes.

Results: A total of 252 PC aneurysms were treated in 248 patients. Clinical and imaging follow-ups were lost in 26 and 47 patients, respectively. Major perioperative complications occurred in 7.5% of the cases, with favorable clinical outcomes in 91.0% and complete occlusion in 79.1%. Eighty-two (32.5%) aneurysms were treated with TFD, while 170 (67.5%) aneurysms were treated with PED. PSM was used to account for these significant variations, producing 82 matched pairs of unruptured aneurysms treated with PED or TFD. In terms of functional and angiographic outcomes, no significant differences were found between PED and TFD (functional outcome, $p =$

Abbreviations: FD, Flow diversion; FDD, Flow-diverting device; IQR, interquartile range; ISS, in-stent stenosis; ISUIA, International Study of Unruptured Intracranial Aneurysms; NIHSS, National Institutes of Health Stroke Scale; PC, Posterior circulation; PED, Pipeline embolization device; TFD, Tubridge flow diverter; PSM, Propensity score matching; SAH, Subarachnoid hemorrhage; SD, Standard deviation.

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0.594 and angiographic outcome, $p = 0.415$). However, more perioperative major complications were found in patients treated with TFD ($p = 0.005$) compared with those receiving PED.
Conclusion: The comparative study of PED and TFD in the treatment of PC aneurysms resulted in positive clinical results and sustained occlusion rates, with acceptable perioperative complications. However, higher quality studies are needed to enhance our understanding of the use of FDs for treating of PC aneurysms.

1. Introduction

Historically, posterior circulation (PC) aneurysms have demonstrated a greater propensity for rupture and less favorable outcome compared to anterior circulation aneurysms [1]. Due to their complexity, treating PC aneurysms using either endovascular or surgical methods remains challenging [2].

In recent years, flow-diverting devices (FDs) have become a new option for treating intracerebral aneurysms, through the reconstruction of the parent vessel. Previous studies have primarily focused on the first FD-the pipeline embolization device (PED), which has considerably decreased the rate of aneurysm recurrence compared with conventional coil-or stent-assisted embolization, leading to improved long-term patient outcomes [3,4].

Currently, FDs are predominantly used for treating anterior circulation aneurysms. To date, there are still some controversies about the use of FDs in the treatment of PC aneurysms [5–7]. However, with the growing use of FDs, numerous studies have reported promising results. Recent research demonstrates that in patients with PC aneurysms undergoing PED treatment, the incidence of achieving complete or near-complete occlusion exceeds 75% (12–15). Despite the widespread use of FDs in China, studies reporting the treatment efficacy of the novel Tubridge flow diverter(TFD) are limited. TFD is a novel device that was developed in China. The TFD is a braided, self-expanding stentlike device with flared ends providing high metal coverage (between 30.0% and 35.0%) at the aneurysmal neck [8–10]. Reducing blood flow to the aneurysm and isolating it from the cerebral circulation, FDs could promote thrombosis and endothelialization of aneurysms [7,11,12]. While the PED and TFD have similar mechanisms of action, their design concept and materials are distinct. The PED is composed of cobalt-chromium (75%) and platinum (25%), facilitating superior visual visibility with a design characterized by increased rigidity. This rigidity could sometimes impede its full deployment in the curved segments of vessels. Conversely, the TFD is constructed from a nickel-titanium alloy, known for its enhanced shape memory and superplastic properties. The design of TFD allows for more flexibility. However, it provides weaker radial support, making it susceptible to displacement due to movements of microcatheters or microwires [9,13]. Recently, the literature has seen a limited exploration of comparative analyses focusing on the safety and efficacy across different types of flow diverters (PED and TFD) [14–16]. Cai et al. conducted a retrospective study involving 92 patients with wide-neck aneurysms. The results indicated that the complete occlusion rate of aneurysms in the PED group was 77.42%, compared with 85.71% in the TFD group, without showing statistically significant difference between the two groups [14]. Additionally, Wang et al. treated basilar artery aneurysms using PED (n = 3) and TFD (n = 13) combined with coil-assisted embolization. They demonstrated that both types of flow diverters were safe and effective in treating basilar artery aneurysms [16]. Therefore, TFD can also be employed as an FD and may have therapeutic potential for treating PC aneurysms.

