Safety and Efficacy of Flow Diversion for Intracranial Aneurysms in Small Parent Vessels: A Retrospective Cohort Study

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Abstract: *Background*: Intracranial aneurysms arising from small parent vessels (<2 mm) are challenging due to their fragile anatomy and distal locations. Flow diversion (FD) offers a promising treatment, but its safety and efficacy in small vessels remain underexplored.

Objective: To evaluate angiographic occlusion rates and procedure-related morbidity associated with flow diversion for intracranial aneurysms arising from parent vessels <2 mm in diameter.

Methods: A retrospective cohort study was conducted at Bicêtre Hospital, Paris, France, from January 2018 to December 2023, analyzing 50 patients undergoing 56 procedures for 55 aneurysms. FD devices (e.g., Silk Vista Baby, Pipeline Flex) were used. Follow-up at 6, 18, and 42 months assessed occlusion via digital subtraction angiography (DSA) using Raymond-Roy and O'Kelly-Marotta scales.

Results: Complete occlusion was achieved in 70.9% (39/55) of aneurysms at a mean follow-up of 17.86 months. At 6, 18, and 42 months, occlusion rates were 56.4%, 55.6%, and 76.5%, respectively. Intraprocedural complications occurred in 28.6% (16/56) of procedures, with 19.6% (11/56) due to in-stent thrombosis. Symptomatic major complications were observed in 17.9% (10/56), including ischemic events and hemorrhage, and permanent FD-related morbidity was 8.0% (4/50).

Conclusion: FD is effective for small vessel aneurysms, with high occlusion rates, but significant complications highlight the need for careful patient selection and refined techniques. Larger studies are needed to optimize outcomes.

Keywords: Intracranial aneurysms, flow diversion, small parent vessels, safety, efficacy, complications.

INTRODUCTION

Intracranial aneurysms in small parent vessels (<2 mm) pose unique challenges due to their distal locations, fragile vascular anatomy, and complex flow dynamics. Traditional treatments like coiling or clipping are limited by high risks of vessel injury and incomplete occlusion in small vessels [1]. Flow diversion, which redirects blood flow to promote aneurysm thrombosis and endothelialization, has revolutionized aneurysm management, particularly for large or complex lesions [2]. However, its application in small vessels is less studied, with concerns about device navigability, thromboembolism, and branch occlusion [3].

Low-profile flow diverters (FDs) have improved access to distal vessels, but challenges like braid deformation, in-stent thrombosis, and neointimal hyperplasia persist [4,5].

Management of aneurysms in vessels <2 mm presents a therapeutic dilemma: while coiling is limited by technical feasibility and recurrence, microsurgical clipping poses significant morbidity in deep-seated or eloquent regions. Flow diversion offers a reconstructive, vessel-sparing alternative that bypasses the need for catheterization of the sac. However, small vessel caliber, tortuosity, and branch-rich anatomy pose navigational and thromboembolic challenges. Evidence remains limited regarding FD performance in this subset, necessitating targeted evaluation [5,6].

This study evaluates angiographic occlusion rates and procedure-related morbidity associated with flow diversion for intracranial aneurysms arising from parent vessels <2 mm in diameter.

METHODS

Study Design and Setting

This retrospective analysis was conducted on a prospectively maintained institutional aneurysm database at the Department of Interventional Neuroradiology, Bicêtre Hospital, Paris, France. The study included patients treated for intracranial aneurysms arising from small parent vessels with flow

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diversion between January 2018 and December 2023. Institutional Review Board (IRB) approval was obtained, and informed consent was waived due to the retrospective design. Data collection and analysis were led by the primary author, with validation and review by the research team to ensure accuracy.

This study was conducted in accordance with the Declaration of Helsinki and adhered to institutional ethical standards for retrospective human subject research.

Inclusion Criteria and Patient Selection

The study included patients with intracranial aneurysms originating from parent vessels with a diameter of 2 mm or less and treated by FDs. The parent vessel diameter was calculated as the average of the proximal and distal diameters at the stented segment.

Parent vessel diameter was defined as the average of proximal and distal segments across the stented segment, measured on 3D digital subtraction angiography (DSA) [6].

Detailed records were maintained for patient demographics, comorbidities (e.g., hypertension, diabetes, dyslipidemia and smoking status), aneurysm morphology, device characteristics and procedural details.

Exclusion criteria included aneurysms treated in the acute rupture phase or with vessels >2 mm in diameter, as determined by 3D DSA measurements.

Aneurysm and Device Characteristics

FDs were selected based on aneurysm morphology, parent vessel anatomy, and operator preference. Devices included:

- Pipeline Flex and Pipeline Vantage (Medtronic, Irvine, CA, USA).
- Silk Vista and Silk Vista Baby (Balt, Montmorency, France).
- FRED Jr. (MicroVention, Aliso Viejo, CA, USA).
- Surpass Evolve (Stryker Neurovascular, Fremont, CA, USA).
- P48 MW, P48 MW HPC, P64 MW, P64 MW HPC (Phenox, Bochum, Germany).

All procedures were performed by experienced interventional neuroradiologists at Bicêtre Hospital. Preoperative and follow-up angiographic data—including aneurysm dimensions, morphological characteristics, parent vessel location and diameter, FD type and dimensions as well as clinical data were systematically reviewed to assess treatment efficacy and safety. Imaging data were analyzed by the primary author and validated by a senior neurointerventionalist, with final results and manuscript approved by all authors.

Procedural Protocol

Procedures were conducted under general anesthesia using the Philips Azurion biplane or monoplane systems (Philips Healthcare, Best, The Netherlands). Treatment decisions were finalized during multidisciplinary meetings involving neurosurgery and neuroradiology teams. Vascular access was primarily femoral, with radial access used in select cases based on anatomical or clinical indications.

Pre-Procedural Anticoagulation and Antiplatelet Therapy

Systemic heparinization was initiated with a bolus of 50 IU/kg after arterial puncture, followed by a continuous infusion of 15 IU/kg/h during the procedure. Heparin was discontinued postoperatively without reversal.

Patients were preloaded with aspirin (160 mg daily) and ticagrelor (90 mg twice daily) for 2–7 days before the procedure. Dual antiplatelet therapy (DAPT) was systematically maintained for a minimum of six months, after which ticagrelor was discontinued, and aspirin was continued for at least one year. If follow-up digital subtraction angiography (DSA) revealed significant neointimal hyperplasia within the stent, DAPT was extended for typically a year or until the next follow-up.

Ticagrelor was preferred over clopidogrel due to high variability in clopidogrel response among Middle Eastern and North African populations, as supported by platelet function assays in our center. Ticagrelor's consistent inhibition of P2Y12 receptors minimized periprocedural thrombotic risks.

Device Placement and Imaging

Pre-procedural simulation of the FD was performed using the Sim&Size software (Sim&Cure, Montpellier, France). Standard anteroposterior (AP) and lateral angiographic views were acquired, followed by 3D rotational imaging to obtain precise aneurysm and vessel measurements. After device deployment, high-resolution diluted-contrast cone beam computed tomography (CT) (Vaso-CT; 20% iodine, 80% saline; Philips Healthcare) was routinely performed to assess stent expansion, vessel wall apposition, and aneurysm neck coverage. In cases of suboptimal apposition, balloon angioplasty was performed, followed by a repeat Vaso-CT. Vaso-CT was also incorporated into follow-up angiographic assessments.

Post-procedural Xper-CT (Philips Azurion system) ruled out hemorrhagic complications, and a femoral angiogram confirmed access site patency before closure with the AngioSeal device (Terumo Corporation, Japan).

