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Original research

Periprocedural safety of saccular aneurysm embolization with the Penumbra SMART Coil System: a SMART registry subset analysis

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ABSTRACT

Background Using data from the SMART registry, we report on periprocedural safety of the Penumbra SMART Coil System for endovascular coil embolization of saccular intracranial aneurysms.

Methods The SMART registry was a prospective, multicenter registry of site standard of care endovascular coiling procedures performed using at least 75% Penumbra SMART Coil, PC400, and/or POD coils. This subset analysis reports on the periprocedural safety outcomes of the saccular intracranial aneurysm cohort. Predictors of rupture/re-rupture or perforation (RRP), thromboembolic complications, and device- or procedure-related adverse events (AEs) were determined in univariate and multivariate analysis.

Results Between June 2016 and August 2018, 851 saccular aneurysm patients (31.0%, 264/851 ruptured) were enrolled across 66 North American centers. Clinically significant (ie, a serious adverse event) RRP occurred in 2.0% (17/851) of cases – 1.9% (5/264) for the ruptured cohort and 2.0% (12/587) for the un-ruptured cohort. Clinically significant thromboembolic events occurred in 3.1% (26/851) of cases – 5.3% (14/264) for the ruptured cohort and 2.0% (12/587) for the un-ruptured cohort. Multivariate predictors of periprocedural RRP were increased packing density and adjunctive treatment with a balloon. For periprocedural thromboembolic events, multivariate predictors were bifurcation location and ruptured status. For device- or procedure-related AEs, multivariate predictors were bifurcation location and adjunctive treatment with stent or balloon.

Conclusion The low rates of thromboembolic complications and RRP events demonstrate the adequate safety profile of the SMART Coil System to treat cerebral aneurysms in routine clinical practice.

Trial registration number NCT02729740.

INTRODUCTION

Since its introduction in the 1990s, endovascular coiling technology has undergone several generations of improvements and has become a widely accepted, safe, and effective method for treating intracranial vascular lesions.[1–3] These lesions represent a significant health burden, with aneurysms alone affecting an estimated 1%–5% of the adult population.[4]

The Penumbra SMART Coil System (SMART; Penumbra Inc., Alameda, USA) is a newer-generation coil system indicated for endovascular embolization in the peripheral and neuro vasculature. The system is comprised of the platinum coil, a composite detachment pusher, and a detachment handle. The coils are bare metal platinum and get softer toward the proximal end to reduce microcatheter deflection during delivery. Coil detachment is performed mechanically using a coil detachment handle.

The SMART registry was initiated in 2016 to prospectively evaluate the safety and efficacy of the SMART system. Before this, the evaluation of the SMART system was limited to small retrospective case series.[5–8] A multicenter retrospective review of 59 aneurysm patients (44% ruptured) treated with at least one SMART coil between July 2015 to January 2016 by Spiotta et al[7] achieved Raymond I or II occlusion in 71.2% of patients with no device malfunctions or rebleeds observed. Sokolowski et al[5] investigated the follow-up angiographic outcomes of aneurysm embolization with SMART coils in a retrospective cohort. Of the 45 consecutive patients treated with SMART coils during the study period, 33 patients with 34 aneurysms had angiographic follow-up. The initial modified Raymond–Roy Classification (MRRC) was I, II, IIIa, and IIIb in 24%, 26%, 35%, and 15%, respectively. The overall complication rate was 12%. At last follow-up (mean duration 7.7 ± 3.2 months), the retreatment rate was 14.7%, the MRRC was I, II, IIIa, and IIIb in 62%, 26%, 3%, and 9%, respectively. The authors found that the majority of residual aneurysms after the initial embolization procedure progressed to complete or near-complete occlusion at interim follow-up. Daniel et al[8] performed a single-center retrospective study of 49 aneurysm patients treated primarily with SMART coil between July 2016 and August 2018. They achieved MRRC I or II in 91.8% of patients with five complications reported (one microcatheter prolapse and four thromboembolic events with no clinical sequelae). No rupture and no technical malfunction were noted.

To our knowledge, the SMART registry is one of the largest coiling studies to date and is the first study to gather safety and efficacy data for the SMART system coils in a prospective setting. Here we focus on the periprocedural safety and

predictors of complications in the SMART registry's saccular aneurysm cohort. This serves as a useful comparison to historical trials[9 10] (to demonstrate any changes to coiling performance over time), and other contemporary trials[11 12] (to help physicians make informed decisions about coil selection).