To the best of our knowledge, studies comparing PED and TFD are extremely rare. Thus, due to the absence of reliable prospective or multicenter retrospective studies that could have served as a reference, we employed PSM to equalize the initial differences between the two groups. PSM could offer notable advantages over conventional regression methods when it comes to adjusting for confounding factors in observational research [17]. In this study, we aimed to evaluate the clinical efficacy of PED and TFD in treating PC aneurysms. Additionally, we sought to illustrate the treatment efficacy of TFD and compare the similarities and differences between these two FDs.

2. Methods

2.1. Study population

Patients with consecutive PC aneurysms who underwent aneurysm treatment with FDs between January 2015 and December 2020, at five academic institutions in China (Beijing Hospital, Beijing Tiantan Hospital, Zhujiang Hospital, The First Affiliated Hospital of Nanchang University, and Shenzhen Second People's Hospital.), were retrospectively identified based on their clinical data. Patients who were treated with either PED (Pipeline™; Medtronic Inc, Dublin, Ireland) or TFD (Tubridge™; MicroPortMedical Company, Shanghai, China) were included in the study. Patients under the age of 18 or those with insufficient angiography scans, (which did not allow for the assessment of aneurysm characteristics-based occlusion results) were excluded.

2.2. Data collection for PED and TFD cases

Information regarding patient demographics, such as age, sex, presence of subarachnoid hemorrhage (SAH) upon admission (with SAH onset within 7 days prior to admission), initial modified Rankin Scale (mRS) score, SAH history, hypertension, hyperlipidemia, diabetes, coronary heart disease, history of hemorrhagic and ischemic stroke, smoking status, and alcohol consumption, were

Table 1
Baseline characteristics.

Number of patients	n = 248
Gender (%)	
Male	186(73.8)
Female	66(26.2)
Age in years (median; IQR)	54(47–61.25)
Previous SAH (%)	
No	244(96.8)
Yes	4(1.6)
Previous Hypertension (%)	
No	114(45.2)
Yes	138(54.8)
Previous Hyperlipidemia (%)	
No	233(92.5)
Yes	19(7.5)
Previous Diabetes (%)	
No	228(90.5)
Yes	24(9.5)
Previous Coronary heart disease (%)	
No	237(94)
Yes	15(6)
Previous Hemorrhage (%)	
No	249(98.8)
Yes	3(1.2)
Previous Ischemic stroke (%)	
No	215(85.3)
Yes	37(14.7)
Smoking status (%)	
Never	190(75.4)
Current	62(24.6)
Drinking status (%)	
Never	211(83.7)
Current	41(16.3)
Previous SAH $\leq$2 weeks (%)	
No	244(96.8)
Yes	8(3.2)
Pretreatment mRS score (%)	
0	149(59.1)
1	83(32.9)
2	12(4.8)
3	5(2.0)
4	3(1.2)
Treated aneurysm baseline characteristics	
Parent vessel location (%)	
Basilar artery	33(13.1)
Posterior cerebral artery	5(2.0)
Vertebral artery	214(84.9)
Morphology (%)	
Saccular	100(39.7)
Dissecting/blister	93(36.9)
Fusiform	59(23.4)
Maximal diameter in mm (median; IQR)	8.6(6.50–12.00)
Neck diameter in mm (median; IQR)	8.6(6.3–11.81)
Parent vessel diameter (median; IQR)	3.3(2.8–3.8)
Tandem aneurysm (%)	14(5.6)
Procedure details	
Type of FD placed (%)	
PED	170(67.5)
TFD	82(32.5)
Adjunctive coil during flow-diverter application (%)	43(17.1)
Adjunctive balloon during flow-diverter application (%)	10(4.0)
Multiple stent (%)	24(9.5)
Number of PEDs placed (%)	
1	152(89.4)
>1	18(10.6)
Number of TFDs placed (%)	
1	76(92.7)
>1	6(7.3)
Stent diameter (median; IQR)[a]	4(3.5–4.25)
Stent length (median; IQR)[a]	30(25–35)

(*continued on next page*)

Table 1 (*continued*)

Number of patients	n = 248
Complications	
Major complications (%)	19(7.5)
Major ischemic stroke (%)	11(4.4)
Hemorrhagic complications (%)	5(1.9)
In-hospital mortality (%)	6(2.3)
Postoperative Major complications (%)	18(7.1)
Total thromboembolic complications (%)	11(4.4)
Aneurysm imaging follow-up	
Last radiographic follow-up elapsed time, months (median; IQR)[d]	9.(5.00,18.00)
Occlusion status at last imaging follow- up (%)[d]	
Occluded (100%)	210(79.1)
Near completely occluded and incompletely occluded	42(20.9)
Postoperative Stenosis of stent complications (%)[e]	
Stenosis of stent	49(24.6)
No Stenosis	151(75.4)
Stent Stenosis Grouping (%)[e]	
25%–50%	22(11.0)
50%–100%	27(13.6)
Aneurysm clinical follow-up	
Time to last follow- up mRS (median; IQR)	28(17.25,37)
mRS score on last follow- up (%)[b]	
0	158(71.2)
1	40(18.0)
2	4(1.8)
3	3(1.4)
5	5(2.3)
6	12(5.4)
Time of dual antiplatelet medication after operation (%)[c]	
3–6 mouth	104(51.0)
>6 mouth	39(19.1)