Management of Complications

In the event of intraoperative thromboembolic events as thrombus formation or branch compromise, tirofiban, a glycoprotein IIb/IIIa inhibitor, was administered (12 µg/kg bolus IV over 30 minutes, followed by a continuous IV infusion of 0.1 µg/kg/min for 12 hours). Incomplete stent opening was addressed with balloon angioplasty for issues like incomplete FD opening or stenosis. Any neurological deficits prompted immediate brain magnetic resonance imaging (MRI) with diffusion-weighted imaging (DWI) to identify ischemic or hemorrhagic changes.

Follow-Up Protocol

Follow-up assessments were scheduled at 6-, 18-, and 42-months post-procedure; however, in some cases, the first follow-up occurred earlier when patients required subsequent treatment prior to the 6-month interval. DSA evaluated:

- Aneurysm occlusion using O'Kelly-Marotta (OKM) scale.
- Stent behavior (e.g., braid changes, neointimal hyperplasia).
- Parent vessel and covered branch patency.

Time-of-flight (TOF) magnetic resonance angiography (MRA) monitored aneurysm and stent status if deemed necessary. Functional status was recorded at each visit using the modified Rankin Scale (mRS).

Study Outcomes

The primary safety outcome was the incidence of treatment-related morbidity, defined as a persistent neurological deficit with a ≥1-point increase in the mRS at the last follow-up (≥6 months), or mortality related to the procedure or aneurysm. The primary efficacy outcome was complete aneurysm occlusion (RROC I) and (OKM D) at the last follow-up (≥6months), as assessed by DSA.

Secondary outcomes included both intraprocedural technical complications and periprocedural symptomatic complications. The term 'periprocedural symptomatic complications' refers to complications occurring during the procedure and up to 30 days afterwards and leading to clinically evident manifestations. Symptomatic complications were further categorized as major—defined as any new neurological symptom, whether transient (e.g., transient ischemic attacks [TIAs]) or persistent, attributable to thromboembolic or hemorrhagic events—and minor, which encompassed non-neurological adverse events such as access site complications (e.g., hematoma, pseudoaneurysm) or other events not associated with neurological symptoms. In addition, secondary outcomes included subgroup analyses of aneurysm occlusion grades and specific complication subtypes.

Statistical Analysis and Data Interpretation

Statistical analyses were conducted using SPSS software, version 26 (SPSS Inc., PASW Statistics for Windows, Chicago, IL, USA). Qualitative data were described as numbers and percentages, while quantitative data were reported as mean ± standard deviation for normally distributed data, confirmed by the Kolmogorov-Smirnov test.

Significance was determined at the 0.05 level. Chi-square or Fisher's exact tests compared qualitative data between groups. Student's t-test evaluated differences between two independent groups for normally distributed quantitative data. Binary logistic regression, using stepwise, forward Wald, or enter techniques, assessed the impact of multiple independent variables, like aneurysm characteristics and procedural factors, on dichotomous outcomes, such as complete occlusion and FD morbidity, reporting odds ratios (OR) with 95% confidence intervals (CI). For the primary safety outcome, logistic regression identified predictors of FD morbidity, supported by chi-square or Fisher's exact tests for associations with demographic, aneurysm, and procedural variables.

Binary logistic regression was employed to assess predictors of dichotomous outcomes (e.g., complete occlusion, morbidity) due to its robustness with categorical dependent variables. Multicollinearity was checked using variance inflation factors (VIF), with all VIFs <2.0. Model fit was assessed using the Hosmer-Lemeshow test (p > 0.05 for all models).

RESULTS

Patient and Aneurysm Characteristics

The study included 50 patients who underwent 56 procedures to treat 55 intracranial aneurysms. A subset of patients underwent multiple endovascular procedures for either the same or different aneurysms, while some procedures treated multiple aneurysms concurrently. None of the aneurysms were treated in the acute rupture phase. The cohort had a mean age of 53.84 ± 10.88 years, with 70.0% female (Table **1**).

Of the 55 aneurysms treated, 92.7% (51/55) were in the anterior circulation, and 7.3% (4/55) were in the posterior circulation. Common locations included AComA (45.5%, 25/55) and MCA bifurcation (21.8%, 12/55). Bifurcation aneurysms predominated (76.4%, 42/55), while sidewall aneurysms accounted for 23.6%.

Complex morphology on 3D imaging (defined as the presence of 2 or more lobes, a bleb, or a branch coming off the sac) was noted in 65.5% of cases. Nearly half (47.3%, 26/55) were recanalized aneurysms previously treated (47.3% coiled, 3.6% treated with Woven EndoBridge (WEB) device (MicroVention, Aliso Viejo, CA, USA), 1.8% clipped). Aneurysm size was predominantly small (≤5 mm, 74.5%, 41/55), with 25.5% (14/55) larger than 5 mm. Wide-necked aneurysms (defined as defined as having a neck width ≥4 mm or a dome-to-neck ratio <2:1) comprised 83.6% (46/55) (Table **2**).

Procedural Details

FD types included Silk Vista Baby (33.9%, 19/56), FRED Jr (25.0%, 14/56), Surpass Evolve (12.5%, 7/56), Silk Vista (8.9%, 5/56), Pipeline Flex (5.4%, 3/56), Pipeline Vantage (3.6%, 2/56), and others (10.7%, 6/56). Angioplasty was required in 7.1% (4/56), and 94.6% (53/56) used a single FD. Access was femoral in 89.3% (50/56) and radial in 10.7% (6/56).

Follow-up showed neointimal hyperplasia in 33.9% (19/56) at FU1, decreasing to 21.4% (12/56) at the final follow-up. Significant stenosis (>25%) decreased from 26.8% (15/56) at FU1 to 12.5% (7/56) at the final follow-up. Covered branch occlusion was 16.1% (9/56) at the final follow-up, with stenosis in 10.7% (6/56) (Table **3**).

Angiographic Outcomes

At 6 months, 56.4% of aneurysms (31/55) achieved complete occlusion. This increased to 55.6% (20/36) at 18 months and 76.5% (13/17) at 42 months, with 70.9% (39/55) occluded at the last follow-up (mean 17.86 months). Progressive occlusion was observed, with 15% transitioning from incomplete to complete between 6 and 18 months, and 27.3% between 18 and

Table 1: Demographic Characteristics of Studied Cases (n=50 Patients)

Characteristic	Total (n=50)	%
Age (years, Mean ± SD, min-max)	53.84 ± 10.88 (33–84)	-
Sex		
Male	15	30.0
Female	35	70.0
Hypertension	27	54.0
Dyslipidemia	11	22.0
Diabetes	2	4.0
Statin Use	9	18.0
Smoking		
Never	32	64.0
Former Smoker	3	6.0
Active Smoker	15	30.0

This table provides a comprehensive profile of the patient population, revealing that the cohort predominantly consisted of middle-aged females with a high prevalence of hypertension (54%).