METHODS

Overview

The SMART registry was a prospective, multi-center registry that included patients treated according to the cleared indications for SMART coils, Penumbra Coil 400 (PC 400), and POD. These indications include embolization of intracranial aneurysms, and other neurovascular abnormalities such as arteriovenous malformation and arteriovenous fistulae. Exclusion criteria were: life expectancy less than 1 year (ie, patients with co-morbidities that may result in a life expectancy less than 1 year were excluded: this exclusion did not apply to the aneurysm disease state); and SMART, PC400, or POD account for less than 75% of total number of coils implanted. Patients were considered enrolled at the time of consent and the procedure began with the intent of implanting coils. Patients who failed to meet entry criteria pertaining to coil selection were considered a screen failure. If the case was emergent, then it was permissible to collect informed consent up to 1 calendar day after the procedure. For all other cases, informed consent was required prior to the procedure. Endovascular coiling procedures were performed as per routine site standard of care. There were no restrictions regarding endovascular technique (eg, stent-assistance, balloon-assistance, etc.) or use of adjunctive technologies. Institutional Review Board approval for each participating institution and informed consent for all included patients were obtained.

This is a subset analysis of the SMART registry and includes only saccular aneurysm cases. Ninety patients with non-aneurysm cerebrovascular pathologies (arteriovenous malformation, arteriovenous fistula, etc.) and 54 non-saccular aneurysms (eg, pseudoaneurysm, fusiform, venous) were excluded. We report on periprocedural safety and predictors of periprocedural rupture/re-rupture/perforation (RRP), thromboembolic complications, and device- or procedure-related adverse events (AEs).

Data collection

Demographics, medical history, procedural, angiographic, and AE data were collected. AEs that were related to procedure or device and all serious adverse events (SAEs) were collected from the time of enrollment though registry exit. Safety data were reviewed by centralized monitors to ensure accurate event reporting.

Study definitions

Periprocedural AEs were defined as events occurring during or within 24 hours of the index procedure. Periprocedural thromboembolic events were defined as events occurring during or within 24 hours of the procedure regardless of presence or absence of symptoms (eg, non-occlusive clot event, temporary intra-operative thromboembolism, stroke, etc.). Periprocedural RRP was defined as events occurring during or within 24 hours of the procedure including symptomatic events and asymptomatic imaging findings for subarachnoid hemorrhage. The investigators determined the relationships of an AE to the device and procedure (definite, probable, possible, unrelated). For this analysis, events reported as definite, probable, or possible were considered as related. Device-related refers specifically to the relationship to Penumbra coils. Procedure-related refers to the relationship to the overall procedure, coils, and/or other accessory devices (eg, microcatheters, guidewires, stents, etc.).

Wide-necked aneurysms were defined as those with dome-to-neck ratio <2 or neck width ≥ 4 mm. Distal locations were defined as the anterior communicating artery and locations distal to the middle cerebral artery (MCA) bifurcation. Bifurcation locations were defined as the internal carotid artery terminus, MCA bifurcation, anterior communicating artery, and basilar artery bifurcation. Aneurysm occlusion status was measured angiographically using the Raymond–Roy Occlusion Classification (RROC). Class I is complete occlusion, Class II is a residual neck, and Class III is a residual aneurysm.[13] The severity of ruptured aneurysms at admission was determined by the Hunt and Hess scale.[14]

Statistical analysis

Descriptive statistics were calculated for demographic, procedural, angiographic, and adverse event data, including the number of observations, mean, SD, median, IQR, minimum and maximum for continuous variables, and counts and percentages for discrete variables.

The associations of aneurysm and procedure characteristics to periprocedural RRP, thromboembolic events, and procedure- or device-related AEs were explored using univariate and multivariate modeling. A P-value of <0.05 was chosen for significance, and correction for multiple testing was not performed. Cases involving flow diverters were included in the stent-assisted coiling group for thromboembolic event and procedure- or device-related event predictive analyses. Multivariate analysis was performed using a logistic regression model with a stepwise selection method using $P<0.20$ for entry and $P\geq 0.05$ for removal criteria. The analysis was done with SAS 9.4, and the maximum likelihood estimate of ORs, P-values, and 95% CIs of the ORs are reported.