TFD, Tubridge Flow Diverter; PED, Pipeline Embolization Device; mRS, modified Rankin Scale. IQR, International Quality Review.
SAH, subarachnoid hemorrhage.

[a] 11 Missing data.
[b] 30 Missing data.
[c] 48 Missing data.
[d] 51 Missing data.
[e] 52 Missing data.

gathered.

The following aneurysm characteristics were assessed: aneurysm size, aneurysm neck, patient artery diameter, and the location of aneurysm [18–20]. Regarding saccular aneurysms, aneurysm size was determined by measuring the largest cross-sectional length of the aneurysm dome. Considering fusiform aneurysms, aneurysm size was determined by measuring the longest dimension perpendicular to the fusiform aneurysm's parent vessel's centerline. Aneurysm neck referred to calculating the greatest span between any two points across the aneurysm neck. Patient artery diameter was calculated as the average of the measurements taken from both the proximal and distal segments adjacent to the aneurysms. Procedural details collected included coil-assisted embolization, balloon-assisted embolization, and PED stent length and diameter. The decision on stent selection was based on the treatment experience and preferences of the participating institution.

The angiographic follow-up method was determined by the participating institution. The aneurysms treated with PED or TFD were categorized according to their morphology: saccular, fusiform, or dissecting/blistering [21]. To ensure consistency, all institutions utilized the uniform data recording form for recording the data listed in Table 1 shown in this article.

2.3. Procedure details

Patients were initiated on a combination of antiplatelet therapy (100 mg aspirin and 75 mg clopidogrel daily) at least 3 days before their procedure. Following the procedure, patients were required to undergo combination antiplatelet therapy for at least 3 months. Subsequently, a daily dose of 100 mg aspirin was prescribed for lifelong maintenance. Platelet function testing was determined at the discretion of researchers from different centers. In patients exhibiting resistance to clopidogrel, ticagrelor was adopted as an alternative antiplatelet regimen. In addition, depending on the intraoperative condition, tirofiban was administered perioperatively at the operators' discretion.

To ensure uniformity in the quality of surgical procedures, we adhered strictly to the standardized guidelines for operative techniques. All surgeons came from advanced neurosurgical centers in China, having undergone rigorous professional training. Furthermore, we mandated that each surgeon has previously completed at least 50 stent implantation procedures for posterior circulation aneurysms. Each procedure was carried out under general anesthesia. A modified Seldinger technique was utilized for accessing the

femoral artery. Cerebral angiography and reconstruction of the vascular in three-dimensional(3D) were initially conducted to assess size, neck width, and relationship of aneurysms with the artery. Additionally, to determine the working angle, 3D imaging was used. A 6F long sheath or 8F guiding catheter was employed; and a 6F Navien guiding catheter (125 cm in length, Medtronic, USA) was inserted into the desired artery using a guidewire. Based on the path diagram, a Synchro14 microwire (200 cm in length) was employed to navigate the SL-10 microcatheter through aneurysm neck and into the farthest-reaching normal vessel. The suitable FD was picked out and skillfully transported to the chosen spot. The head end was then inserted into the downstream straight section of the vessel after making sure the microcatheter perfectly fit and completely covered the aneurysm neck. In some instances, balloons were utilized to expand the proximal part of the FD, leading to a notable decrease in ischemia complications. Coil embolization was performed using a pre-inserted Echelon-10 microcatheter for aneurysms that required supplementary coil embolization (EV3, Irvine, California, USA). After the stent was released, an angiography was conducted to assess the patency of the aneurysm-affected artery, including the inspection of any branches or perforating vessels.