Table 2: Angiographic Characteristics of the Aneurysms (n=55)

	Total Number=55 N/mean ±SD	%/median (min-max)
Complete occlusion on last control	39	70.9
Location of FD		
AComA	25	45.5
Pericallosal	13	23.6
MCA bifurcation	12	21.8
PCA	1	1.8
M3	1	1.8
P2	1	1.8
PICA	1	1.8
V4*	1	1.8
Location		
Anterior circulation	51	92.7
Posterior circulation	4	7.3
Aneurysm situation		
Bifurcation	42	76.4
Sidewall	13	23.6
Complex aneurysm on 3D		
No	19	34.5
Bilobed/Bleb	26	47.3
Branch comes off	6	10.9
Both Bilobed & Branch comes off	4	7.3
Recanalized aneurysm?		
No	26	47.3
Yes, coiled	26	47.3
Yes, WEB	2	3.6
Yes, clipping	1	1.8
Size of aneurysm (max diam)		
Small≤5mm	41	74.5
Big>5mm	14	25.5
Wide-necked	46	83.6
Neck (mm)	3.12±1.14	3.0(1.15-6.0)
Height (mm)	3.60±1.80	3.1(0.92-10.2)
Aspect ratio	1.22±0.56	1(0.56-3.1)
Width (mm)	3.96±2.01	3.7(1.41-12.81)
Max diameter (mm)	4.37±2.05	3.9(1.5-12)
Time of last FU DSA	17.86±11.82	17.97(2.93-50.5)

*V4: The fourth part of the vertebral artery.
Table **2** highlights the complex anatomical and morphological profiles of treated aneurysms, including the predominance of bifurcation locations (76.4%) and wide-necked morphology (83.6%).

42 months (Table **4**). Complete occlusion at 6 months predicted sustained occlusion (OR 58.13, p=0.001).

Complications

A total of 56 procedures were performed, with intraprocedural technical complications occurring in 28.6% (16/56) of cases and peri-procedural symptomatic complications (major and minor) in 23.3% (13/56). Flow diverter (FD)-related morbidity, defined as a ≥1-point increase in the modified Rankin Scale (mRS) at the last follow-up attributable to endovascular treatment, was observed in 8.0% (4/50) of patients.

Intraprocedural complications (16/56, 28.6%) primarily consisted of in-stent thrombosis (19.6%,

Table 3: Procedural Characteristics Among Studied Cases (n=56 Procedures)

Characteristic	Total (n=56)	% / Median (min–max)
Access Type		
Femoral	50	89.3
Radial	6	10.7
FD Type		
Silk Vista Baby	19	33.9
FRED Jr	14	25.0
Surpass Evolve	7	12.5
Silk Vista	5	8.9
Pipeline Flex	3	5.4
Pipeline Vantage	2	3.6
Others (P48 MW, P64 MW, etc.)	6	10.7
Material		
Nitinol	44	78.6
Cobalt-Nickel-Chromium	12	21.4
Non-DFT / DFT	50 / 6	89.3 / 10.7
FD Diameter (mm, Mean ± SD)	2.48 ± 0.28	2.5 (2.0–3.25)
FD Length (mm, Mean ± SD)	13.8 ± 2.52	13 (10–20)
Angioplasty	4	7.1
Number of FDs		
1	53	94.6
2	3	5.4
Fluoroscopy Time (min, Mean ± SD)	29.63 ± 11.53	29 (12–80)
Total DAP (Gy·cm², Mean ± SD)	180.91 ± 130.76	146.5 (68–985)
Intimal hyperplasia FU1	19	33.9
Intimal Hyperplasia Final FU	12	21.4
Significant Stenosis (>25%) FU1	15	26.8
Significant Stenosis (>25%) Final FU	7	12.5
Covered Branch Occlusion Final FU	9	16.1

This table details the procedural landscape, including device selection, access routes, and angiographic adjuncts like angioplasty. The frequent use of low-profile FDs (e.g., Silk Vista Baby, FRED Jr) reflects adaptation to small-caliber anatomy.

Table 4: Occlusion Trends of the Studied Aneurysms

	Total Number=55	%
Aneurysm complete exclusion FU1	31	56.4
RROC FU1		
1 (complete occlusion)	31	56.4
2	7	12.7
3	17	30.9
OKAM FU1		
A2	5	9.1
A3	3	5.5
B2	10	18.2
B3	2	3.6
C1	1	1.8
C2	2	3.6
C3	1	1.8
D	31	58.2

(Table 4). Continued.

	Total Number=55	%
Aneurysm complete exclusion FU2(n=36)		
No	16	29.1
Yes	20	36.4
NA	19	34.5
Aneurysm complete exclusion FU3(n=17)		
No	4	7.3
Yes	13	23.6
NA	38	69.1
Aneurysm complete exclusion (last)		
No	16	29.1
Yes	39	70.9
RROC last		
1	39	70.9
2	7	12.7
3	9	16.4
OKM last		
A1	1	1.8
A2	2	3.6
B2	6	10.9
B3	2	3.6
C2	5	9.1
D	39	70.9

Table **4** outlines the progressive improvement in occlusion rates over time, with a 70.9% complete occlusion at last follow-up. The increase from 56.4% at 6 months to 76.5% at 42 months supports the delayed therapeutic effect of FD and emphasizes the need for long-term imaging.

Table 5: Complications and Treatment-Related Morbidity

Intraprocedural Complications	16	28.6
None	40	71.4
In-Stent Thrombosis	11	19.6
Intracranial Vessel Rupture	2	3.6
Supraaortic Dissection	1	1.8
Incomplete Opening	1	1.8
Access Complications	1	1.8
Symptomatic Complications	13	23.3
None	43	76.7
Major	10	17.9
Minor	3	5.4
FD Morbidity (per patient, n=50)	4	8.0

The table stratifies complications by type and severity, showing a 28.6% intraprocedural complication rate, mostly from in-stent thrombosis, and 17.9% symptomatic complications. Importantly, FD-related permanent morbidity was limited to 8%, indicating a favorable safety profile considering the challenging anatomy.

Table 6: Incidence of Vascular and Device Changes at Final Follow-Up

Overall Braid Changes	7	12.5
Fish-mouth	4	7.2
Bump	4	7.2
Foreshortening	1	1.8
Collapse	2	3.6
Covered Branch Occlusion	15	26.8
Parent Vessel Stenosis	6	10.9

This table captures device-related mechanical issues such as braid deformations and vascular changes like branch occlusions and stenosis. The 12.5% incidence of braid changes, while not significantly associated with outcomes, raises important design considerations.

Table 7: Relationship Between Aneurysm Characteristics and Complete Aneurysm Occlusion at Final Follow-Up

	Total Number = 55	Complete Occlusion on Last Control		Test of Significance
		No n=16	Yes n=39	
Location of FD				
A1-AcoA	25	9(36)	16(64)	χ^2= 8.46
A2 - pericallosal	13	1(7.7)	12(92.3)	p= 0.294
Basilar artery (BA)-PCA	1	1(100)	0	
M3	1	0	1(100)	
MCA bifurcation	12	5(41.7)	7(58.3)	
P2	1	0	1(100)	
PICA	1	0	1(100)	
V4	1	0	1(100)	
Anterior circulation	51	15(29.4)	36(70.6)	FET=0.035
Posterior circulation	4	1(25)	3(75)	p=1.0
Multiple aneurysms treated with one FD	4	1(25)	3(75)	FET=0.035 p=1.0
Aneurysm situation				
Bifurcation	42	13(31)	29(69)	χ^2= 0.298
Sidewall	13	3(23.1)	10(76.9)	p=0.585
Irregular aneurysm on 3D				
No	19	4(21.1)	15(78.9)	χ^2= 2.77
Yes, bilobed/with bleb	26	7(26.9)	19(73.1)	p=0.428
Yes, branch comes off	6	3(50)	3(50)	
Yes, both	4	2(50)	2(50)	
Recanalized aneurysm				
No	26	7(26.9)	19(73.1)	χ^2= 1.68
Yes, coiled	26	9(34.6)	17(65.4)	p= 0.643
Yes, WEB	2	0	2(100)	
Yes, clip	1	0	1(100)	
Size of aneurysm (max diam)				
Small≤5mm	41	10(24.4)	31(75.6)	χ^2= 1.73
Big>5mm	14	6(42.9)	8(57.1)	p= 0.189
Wide-necked	46	13(28.3)	33(71.7)	χ^2=0.094 p=0.759
Apex ratio	55	1.063±0.56	1.282±0.56	t=1.32 p=0.194
Max diameter (mm)	55	5.20±1.70	4.03±2.11	t=1.97 p=0.054
Vessel diameter (Mean)	55	1.88±0.12	1.78±0.27	t=1.38 p=0.175

FET: Fisher's exact test, χ^2=Chi-square test.
This analysis attempts to link occlusion success with aneurysm-level variables such as location, size, morphology, and prior treatment. While no variable reached significance, a borderline trend was observed with larger aneurysm size (p=0.054).