RESULTS

Between June 2016 and August 2018, the SMART registry enrolled 851 saccular aneurysm patients across 66 centers in North America (65 in the United States and one in Canada).

Baseline characteristics

Baseline information and aneurysm characteristics are summarized in tables 1 and 2, respectively. Of the included 851 saccular aneurysm cases, 7.5% (64/851) were irregular saccular aneurysms and 0.4% (3/851) were recurrent saccular aneurysms. Mean age ±SD was 59.9±12.5 years (n=851), 75.9% (646/851) were female, 78.6% (221/281) were Caucasian, and 90.5% (496/548) had pre-morbid mRS 0–2. The majority of aneurysms were unruptured (69.0% [587/851]) and wide neck (63.1% [526/833]). Size distribution was: 17.3% very small (<4 mm), 43.9% small (≥4 to<7 mm), 25.4% medium (≥7 to≤10 mm), 13.2% large (>10 to≤25 mm), and 0.2% giant (>25 mm). Locations were: 82.4% (701/851) anterior circulation and 17.6% (150/851) posterior circulation. The most common location was the intradural internal carotid artery (ICA, 38.0%), followed by the anterior cerebral artery (ACA, 30.7%). Bifurcation aneurysms accounted for 49.8% (424/851) of cases, and distal aneurysms for 27.8% (237/851). Hunt and Hess grades at admission for ruptured aneurysms were 79.6% (207/260) grades I–III and 20.4% (53/260) grades IV–V.

Table 1 Baseline characteristics

Characteristic	Results
Demographics, mean±SD (range) or % (n/N)	
Age	59.9±12.5 (20–93) (n=851)
Female	75.9% (646/851)
Race	
White/Caucasian	78.6% (221/281)
Black/African-American	12.8% (36/281)
Asian	2.1% (6/281)
Native American or Alaska Native	1.1% (3/281)
Other	5.3% (15/281)
Medical history, % (n/N)	
Smoking	63.3% (539/851)
Diabetes	14.5% (123/851)
Hypertension	62.2% (529/851)
Pre-morbid mRS, % (n/N)	
0 to 2	90.5% (496/548)
0	55.5% (304/548)
1	28.6% (157/548)
2	6.4% (35/548)
3	2.6% (14/548)
4	4.0% (22/548)
5	2.9% (16/548)
Hunt and Hess score at admission*, % (n/N)	
I	21.9% (57/260)
II	33.5% (87/260)
III	24.2% (63/260)
IV	14.2% (37/260)
V	6.2% (16/260)

*Four ruptured aneurysm patients with missing Hunt and Hess Classification data

Table 2 Aneurysm characteristics

Aneurysm characteristic	Results
Location, % (n/N)	
ICA, Extradural	1.4% (12/851)
Cervical	25.0% (3/12)
Petrous	8.3% (1/12)
Cavernous	66.7% (8/12)
ICA, Intradural	38.0% (323/851)
Superior Hypophyseal	15.8% (51/323)
Ophthalmic	22.9% (74/323)
Posterior Communicating	49.5% (160/323)
Anterior Choroidal	3.1% (10/323)
ICA Terminus	8.7% (28/323)
ACA	30.7% (261/851)
Proximal to anterior communicating	3.8% (10/261)
Anterior communicating	87.4% (228/261)
Pericallosal	8.8% (23/261)
MCA	12.3% (105/851)
Proximal to MCA bifurcation	14.3% (15/105)
MCA bifurcation	77.1% (81/105)
Distal to MCA bifurcation	8.6% (9/105)
Posterior circulation	17.6% (150/851)
Vertebral	8.0% (12/150)
Basilar trunk	6.0% (9/150)
PICA	10.7% (16/150)
AICA	0.7% (1/150)
SCA	10.0% (15/150)
Basilar bifurcation	58.0% (87/150)
Distal location*, % (n/N)	27.8% (237/851)
Bifurcation location†, % (n/N)	49.8% (424/851)
Aneurysm size, % (n/N)	
Giant (>25 mm)	0.2% (2/851)
Large (>10 to ≤25 mm)	13.2% (112/851)
Medium (≥7 to ≤10 mm)	25.4% (216/851)
Small (≥4 to <7 mm)	43.9% (374/851)
Very Small (<4 mm)	17.3% (147/851)
Aneurysm neck size, % (n/N)	
Non-wide-neck	36.9% (307/833)
Wide-neck‡	63.1% (526/833)
Aneurysm rupture status, % (n/N)	
Ruptured	31.0% (264/851)
Unruptured	69.0% (587/851)