2.4. Outcome

Digital subtraction angiography was utilized for routine postoperative follow-up at intervals of 6–12 months. As per the O'Kelly-Marotta (OKM) grading scale, uncoiled treated aneurysms occlusion rates were classified as complete occlusion, Substantial Filling, Minor Residual, or no filling [22]. As per the Raymond–Roy occlusion classification (RROC), coiled treated aneurysm occlusion rates were classified as fully closed (100%), almost fully closed with a remaining neck (90–100%), or residual aneurysm (<90%) [23]. Complete occlusion referred to the occlusion status classified as complete occlusion according to both the OKM grading scale and the RROC, whereas the remaining classifications denoted incomplete occlusion. These definitions were adopted in this study to evaluate the occlusion rate of the aneurysms. Follow-up angiography was performed to assess the patency of the parent artery and its branches, along with in-stent stenosis (ISS), referring to the process of growth that exceeded the boundaries of the metal mesh. Regarding angiographic observations, in-stent stenosis was identified as a 'space' between the vessel lumen containing contrast dye and the physical stent barrier. A gap measurement within the range of 1–25% was classified as intimal hyperplasia. In-stent stenosis, indicating constriction in the main vessel, was classified as slight (25–50%), moderate (50–75%), or extreme (>75%) [24,25].

Perioperative complications were referred to those occurred during the perioperative period. These complications included intraoperative hemorrhage, intraoperative thrombosis, postoperative hemorrhage, transient ischemic attack, postoperative major stroke (defined as a change in the National Institutes of Health Stroke Scale [NIHSS] score >4, lasting >7 days), postoperative minor stroke, and mortality. The total ischemic stroke complications included both the postoperative major stroke and postoperative minor stroke. Major perioperative complications included intraoperative hemorrhage, intraoperative thrombosis, postoperative hemorrhage, postoperative major stroke, and mortality. The functional outcomes at the time of follow-up were evaluated using mRS score, which a score between 3 and 6 indicates a poor clinical outcome. Additionally, a reduction in the mRS score of one point or more (mRS score at admission minus mRS score at follow-up $\geq$ 1).

2.5. Statistics

Continuous variables are presented as mean $\pm$ standard deviation (SD) or median with interquartile range (IQR). Total number and percentage are used to display categorical variables. For comparing proportions, the Chi-square test was utilized, and for continuous variables, the Mann-Whitney *U* test or T-test was employed. PSM was utilized to account for variables that could have an impact on the results. A multivariate logistic analysis was utilized to evaluate the propensity score of the patients to reduce the covariate imbalance between the PED and TFD groups. Variables with statistical differences from the univariable analysis were fitted into the multivariable logistic analysis to generate the propensity scores. Statistical analyses utilized two-tailed tests with a significance threshold of $p < 0.05$. R software (version 4.1.0) was employed for all statistical calculations.

3. Results

3.1. Patient, aneurysm, and treatment characteristics

In total, 248 patients received interventions for 252 posterior circulation aneurysms (Table 1). Among these, only 244 aneurysms were unruptured. Patients had a median age of 54 years (range, 47–61.25) with 26.2% being female (66/248). Aneurysm morphology was classified as saccular (39.7%), dissecting/blister (36.9%), or fusiform (23.4%). The parent artery diameter was 3.3 (range, 2.8–3.8) mm, the aneurysm size was 8.6 (range, 6.5–12) mm, and the neck was 8.66 (range, 6.3–11.81) mm. The mean stent diameter and stent length were 4 (range, 3.5–4.25) mm and 30 (range, 25–35) mm, respectively. Out of the 248 aneurysms, coiling was used in only 43 cases (17.1%), while balloon assistance was utilized in 10 cases (4%). The middle last angiographic and clinical times were 9 (range, 5–18) and 28 (range, 17.25–37) months. During the final angiographic evaluation, the complete occlusion and near completely occlusion rate was 79.1% (210/252). Twenty-seven aneurysms, which accounted for 13.6% of the total, exhibited in-stent stenosis of >25%. The total major complications, total ischemic stroke complications, ischemic major stroke complications, and major postoperative complications were 7.5% (19/248), 7.1% (18/248), 4.4% (11/248) and 7.1% (18/248), respectively.

3.2. Unmatched comparison of PED and TFD patients

Several important differences were found between the groups. The patients treated with TFD had a higher median age (57 versus 54, $p < 0.01$) than did those treated with PED. Additionally, the TFD group exhibited higher rate of history of ischemic stroke than did the PED group (26.8 versus 8.8, $p < 0.01$). Furthermore, the median diameter of the neck aneurysms treated with PED was greater (9.8 versus 7.2 mm, $p < 0.001$). The length of the stent was longer in the TFD group compared to the PED group (35 versus 30, $p < 0.01$). Regarding the outcomes, at the 9 months median imaging evaluation, complete or near-complete occlusion was observed in 74.1% of the aneurysms, with no significant differences in occlusion rates between the groups. Additionally, at a median clinic follow-up of 28 months, 90.5% of the patients achieved good functional result. It should be highlighted that patients in the PED group were on dual antiplatelet therapy for a longer period than those in the TFD group ($p < 0.01$). The median length of follow-up was substantially

Table 2
Comparison for type of flow diverter used before propensity score matching analyzed per aneurysm.