11/56), ranging from partial flow impairment to complete occlusion. All cases were successfully managed with intravenous tirofiban, with one requiring adjunctive intra-arterial alteplase (13 mg) (Figure **2**). Although flow was restored in all instances, two patients experienced transient postoperative deficits, including dysphasia and hemiparesis. Intracranial vessel rupture (3.6%, 2/56) occurred in two cases: one resulted in a Sylvian hematoma and monoparesis (mRS 3) following guidewire-induced injury (Figure **5**), while the other, involving an opercular branch dissection during MCA aneurysm treatment, led to SAH

Table 8: Relationship Between Procedural Characteristics and Complete Aneurysm Occlusion at Final Follow-Up

FD Characteristics	Total Number = 55	Complete Occlusion on Last Control		Test of Significance
		No n=16	Yes n=39	
FD type				
FRED Jr	13	3(23.1)	10(76.9)	χ^2=7.67
P48 MW	1	1(100)	0	p=0.568
P48 MW HPC	2	1(50)	1(50)	
P64 MW	1	0	1(100)	
P64 MW HPC	3	1(33.3)	2(66.7)	
Pipeline Flex	2	0	2(100)	
Pipeline Vantage	2	0	2(100)	
Silk Vista	5	1(20)	4(80)	
Silk Vista Baby	19	8(42.1)	11(57.9)	
Surpass Evolve	7	1(14.3)	6(85.7)	
Coated FD	7	2(28.6)	5(71.4)	χ^2=0.001 p=0.974
Nitinol	44	15(34.1)	29(65.9)	χ^2=2.66
Cobalt nickel	11	1(9.1)	10(90.9)	p=0.102
Non-DFT	22	4(18.2)	18(81.8)	χ^2=2.12
DFT	33	12(36.4)	21(63.6)	p=0.146
FD diameter (mm)	55	2.39±0.24	2.51±0.31	t=1.33 p=0.189
FD length (mm)	55	14.81±2.83	13.47±2.33	t=1.81 p=0.08
Intraoperative braid change				
No	53	16(30.2)	37(69.8)	FET=0.429 p=1.0
Wall apposition at the neck				
Not perfect	1	0	1(100)	FET=0.418
Yes	54	16(29.6)	38(70.4)	p=1.0
Neck coverage				
None	1	0	1(100)	χ^2=1.85
Partial	34	12(35.3)	22(64.7)	p=0.397
Full	20	4(20)	16(80)	
Neointimal hyperplasia at final FU	10	1(10)	9(90)	χ^2=2.16 p=0.142
Aneurysm complete occlusion at FU1	31	0(0)	31(100)	χ^2=29.14 p=0.001*
Intimal hyperplasia at final FU	20	3(15)	17(85)	χ^2=3.03 p=0.082
FU1 braid change				
No	48	14(29.2)	34(70.8)	p=0.974
Fish-mouth	3	0	3(100)	p=0.548
Foreshortening	1	0	1(100)	p=1.0
Bump	4	1(25)	3(75)	p=1.0
Collapse	2	2(100)	0	p=0.081
Overall braid change				
No	48	14(29.2)	34(70.8)	p= 0.974
Fish-mouth	3	0	3(100)	p=0.548
Foreshortening	1	0	1(100)	p=1.0
Bump	5	1(20)	4(80)	p=1.0
Collapse	2	2(100)	0	p=0.08

t: Student's t-test, FET: Fisher's exact test, χ^2=Chi-square test, *statistically significant.

Table **8** examines how technical variables, including FD type, material, and deployment parameters, influence treatment efficacy. While most procedural factors were not statistically significant, full neck coverage and early occlusion (at 6 months) strongly predicted durable exclusion (p=0.001).

Table 9: Relationship Between FD Characteristics and Intraprocedural Complications

FD Characteristics	Total Number = 56	Intraprocedural Complications		Test of Significance
		No n=41	Yes n=15	
FD type				
FRED Jr	14	9(64.3)	5(35.7)	χ^{2MC}=11.91
P48 MW	1	1(100)	0	p=0.281
P48 MW HPC	1	0	1(100)	
P64 MW	1	1(100)	0	
P64 MW HPC	3	3(100)	0	
Pipeline Flex	3	3(100)	0	
Pipeline Vantage	2	2(100)	0	
Silk Vista	5	4(80)	1(20)	
Silk Vista Baby	19	11(57.9)	8(42.1)	
Surpass Evolve	7	7(100)	0	
Coated FD	6	5(83.3)	1(16.7)	χ^2=0.351 p=1.0
Nitinol	44	29(65.9)	15(34.1)	χ^2=5.58
Cobalt nickel	12	12(100)	0	p=0.018*
Non-DFT	24	19(79.2)	5(20.8)	χ^2=0.759
DFT	32	22(68.8)	10(31.3)	p=0.384
FD diameter (mm)	56	2.52±0.29	2.38±0.23	t=1.59 p=0.118
FD length (mm)	56	13.58±2.66	14.40±2.09	t=1.08 p=0.285

t: Student's t-test, FET: Fisher's exact test, χ2=Chi-square test, *statistically significant.
This table explores associations between specific FD materials and procedural risks. Notably, nitinol-based devices were significantly associated with higher complication rates (p=0.018), likely due to limited conformability in tortuous vessels.

Table 10: Predictors of Intraprocedural Complications Among Studied Cases

Predictor	β	p-Value	Odds Ratio (95% CI)
Anti-GpIIb/IIIa Use			
Yes	3.68	<0.001*	39.58 (6.28–250)
Angioplasty	2.35	0.024*	10.52 (0.624–177.77)
Material			
Nitinol	-20.54	0.999	Undefined†

β: regression coefficient, statistically significant.
†Undefined OR due to perfect separation (all complications in nitinol group).
Through multivariate logistic regression, this table identifies tirofiban use and angioplasty as predictors of complications. The large odds ratio for anti-GPIIb/IIIa use reflects its role as a response marker to thrombotic complications, not a risk factor per se.

and transient aphasia (mRS 1) after branch sacrifice. Less frequent complications included an asymptomatic cervical ICA dissection (1.8%), incomplete FD expansion (1.8%) corrected by balloon angioplasty, and femoral artery thrombosis (1.8%) resolved surgically.