*Distal locations are defined as aneurysms located in the anterior communicating artery or located distal to the middle cerebral artery (MCA) bifurcation.
†Bifurcation locations are defined as ICA terminus, MCA bifurcation, anterior communicating artery, and basilar artery bifurcation.
‡Wide neck defined as neck size ≥4mm or dome-to-neck ratio<2.
ACA, Anterior cerebral artery; AICA, Anterior inferior cerebellar artery; ICA, Internal carotid artery; MCA, Middle cerebral artery; PICA, Posterior inferior cerebellar artery; SCA, Superior cerebellar artery.

Procedural characteristics

Procedure information is summarized in table 3. Coiling alone was used in 43.2% (368/851) of cases, and adjunctive therapy was used in 56.8% (483/851) of cases (34.8% [296/851] stent-assisted, 17.4% [148/851] balloon-assisted, 2.8% [24/851] both balloon- and stent-assisted, and 1.8% [15/851] flow diverter assisted. Mean fluoroscopic time was 43.4 mins±28.9 (n=848). RROC class I–II at the end of the procedure was achieved in 80.3% (681/848) of cases.

Mortality through discharge

Twenty-two deaths (2.6%, 22/851) occurred before discharge. Twenty deaths were in patients with ruptured aneurysms, of which 95% were reported as unrelated to the device or procedure. Two deaths were in patients with unruptured aneurysms. One was a 64-year-old woman with an unruptured anterior communicating artery aneurysm (preloaded with clopidogrel and aspirin, successfully treated with stent-assisted coiling). Post-procedure, a small subarachnoid hemorrhage located in the interpeduncular cistern was identified. This hemorrhage rapidly expanded over the course of several hours and the patient died. The second was a 66-year-old woman with an unruptured posterior communicating artery aneurysm who developed a right frontal hemorrhagic stroke during inpatient recovery and died

Table 3 Procedural characteristics

Procedural characteristic	Results
Total fluoroscopy time, mins mean±SD (range)	43.4±28.9 (3–266) (n=848)
Overall procedure time*, mins mean±SD (range)	83.2±45.7 (11–370) (n=787)
Day of procedure, % (n/N)	
Weekday	93.4% (795/851)
Weekend	6.6% (56/851)
Packing density†, mean±SD (range)	32.3±18.3 (0.4–218.7) (n=811)
Adjunctive techniques used, % (n/N)	
Coils only	43.2% (368/851)
Stent-assisted only	34.8% (296/851)
Balloon-assisted only	17.4% (148/851)
Balloon-assisted and stent-assisted	2.8% (24/851)
Flow diverter-assisted‡	1.8% (15/851)
RROC at the end of the procedure, % (n/N)	
Class I to II	80.3% (681/848)
Class I	40.2% (341/848)
Class II	40.1% (340/848)
Class III	19.7% (167/848)
Re-access attempts with guidewire due to catheter kckout§, % (n/N)¶	6.2% (280/4517)

*Defined as time from arterial puncture to last coil detached
†For patients with constructively treated saccular aneurysm
‡For one patient, both balloon and flow-diverter adjunctive techniques were used
§For Penumbra coils only. Thirteen patients are missing re-access information for Penumbra coils.
¶Reported by device (# of kickout occurrences over # of Penumbra coils used)
RROC, Raymond–Roy Occlusion Classification.

3 weeks after the procedure from complications associated with pre-existing end-stage renal disease.

Periprocedural (within 24 hours) rupture/re-rupture and perforation

In the ruptured aneurysm cohort, periprocedural RRP occurred in 3.4% (9/264) of cases (1.9% [5/264] serious, 1.5% [4/264] not serious). Site investigators reported that six were related to coils (ie, device-related). In the unruptured aneurysm cohort, periprocedural RRP occurred in 2.7% (16/587) of cases (2.0% [12/587] serious, 0.7% [4/587] not serious). Eleven were related to coils. Details are available in table 4 and online supplemental table 4.