Variable	Type of flow diverter (%)		*P* value
	PED 170 (67.46)	TFD 82 (32.54)	
Age at time of treatment			
Years (median; IQR)	54(46,59)	57(50.25,63.75)	**0.003**
Female (%)	45(26.5)	21(25.6)	1
SAH history (%)	5(2.9)	3(3.7)	0.718
Hypertension (%)	86(50.6)	52(63.4)	0.075
Hyperlipidemia (%)	14(8.2)	5(6.1)	0.62
Diabetes (%)	12(7.1)	12(14.6)	0.067
Coronary heart disease (%)	12(7.1)	3(3.7)	0.398
Hemorrhage history (%)	1(0.6)	2(2.4)	0.248
Ischemic stroke history (%)	15(8.8)	22(26.8)	<**0.001**
Never smoker status (%)	46(27.1)	16(19.5)	0.251
Never Drinking status (%)	27(15.9)	14(17.1)	0.954
Previous SAH ≤2 weeks (%)	5(2.9)	3(3.7)	0.718
Parent vessel location (%)			0.439
Basilar artery	19(11.2)	14(17.1)	
Posterior cerebral artery	4(2.4)	1(1.2)	
Vertebral artery	147(86.5)	67(81.7)	
Morphology (%)			0.068
Saccular	63(37.1)	37(45.1)	
Dissecting/blister	71(41.8)	22(26.8)	
Fusiform	36(21.2)	23(28.0)	
Maximal diameter in mm (median; IQR)	8.90(6.55,12.33)	8.00(6.15,11.38)	0.136
Neck diameter in mm (median; IQR)	9.80(7. 03,12.78)	7.20(5.04,8.83)	**< 0.001**
Parent vessel diameter (median; IQR)	3.30(2.80,3.80)	3.30(2.70,3.90)	0.866
Tandem aneurysm (%)	12(7.1)	2(2.4)	0.156
Adjunctive coil during flow-diverter application (%)	31(18.2)	12(14.6)	0.594
Adjunctive balloon during flow-diverter embolization (%)	4(2.4)	6(7.3)	0.083
Multiple stent (%)	18(10.6)	6(7.3)	0.497
Stent diameter (median; IQR)a	4.00(3.25,4.25)	4.00(3.5,4.5)	0.229
Stent length (median; IQR)a	30.00(25,35)	35.00(25,35)	**0.011**
Outcomes			
Major complications (%)	6(3.5)	13(15.9)	**0.001**
Major ischemic stroke (%)	2(1.2)	9(11.0)	**0.001**
Postoperative Major complications (%)	5(2.9)	13(15.9)	<**0.001**
Total thromboembolic complications (%)	7(4.1)	11(13.6)	**0.015**
Time to last follow- up mRS (median; IQR)	31.00(19.75,38.25)	19.00(6.25,32.75)	<**0.001**
mRS score on last follow- up (%)			0.594
≥2	14(8.6)	6(12.5)	
Time to last follow- up imaging (median; IQR)d	9(5,18)	7(5.50,13.00)	0.327
Aneurysm occlusion (Incomplete embolism, %)d	26(18.3)	16(27.1)	0.227
Postoperative Stenosis of stent complications			
Stenosis of stent (%)e	20(14.1)	7(12.3)	0.186
Stent Stenosis Grouping (>50%, %)e	32 (22.5)	17 (29.8)	0.281
Time of dual antiplatelet medication after operationc			<**0.001**
3–6(mouth)	85(59.9)	19(30.6)	
> 6(mouth)	34(23.9)	5(8.1)	

TFD, Tubridge Flow Diverter; PED, Pipeline Embolization Device; mRS, modified Rankin Scale. IQR, International Quality Review.
SAH, subarachnoid hemorrhage.
11 Missing data.
30 Missing data.
48 Missing data.
51 Missing data.
52 Missing data.

greater than for those in the PED group (31 versus 19, $p < 0.01$). The major perioperative complications occurred in 19 patients (7.5%), including severe ischemic strokes (n = 11), hemorrhagic complications (n = 5), in-hospital deaths (n = 6), and intraoperative complication (n = 1). The major complication rate was higher in the TFD group than in the PED group (15.9% versus 3.5%, $p < 0.01$) (Table 2).