Symptomatic complications arose in 23.3% (13/56) of procedures, with major neurological events (17.9%, 10/56) predominating. These included transient ischemic symptoms (6 cases), such as dysphasia or hemiparesis, which resolved within days—some with correlative MRI findings, others attributed to contrast encephalopathy. One patient developed ACA-territory infarction 30 days post-procedure, resulting in mild residual weakness (mRS 1), while another with a ruptured AComA aneurysm exhibited multifocal ischemia and hemorrhage on MRI but returned to baseline status (mRS 2). The two aforementioned vessel ruptures contributed to this cohort, causing

Table 11: Relationship Between Aneurysm Characteristics and Symptomatic Major Complications

Aneurysm Characteristics	Total Number = 56	Symptomatic Major Complications		Test of Significance
		No n=46	Yes n=10	
Overall braid change				
No	49	41(83.7)	8(16.3)	p=0.429
Fish-mouth	4	2(50)	2(50)	p=0.142
Forehortening	1	1(100)	0	p=1.0
Bump	4	3(75)	1(12.5)	p=0.556
Collapse	2	2(100)	0	p=1.0
Location of FD				
A1-AcoA	28	24(85.7)	4(14.3)	χ^2=3.91
A2 - pericallosal	12	10(83.3)	2(16.7)	p=0.790
BA-PC	1	1(100)	0	
M3	1	1(100)	0	
MCA bifurcation	11	7(63.6)	4(36.4)	
P2	1	1(100)	0	
PICA	1	1(100)	0	
V4	1	1(100)	0	
Anterior circulation	52	42(80.8)	10(19.2)	χ^{2FET}=0.936
Posterior circulation	4	4(100)	0	p=0.333
Aneurysm situation	n=56			
Bifurcation	43	36(83.7)	7(16.3)	χ^2=0.314
Sidewall	13	10(76.9)	3 (23.1)	p=0.575
Irregular aneurysm on 3D				
No				
Yes, bilobed/with bleb	17	14(82.4)	3(17.6)	p=0.978
Yes, branch comes off	29	25(86.2)	4(13.8)	p=0.410
Yes, both	6	5(83.3)	1(16.7)	p=0.935
	4	2(50)	2(50)	p=0.14
Recanalized aneurysm				
No	29	27(93.1)	2(6.9)	p=0.026*
Yes, coiled	24	16(66.7)	8(33.3)	p=0.009*
Yes, WEB	2	2(100)	0	p=1.0
Yes, clip	1	1(100)	0	p=1.0
Others	3	3(100)	0	p=1.0
Size of aneurysm (max diam)				
Small≤5mm				χ^2=1.46
Big>5mm	42	36(85.7)	6(14.3)	p=0.227
	14	10(71.4)	4(28.6)	
Wide-necked	46	37(80.4)	9(19.6)	χ^2=0.512 p=0.474
Apex ratio	56	1.21±0.59	1.27±0.47	t=0.304 p=0.762
Max diameter (mm)	56	4.19±1.68	5.27±3.17	t=1.54 p=0.128
Vessel Diam Fin (Mean)	56	1.82±0.24	1.78±0.23	t=0.639 p=0.526

FET: Fisher's exact test, χ2=Chi-square test, *statistically significant.
This table links symptomatic events with aneurysm morphology and treatment history. Recanalized aneurysms, especially those previously coiled, showed a significant association with major complications (p=0.009 and p=0.026, respectively).

Table 12: Relation Between Procedure Characteristics and Symptomatic Major Complications

Procedure Characteristics	Total Number = 56	Symptomatic Major Complications		Test of Significance
		No n=46	Yes n=10	
Number of FDs				
1	53	44(83)	9(17)	FET= 0.518
2	3	2(66.7)	1(33.3)	p=0.452
Intraoperative braid change				
No				
Fish-mouth	53	44(83)	9(17)	χ^2=5.06
Bump	1	0	1(100)	p=0.167
collapse	1	1(100)	0	
	1	1(100)	0	
Access				
Femoral	50	40(80)	10(20)	χ^2=1.46
Radial	6	6(100)	0	p=0.227

FET: Fisher's exact test, χ^2=Chi-square test, *statistically significant.
Procedural variables were assessed for their predictive value in symptomatic complications. Although no factor reached statistical significance, trends suggest that dual FD placement and certain braid deformations may elevate risk.

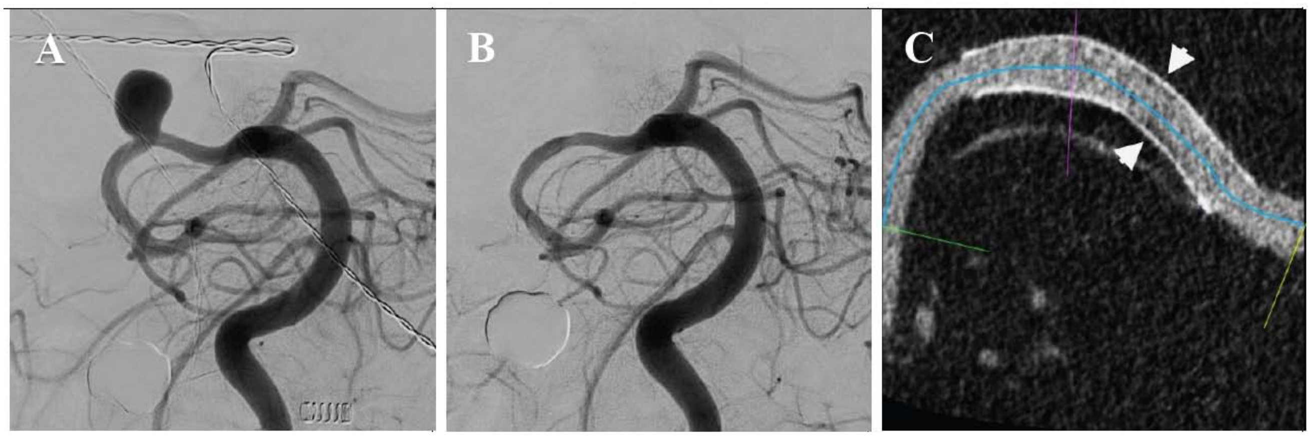

Figure 1: 85-year-old patient with a large right posterior cerebral artery (PCA) P2 segment aneurysm treated with a Silk Vista Baby FD (2.75 mm × 10 mm), demonstrating complete occlusion at 6-month follow-up. **A**: DSA in the working projection (WP), showing the unruptured P2 aneurysm. **B**: Six-month follow-up DSA in the same WP confirming complete aneurysm occlusion. **C**: Six-month follow-up Vaso-CT with maximum intensity projection (MIP) reconstruction, revealing mild neointimal hyperplasia (arrows) within the FD without significant stenosis.

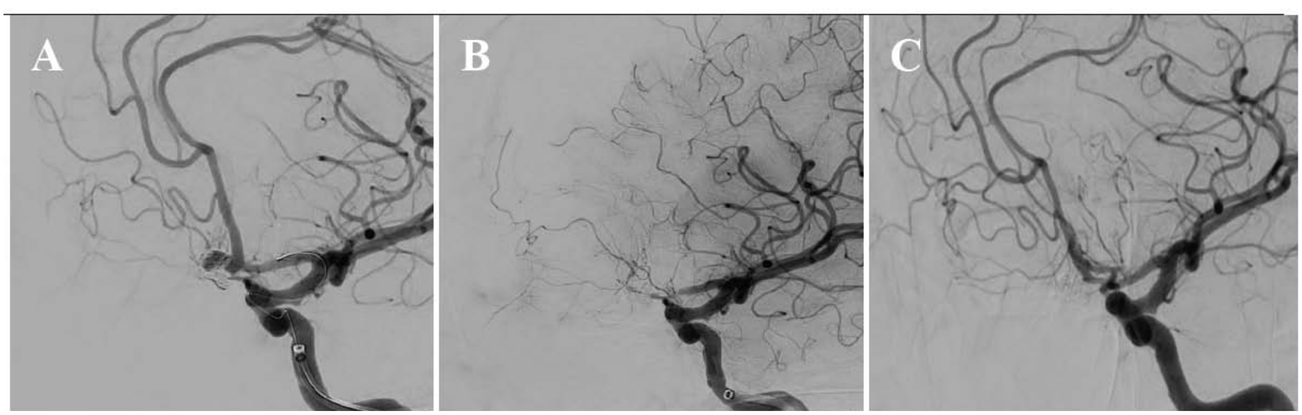

Figure 2: DSA of a left A1-ACom aneurysm: (**A**) residual aneurysm after prior coiling, before FRED Jr (2.5 × 13 mm) placement; (**B**) intra-procedural in-stent thrombosis, resolved with tirofiban bolus and intra-arterial alteplase (13 mg); (**C**) complete occlusion at six-month follow-up.