3.3. Comparison of PED and TFD patients after PSM and exclusion of cases of SAH

PSM was used to adjust for age, history of ischemic stroke, aneurysm morphology, location, size, neck, number of FDDs, parent vessel diameter, adjunctive coiling, and adjunctive balloon; the patients with aneurysmal SAH were excluded. Eighty-two aneurysm pairs were matched. Regarding the information of devices, the median length of TFD group was larger (30 versus 35 mm, $p < 0.01$). No significant variances were observed in aneurysm occlusion. However, the PED group had fewer major complications than the TFD group (15.9% versus 3.7%, $p = 0.016$) (Table 3).

Table 3
Comparison for type of flow diverter used after excluding previously ruptured aneurysms and propensity score matching controlling for age, aneurysm location group, size, and morphology, adjunctive coiling, and last follow-up imaging elapsed time analyzed per aneurysm (n = 82).

Variable	Type of flow diverter (%)		*P* value
	PED 82	TFD 82	
Age at time of treatment			
Years (median; IQR)	55.00(51,62)	57.00(50.25,63.75)	0.427
Female (%)	22(26.8)	21(25.6)	1
SAH history (%)	1(1.2)	2(2.4)	1
Hypertension (%)	48(58.5)	52(63.4)	0.631
Hyperlipidemia (%)	8(9.8)	5(6.1)	0.565
Diabetes (%)	7(8.5)	12(14.6)	0.329
Coronary heart disease (%)	7(8.5)	3(3.7)	0.328
Hemorrhage history (%)	0	2(2.4)	0.497
Ischemic stroke history (%)	11(13.4)	22(26.8)	0.051
Never smoker status (%)	21(25.6)	16(19.5)	0.455
Never Drinking status (%)	11(13.4)	14(17.1)	0.664
Previous SAH ≤2 weeks (%)	2(2.4)	3(3.7)	1
Parent vessel location (%)			0.682
Basilar artery	9(11)	14(17.1)	
Posterior cerebral artery	1(1.2)	1(1.2)	
Vertebral artery	72(87.8)	67(81.7)	
Morphology (%)			0.406
Saccular	32(39)	37(45.1)	
Dissecting/blister	30(36.6)	22(26.8)	
Fusiform	20(24.4)	23(28)	
Maximal diameter in mm (median; IQR)	8.9(6.73,11.3)	8(6.15,11.38)	0.43
Neck diameter in mm (median; IQR)	8.25(6.23,10)	7.2(5.04,8.83)	0.052
Parent vessel diameter (median; IQR)	3.3(2.9,3.9)	3.3(2.7,3.9)	0.359
Tandem aneurysm (%)	8(9.8)	2(2.4)	0.099
Adjunctive coil during flow-diverter application (%)	12(14.6)	12(14.6)	1
Adjunctive balloon during flow-diverter embolization (%)	2(2.4)	6(7.3)	0.277
Multiple stent (%)	6(7.3)	6(7.3)	1
Stent diameter (median; IQR)[a]	4(3.5,4.25)	4(3.5,4.5)	0.342
Stent length (median; IQR)[a]	30(25,35)	35(25,35)	**0.007**
Outcomes			
Major complications (%)	2(2.4)	13(15.9)	**0.005**
Major ischemic stroke (%)	0	9(11)	**0.003**
Postoperative Major complications (%)	2(2.4)	13(15.9)	**0.005**
Total thromboembolic complications (%)	2(2.4)	11(13.4)	**0.018**
Time to last follow- up mRS (median; IQR)	26.5(18,36)	19.0(6.25,32.75)	**0.002**
mRS score on last follow- up (%)			0.594
≥2	8(10)	6(10.3)	1
Time to last follow- up imaging (median; IQR)[d]	10(5,18.5)	7(5.5,13)	0.289
Aneurysm occlusion (Incomplete embolism, %)[d]	13(19.4)	16(27.1)	0.415
Postoperative Stenosis of stent complications			
Stenosis of stent (%)[e]	11(16.4)	7(12.3)	0.613
Stent Stenosis Grouping (>50%, %)[e]	17(25.4)	(29.8)	0.687
Time of dual antiplatelet medication after operation[c]			**<0.001**
3–6(mouth)	37(55.2)	19(30.6)	
> 6(mouth	18(26.9)	5(8.1)	

TFD, Tubridge Flow Diverter; PED, Pipeline Embolization Device; mRS, modified Rankin Scale. IQR, International Quality Review.
SAH, subarachnoid hemorrhage.