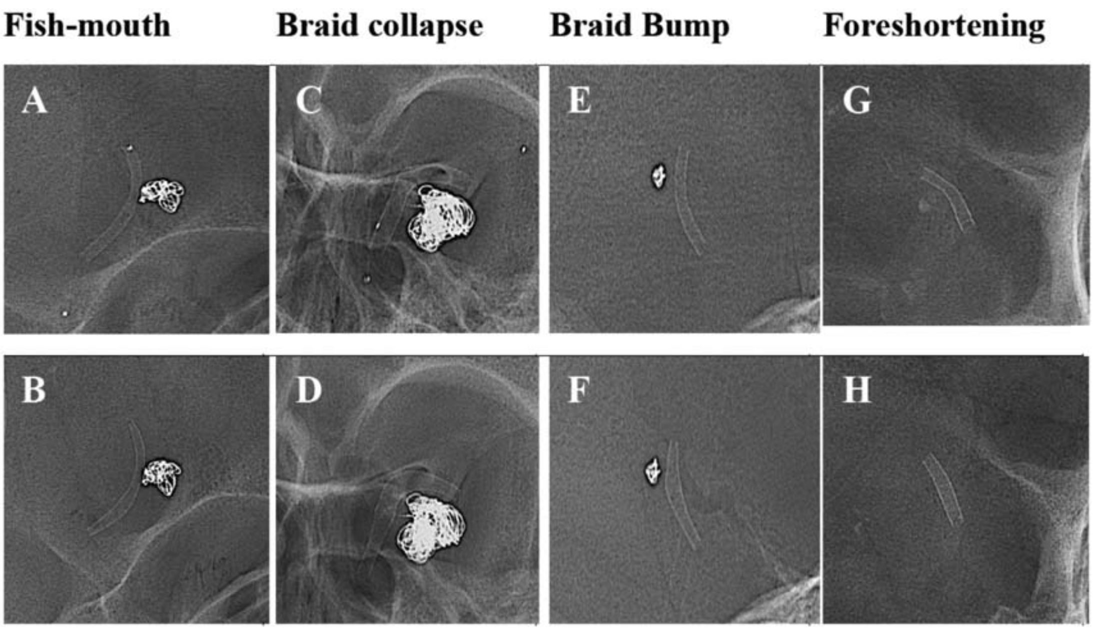

Figure 3: Examples of braid deformation types: unsubtracted radiographs at the end of the treatment (upper row) and at follow-up (lower low) showing: fish-mouthing (**A,B**), braid collapse (**C,D**), braid bump (**E,F**) and foreshortening (**G,H**).

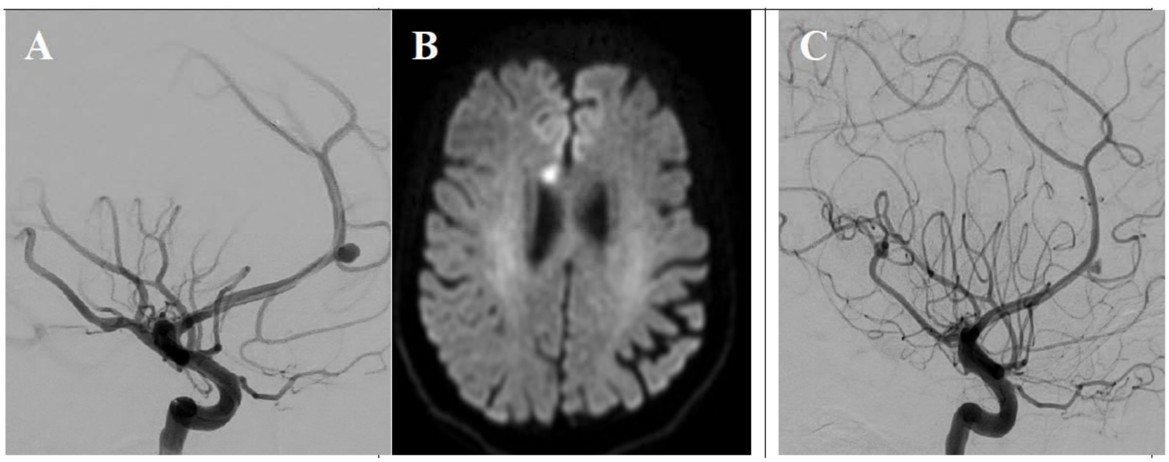

Figure 4: Imaging and long-term follow-up of a right pericallosal aneurysm with associated frontal infarct. (**A**) DSA of the right ICA in the WP showing a right pericallosal aneurysm. (**B**) Diffusion-weighted MRI revealing a small right frontal paramedian infarct corresponding to left lower limb monoparesis. (**C**) Eighteen-month follow-up DSA in the same projection demonstrating near-complete occlusion with a minimal residual remnant of the aneurysm.

persistent monoparesis and aphasia. Minor complications (5.4%, 3/56) were exclusively access-related, encompassing groin hematoma, femoral pseudoaneurysm, and radial arteriovenous fistula.

Neointimal Hyperplasia and Braid Changes

Neointimal hyperplasia was initially observed in 33.9% of cases and decreased to 21.4% at final follow-up. Significant stenosis (>25%) reduced from 26.8% to 12.5%, suggesting transient remodeling.

Overall braid changes occurred in 12.5% of procedures (7/56), including fish-mouth (7.2%, 4/56), bump (7.2%, 4/56), foreshortening (1.8%, 1/56), and collapse (3.6%, 2/56). Some stents showed more than one type of deformation (Figure **3**).

Anatomical Outcomes

Among the aneurysms treated, anterior communicating artery (AComA) aneurysms (24/55) exhibited complex flow dynamics, prompting the need of retreatment by flow diversion from the other side in three cases. Bilateral flow diverter deployment was attempted but failed to achieve occlusion in two of them. Distal anterior cerebral artery (ACA) aneurysms (13/55) demonstrated a high occlusion rate of 92.3%