4. Discussion

PC aneurysms, which have worse natural course, high complication rates, and high risk of recurrence, remain a challenge in treatment. The application of PED in AC aneurysms may make FD a feasible treatment choice for these complex lesions [26–29]. In recent years, off-label use of FDs has broadened to include treating aneurysms in PC. However, there are still no randomized controlled trials evaluating using FD for PC aneurysms. Controversy remains regarding the use of FD for treating PC aneurysms. Our study retrospectively evaluated 252 aneurysms in 248 patients treated with FDs (PED and TFD) at five centers in China. complete and near-complete occlusion was found at the last follow-up imaging in 79.1%. The major perioperative complications occurred in 7.5% of the cases. This is the first multicenter study on PC aneurysms treated with FDs and could represent the largest sample size in such research to date.

Prior research has shown the effectiveness of TFD in treating aneurysms in the PC [30]. Our study aimed to further explore treatment using TFDs, representing the first multicenter study to compare TFD with PED, which both are FDs used for treating PC aneurysms. In our study, we found that there was no notable disparity in the percentage of aneurysm occlusion that was either complete or near-complete. After conducting a comprehensive comparison between the PED and TFD-treated groups, PSM was used to adjust for age; history of ischemic stroke; aneurysm size; morphology; location and aneurysm neck; number of FDs; parent vessel diameter; adjunctive coiling; and adjunctive balloon. Patients with aneurysmal SAH were excluded. Angiographic and functional outcomes showed significant similarities. The rate of completely occluded aneurysms did not differ significantly. Nevertheless, perioperative problems were more prevalent in the TFD group.

4.1. Flow diversion for PC aneurysms

Aneurysms in the PC are more likely to rupture and have a greater risk of complications than those in the AC. According to the International Study of Unruptured Intracranial Aneurysms (ISUIA), the PC aneurysm led to a negative result in multivariate analysis, whether the lesion was treated with endovascular therapy or surgery [1]. In this study, we found some important differences. The age in the TFD group was higher compared with PED (57 versus 54, $p = 0.003$). Patients who had previously experienced an ischemic stroke were more likely to be in the TFD group than in the PED group (22 versus 15, $p < 0.001$). The median neck of aneurysms treated with PED was larger (9.8 versus 7.2 mm, $p < 0.001$). The length of devices that were applied in TFD group was longer compared with the PED group (35 versus 30, $p = 0.012$). The median length of most recent clinic follow-up for PED was double that of TFD (31 versus 19, $p < 0.001$). The number of 4′-6-diamidino-2-phenylindole (DAPI) staining for PED was used more compared with the TFD group ($P < 0.001$).

Flow diversion can effectively occlude aneurysms with reduced chance of recurrence compared with coiling with or without an assist device [3]. The occlusion rates, both complete and nearly complete, observed in our cohort were 74.1%, mirroring results previously documented in FD studies targeting PC aneurysms [31,32]. The occlusion rates of aneurysms did not vary between the two devices. Regarding perioperative complications, there were 18 cases of thromboembolic complications, 5 cases of hemorrhagic complications, and six in-hospital mortality. Among the ischemic complications, 11 were categorized as major, while the remaining seven were classified as mild. In our study, thrombotic complications dominated, which is consistent with other reports. This may be related to the hemodynamic changes caused by the dense mesh stent [33].

However, thromboembolic and other procedure-related problems were more common in the TFD group than in the PED group. The morphological and etiological characteristics of PC aneurysms can vary, affecting both their natural progression and potential treatment options [34]. There may be some baseline and anatomical features that make the TFD group more prone to complications [35–37]. To balance between these potential influencing factors, we used a PSM approach. Then, we focus on the differences between the two devices in treating PC aneurysms.