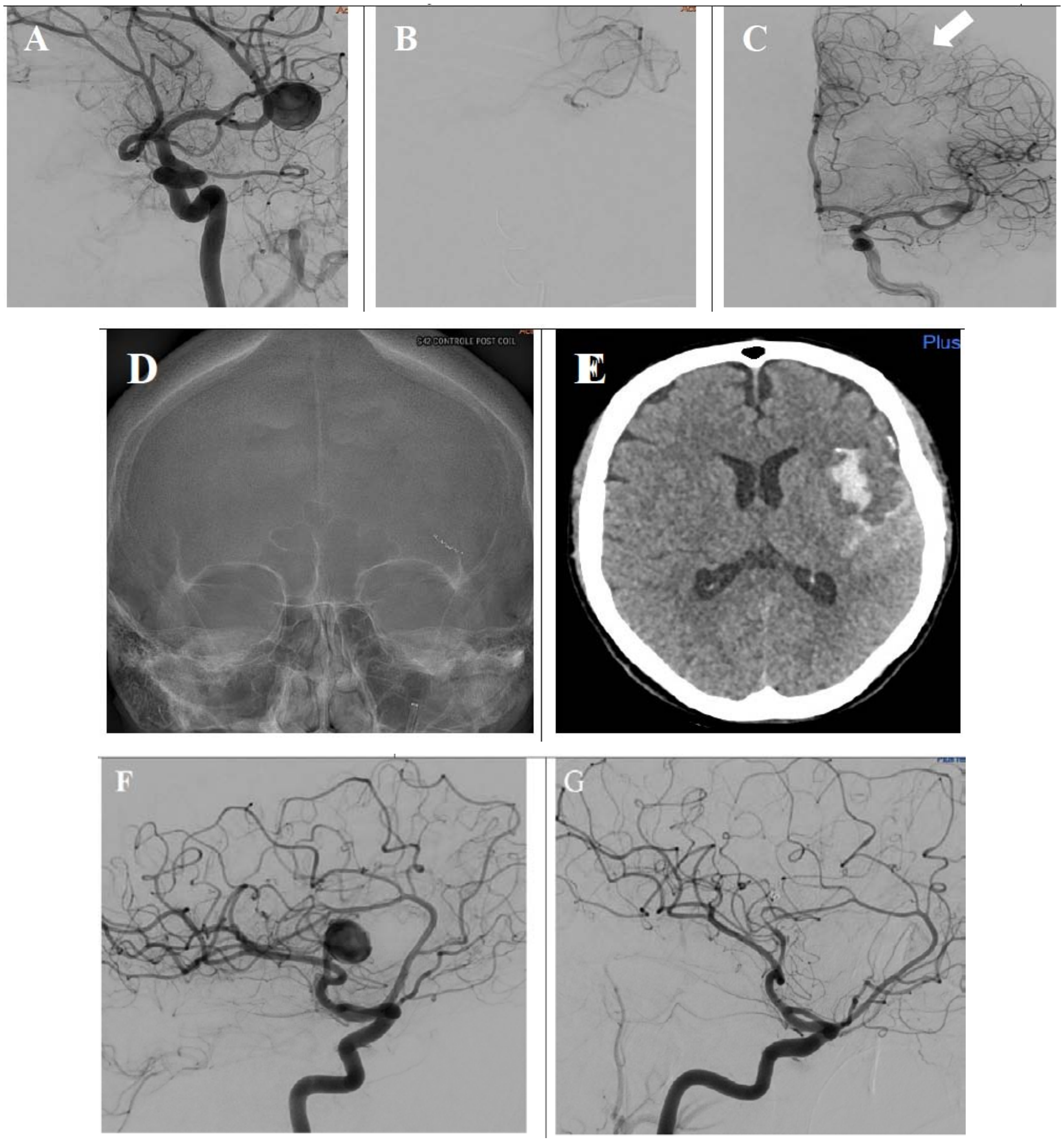

Figure 5: Management and follow-up of an MCA aneurysm with associated opercular branch dissection. (**A**) DSA of the ICA in a WP, demonstrating a large aneurysm arising from the superior branch of MCA (M2 segment). (**B**) Selective microcatheter injection revealing dissection of the opercular branch with mild contrast extravasation. (**C**) Post-coiling DSA of the left ICA confirming occlusion of the culprit branch and parenchymal defect (arrow). (**D**) Unsubtracted AP radiograph of the skull demonstrating coil placement within the culprit branch. (**E**) 1-day FU head CT showing the intracerebral hemorrhage. (**F**) Initial DSA in the second WP prior to treatment, illustrating baseline aneurysm morphology. (**G**) Six-month follow-up DSA showing complete occlusion of the aneurysm and coiled opercular branch.

with minimal morbidity. In contrast, middle cerebral artery (MCA) bifurcation aneurysms (12/55) showed a lower occlusion rate of 58.3% and were associated with a higher complication rate of 36.4%.

Factors Associated with Complete Occlusion

No significant associations were found between demographic, aneurysm, or procedural factors and complete occlusion at the last follow-up (all $p > 0.05$), FD location ($p=0.294$), recanalization status ($p=0.643$) or FD type ($p=0.568$). However, aneurysms with larger maximum diameters trended toward lower occlusion rates ($p=0.054$), suggesting size may influence outcomes in larger studies.

Factors Associated with Complications

No significant association was found between intraprocedural complications and aneurysm characteristics as location, morphology, dimensions of the aneurysms. Similarly, no significant difference was depicted between sidewall and bifurcation aneurysms, nor between unruptured and recanalized aneurysms.

However, symptomatic major complications were significantly associated with recanalized aneurysms (p=0.009), particularly those previously coiled (p=0.026). No other aneurysm, FD, or procedural factors were significantly associated with complications, including aneurysm circulation, bifurcation vs sidewall position , neck status or FD type.

DISCUSSION

Flow diversion has emerged as a pivotal strategy for managing complex intracranial aneurysms, particularly over the past 15 years. Initially developed for large and giant internal carotid artery (ICA) aneurysms with wide necks, its indications have expanded to include diverse aneurysm types, such as dissecting, blister, and recurrent aneurysms previously treated with coiling or intrasaccular devices [6,7]. These cases are often technically challenging due to scar tissue and altered vascular anatomy, making flow diversion an attractive off-label option for complex aneurysms in critical locations.

This study evaluated the safety and efficacy of flow diversion in 55 intracranial aneurysms arising from small parent vessels (<2 mm) in 50 patients, with a mean follow-up of 17.86 months. Complete occlusion was achieved in 70.9% of cases, with intraprocedural complications in 28.6% of 56 procedures (mostly asymptomatic) and symptomatic major complications in 17.9%. Flow diverter (FD)-related morbidity occurred in 8.0%, reflecting the technical challenges of navigating and deploying devices in small, distal vessels.

Regarding Efficacy in Context, compared to conventional endovascular techniques like stent-assisted coiling, flow diversion offers distinct advantages for small-vessel aneurysms. Stent-assisted coiling achieves occlusion rates of 79.5–88.6% but is associated with thromboembolic complications (3.8–13.6%) and issues like coil compaction, particularly in small vessels (<2 mm) [8,9]. In our cohort, 52.7% of aneurysms were recanalized, and 76.4% were located at bifurcations—scenarios where conventional techniques often falter due to complex inflow dynamics. Flow diversion, by promoting parent vessel remodeling, yielded lower retreatment rates than coil-based series. Our major complication rate (17.9%) aligns with the 10.2–13.6% reported for stent-assisted coiling [8,10], despite the anatomical complexity of our cases. Notably, thromboembolic complications were most frequent in MCA bifurcation aneurysms (36.4%), consistent with prior reports [10,11]. In contrast, studies like Li *et al.* [12] reported lower complication rates (2.22%) with devices like Neuroform Atlas (Stryker, Fremont, CA, USA), but these involved simpler, unruptured aneurysms, underscoring flow diversion's utility for recurrent or morphologically complex lesions.

Compared to large FD trials, our occlusion rate (70.9%) aligns with major trials like SCENT (62.8%), IntrePED (74.8%), SAFE (73.3%), ASPIRe (74.8%), and DIVERSION (68.4%), but is lower than PUFS (86.8%) and PREMIER (83.3%) [13-19]. These differences likely stem from our focus on distal, small-caliber vessels, which pose challenges in device navigation and wall apposition compared to the larger proximal ICA vessels in comparator trials. Our intraprocedural complication rate (28.6%) exceeds that of DIVERSION (24.3%) and SCENT (8.3%), driven by in-stent thrombosis (19.6%), likely due to device oversizing and low-flow hemodynamics. However, symptomatic complications (17.9%) and FD-related morbidity (8.0%) remain comparable to DIVERSION (5.9%), with no periprocedural mortality, unlike PUFS (3.7%) or SCENT (2.2%) [13,17,18]. The use of tirofiban for thrombotic events mitigated severe outcomes, highlighting its role in procedural rescue.

Regarding Complications and Procedural Challenges, The 28.6% procedural complication rate highlights the technical difficulties of FD in small vessels. In-stent thrombosis (19.6%) was the most common issue, driven by the high shear stress and low flow in small-caliber vessels, which promote platelet aggregation [20]. Tirofiban resolved 91.7% of thrombosis cases, reinforcing its role as an effective rescue therapy, though its use requires careful monitoring to avoid hemorrhagic risks [7]. Vessel perforation (3.6%) and dissection (1.8%) were less frequent but underscore the fragility of small vessels during navigation and deployment. The significant association between recanalized aneurysms and complications (p=0.009), particularly those previously coiled (p=0.026), suggests that prior interventions may alter vascular biology, increasing endothelial reactivity or scarring, which complicates FD deployment [21].

Material-specific differences further complicate FD use. Nitinol-based FDs had higher complication rates than cobalt-nickel-chromium FDs (p=0.018), potentially due to nitinol's lower flexibility in tortuous small vessels, leading to suboptimal apposition or braid deformation [5]. This finding warrants further investigation into device material optimization for small vessel applications. Delayed complications (3.6%), including one ischemic and one hemorrhagic event, emphasize the need for prolonged monitoring, as late thromboembolism or rupture can occur months after FD placement [22].

Regarding Anatomical Nuances, AComA aneurysms presented unique challenges due to bilateral A1 segment flow. In 3 of 24 cases, contralateral FD deployment was required to address persistent flow, yet two cases failed to achieve occlusion, likely due to complex flow dynamics. Our findings align with Cagnazzo *et al.* [23], who reported an 85% occlusion rate for unruptured AComA aneurysms. Pagiola *et al.* [24] have depicted that H3 configurations (asymmetric A1 diameters) had lower occlusion (60%) and higher thromboembolic complications (50%) than the other AComA configurations. Hemodynamic modeling could improve treatment planning in such cases.

Distal ACA aneurysms, primarily pericallosal, achieved a 92.3% occlusion rate, the highest in our cohort, likely due to simpler distal flow dynamics. Asymptomatic branch occlusion occurred in 25% of procedures, consistent with Cagnazzo *et al*. [25], who reported a 75% occlusion rate and 13% persistent complications. Combining flow diversion with coiling may enhance outcomes, as noted by Ravindran *et al.* [26].

MCA bifurcation aneurysms had a 58.3% occlusion rate, comparable to Salem *et al.* [27] (59% complete, 18% near-complete), but with a higher complication rate (36.4%). A notable case involving multiple MCA aneurysms achieved complete occlusion despite suboptimal neck coverage, suggesting sufficient flow modification can overcome imperfect device positioning.

The lower occlusion rate in bifurcation aneurysms may be attributable to complex flow dynamics and persistent inflow from multiple limbs. Prior computational fluid dynamics (CFD) studies have demonstrated reduced flow stagnation at bifurcations compared to sidewall aneurysms, limiting neointimal coverage. Incorporating CFD simulations into preoperative planning could refine FD placement strategies in such anatomies.

Regarding Device-Specific Considerations, Braid deformation occurred in 12.5% of cases but did not significantly impact occlusion, consistent with Popica *et al.* [28]. This suggests that while low-profile FDs improve access, their design must balance flexibility and radial force to optimize flow diversion in small vessels.

Neointimal hyperplasia, observed in 33.9% of procedures at 6 months, decreased to 21.4% at the last follow-up, with significant stenosis (>25%) dropping from 26.8% to 12.5%. This transient remodeling aligns with Cooper *et al.* [29] and suggests that FD-induced vessel changes are generally self-limiting, though long-term stenosis risks remain a concern, particularly in patients with comorbidities like hypertension or smoking [30].

When compared to studies focusing exclusively on low-profile flow diverters in small-caliber arteries, our occlusion rate of 70.9% and major complication rate of 17.9% are in line with findings by Bhogal *et al.* (5) and Martínez-Galdámez *et al.* (4), who reported occlusion rates of 72–78% with Silk Vista Baby and complication rates ranging from 10–20%. These similarities affirm the device's effectiveness, although procedural challenges persist in anatomically complex settings like MCA bifurcations

Clinical Implications

The high occlusion rate supports FD as a primary treatment for small vessel aneurysms, particularly in distal ACA or recanalized cases, where traditional methods are less effective. However, the 17.9% symptomatic complication rate and 8.0% permanent morbidity underscore the need for rigorous patient selection. Factors such as aneurysm morphology, prior treatment, and vessel tortuosity should guide decision-making. The effectiveness of tirofiban and the low rate of delayed complications suggest that standardized antithrombotic protocols and extended follow-up can mitigate risks. Clinicians should weigh FD's benefits against its challenges, potentially reserving it for cases where coiling or clipping is infeasible.

Preoperative vessel tortuosity and the presence of coil mass were not statistically significant predictors of complications or occlusion in this cohort. However, these anatomical features often complicated device delivery and wall apposition, warranting careful angiographic review during case selection. Future studies should systematically assess their predictive value for procedural complexity.

These findings suggest that flow diversion may be optimally suited for aneurysms located in distal ACA or pericallosal segments with favorable vessel trajectories, and for previously treated aneurysms resistant to conventional coiling. Patients with significant vessel tortuosity, low baseline mRS, and contraindications to long-term dual antiplatelet therapy may require alternative strategies or enhanced monitoring

LIMITATIONS

The retrospective design introduces selection bias, and the small sample size (50 patients) limits generalizability. Heterogeneous FD use and variable follow-up (6-50 months) confound device-specific comparisons. The lack of long-term data beyond 42 months may underestimate delayed complications or occlusion durability. Unadjusted confounders, such as smoking or aneurysm size, may influence outcomes. Finally, the single-center setting may not reflect diverse procedural practices, necessitating multicenter validation.

The decreasing sample sizes at later follow-up intervals (36 at 18 months and 17 at 42 months) may introduce selection bias, as patients with complications or suboptimal outcomes may be underrepresented in long-term data. This attrition could overestimate late occlusion rates and limit generalizability.

Future Directions

Larger, multicenter studies are essential to confirm complication rates, particularly in recanalized and bifurcation aneurysms, and to evaluate material-specific effects (e.g., nitinol vs. cobalt-nickel-chromium). Long-term follow-up (>5 years) will clarify occlusion durability and late complications like in-stent stenosis or delayed rupture. Computational fluid dynamics and high-resolution imaging could optimize FD deployment by predicting flow alterations in complex anatomies like AComA or MCA bifurcations. Platelet function testing may reduce thrombosis risks by tailoring antithrombotic regimens. Finally, next-generation FDs with improved porosity control and anti-thrombogenic coatings could enhance safety and efficacy, potentially expanding FD indications to even smaller or more distal vessels.

CONCLUSION

FD is a viable treatment for small vessel intracranial aneurysms, achieving high occlusion rates but with notable procedural challenges. Complications, particularly in recanalized aneurysms, underscore the need for careful patient selection and advanced techniques. This study provides critical insights into FD's role in small vessels, advocating for further research to enhance safety and efficacy.

CONFLICT OF INTEREST

LS is a consultant for Microvention, Balt, Phenox, Stryker, and Medtronic; DSMB or Advisory Board for INSPIRE Study and COATING study; grant or contract from Philips with institution.

DATA AVAILABILITY

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request, to support replication and meta-analytical use.

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