4.2. Comparison between PED and TFD in the patients after PSM and exclusion of SAH cases

PED was the initial FD authorized for clinical application, whereas the TFD is a novel device developed in China that has reportedly produced positive outcomes in treating PC aneurysms. The abundance of PED cases facilitated the successful matching of the aneurysms treated with TFD that were available. After excluding ruptured aneurysms, a sample of 82 PED-treated and 82 TFD-treated aneurysms with matched propensity scores was identified. The two groups did not show any notable differences in aneurysm occlusion rates. However, it is worth noting that the total major complication in the TFD cohort remained greater than that in the PED cohort. Thromboembolic events were the primary cause of unfavorable outcomes. Several factors may have contributed to the higher rate of complications in the TFD cohort. First, the association between higher baseline mRS scores and less favorable outcomes in aneurysm treatment, FD may be more suitable for patients who are asymptomatic or who have milder symptoms [38]. The TFD group had high proportion of previous ischemic stroke at 26.8% compared with the PED group. Second, ischemic stroke symptoms are the most common presenting symptoms (44%) for fusiform aneurysms [35]. In one report on fusiform aneurysms in the PC by Ephraim et al., six patients underwent FD. However, this approach failed to contribute a decreased incidence of ischemic complications compared with other treatments [2]. In another multicenter study that focused on PED therapy for PC aneurysms, it was found that 53 out of 131 aneurysms in this region were classified as fusiform. This type of aneurysm was linked to a higher incidence of major complications (11.5%) and thromboembolic complications (25%) [31]. The findings of our study indicated a higher prevalence of fusiform aneurysms in the TFD group (28% versus 24.4%) compared with the PED group. Third, aneurysm location (the basilar artery) is associated with neurological mortality. Basilar aneurysms have a poor outcome due to variables such as basilar artery perforator

ischemia, and probable brainstem compression from aneurysms treated with PED [39]. Siddiqui et al. conducted a study including 7 patients who received FD treatment for non-saccular PC aneurysms (6 received PED and 1 received TFD). The results were alarming, showing a mortality rate of 57% and a incidence of thromboembolic complications at 72%. The study also found a low rate of favorable neurological outcomes at 29% [36]. Subsequently, at the same institution, a study found that selecting the location of PC aneurysms distal to V3/V4 or distal to the PC (excluding aneurysms situated in the basilar artery) led to decreased occurrence of thromboembolism and a favorable functional prognosis of 92% [37]. In our study, the percentage of basilar arteries in the TFD group was greater compared to the PED group (17.1% versus 11%). The material and design of the FD itself may contribute to the occurrence of perioperative complications. Compared with PED, the TFD possesses superior shape memory and adaptability. However, this design may compromise stability and adaptability in recanalized vascular structures, leading to suboptimal vessel wall apposition and, consequently, an increased risk of thrombus formation [40]. At the same time, the length of the stent in TED therapy exceeded that in PED, which may result in an increased probability of occluded vascular branches and more platelet activation contact surface.

In addition to functional results, the two groups showed differences in duration of dual antiplatelet medication after operation following PSM. After the PSM, The PED group had a longer time of dual antiplatelet therapy (>6 months) than did the TFD group (82.1% versus 38.7%, $p < 0.001$). No notable variations were observed in mRS score on last follow-up. In a case report, these devices may still be vulnerable to delayed occlusion in patients with PC aneurysm, more than 1-year post-implantation [41]. The current research found that the duration of clinical follow-up was longer for the PED group ($p = 0.002$). Long-term symptomatic complications require further follow-up to evaluate this phenomenon.

4.3. Limitations

There are certain constraints in our research. First, the retrospective nature of our study might limit the generalizability of its results. However, this can be circumvented in future, multicenter collaborations reporting on treatment safety and efficacy across diverse patient demographics and various treatment facilities could increase the generalizability. Second, highlighting that patient selection bias may have existed due to the varied treatment strategies used among the different centers is important. Third, PSM revealed some statistical differences in certain parameters, which may have affected the overall findings.

5. Conclusion

This study compared between two different FDs for the treatment of aneurysms in the PC using data from five academic institutions in China. A PSM method was utilized to evaluate and analyze the treatment of PED and TFD on unruptured PC aneurysms, revealing no significant difference in the aneurysm occlusion and functional result at the last imaging follow-up between the two groups. Perioperative complications in patients with TFD were found to be relatively higher, possibly due to the location and shape of the aneurysm. However, the complications were still considered acceptable. Consequently, an independent, multicenter, high-quality prospective study is warranted to further elucidate the complication of PC aneurysms after TFD treatment.

Ethics approval and consent to participate

This study was approved by the institutional research ethics boards of Beijing Tiantan Hospital (KY-2018-086-03). The requirement for informed consent has been waived due to the retrospective design.

Consent for publication

Not applicable.

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Availability of data and materials

The supporting data of this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Xin Liang: Writing – review & editing, Writing – original draft, Methodology, Data curation. **Xin Tong:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Xiaopeng Xue:** Data curation. **Aihua Liu:** Supervision, Conceptualization. **Zhiqiang Hu:** Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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