In the multivariate model (including aneurysm size, location, neck width, rupture status, weekend/weekday procedure, packing density, and adjunctive device use), balloon-assisted treatment (OR 6.92, 95% CI 2.15 to 22.28), and packing density per 5% increase (OR 1.09, 95% CI 1.01 to 1.17) were independent predictors of RRP. The full results of the univariate and multivariate predictive analyses are available in online supplemental table 1.

Periprocedural (within 24 hours) thromboembolic events

In the ruptured aneurysm cohort, periprocedural thromboembolic events occurred in 8.3% (22/264) of cases (5.3% [14/264] serious, 3.0% [8/264] not serious). Eleven were related to coils. Adjunctive stents or flow diverters were used in 13.6% (3/22) and balloons were used in 27.3% (6/22) of these cases. In the unruptured aneurysm cohort, a periprocedural thromboembolic event occurred in 3.6% (21/587) of cases (2.0% [12/587] serious, 1.5% [9/587] not serious). Sixteen were related to coils. Adjunctive stents or flow diverters were used in 61.9% (13/21) and balloons were used in 9.5% (2/21) of these cases. Details are available in table 4 and online supplemental table 4.

In the multivariate model (including aneurysm size, location, rupture status, neck width, weekend/weekday procedure,

Table 4 Periprocedural complications

	Aneurysm		
	Ruptured	Un-ruptured	Overall
Access site complications, % (n/N)			
Total	0.4% (1/264)	4.1% (24/587)	2.9% (25/851)
Event status*			
Not serious	0.4% (1/264)	3.7% (22/587)	2.7% (23/851)
Serious	0.0% (0/264)	0.3% (2/587)	0.2% (2/851)
Relationship†			
Procedure-related	0.4% (1/264)	4.1% (24/587)	2.9% (25/851)
Device-related	0.0% (0/264)	0.0% (0/587)	0.0% (0/851)
Aneurysm re-rupture/rupture or perforation, % (n/N)			
Total	3.4% (9/264)	2.7% (16/587)	2.9% (25/851)
Event status*			
Not serious	1.5% (4/264)	0.7% (4/587)	0.9% (8/851)
Serious	1.9% (5/264)	2.0% (12/587)	2.0% (17/851)
Relationship†			
Procedure-related	2.7% (7/264)	2.6% (15/587)	2.6% (22/851)
Device-related	2.3% (6/264))	1.9% (11/587)	2.0% (17/851)
Dissection, % (n/N)			
Total	0.0% (0/264)	0.7% (4/587)	0.5% (4/851)
Event status*			
Not serious	0.0% (0/264)	0.2% (1/587)	0.1% (1/851)
Serious	0.0% (0/264)	0.5% (3/587)	0.4% (3/851)
Relationship†			
Procedure-related	0.0% (0/264)	0.7% (4/587)	0.5% (4/851)
Device-related	0.0% (0/264)	0.0% (0/587)	0.0% (0/851)
Thromboembolic events, % (n/N)			
Total	8.3% (22/264)	3.6% (21/587)	5.1% (43/851)
Event status*			
Not serious	3.0% (8/264)	1.5% (9/587)	2.0% (17/851)
Serious	5.3% (14/264)	2.0% (12/587)	3.1% (26/851)
Relationship†			
Procedure-related	7.2% (19/264)	3.2% (19/587)	4.5% (38/851)
Device-related	4.2% (11/264)	2.7% (16/587)	3.2% (27/851)

*An event is reported as serious if it led to death or led to a serious deterioration in the health of the patient that resulted in life-threatening illness or injury, resulted in permanent impairment of a body structure or body function, required inpatient hospitalization or prolongation of existing hospitalization, or resulted in medical or surgical intervention to arrest permanent impairment to body structure or body function.
†An event can be reported as both procedure- and device-related. Any relationship (possible, probable, or definite) besides unrelated was considered as related.

adjunctive device use, and patient age), bifurcation location (OR 2.08, 95% CI 1.07 to 4.05) and ruptured status (OR 2.32, 95% CI 1.23 to 4.38) were independent predictors of thromboembolic events. The full results of the univariate and multivariate predictive analyses are available in online supplemental table 2.

Periprocedural device- or procedure-related AEs

In the multivariate model (including aneurysm size, location, neck width, rupture status, weekend/weekday procedure, packing density, adjunctive device use, and patient age), bifurcation location (OR 1.82, 95% CI 1.24 to 2.65), balloon-assisted adjunctive technique (OR 1.86, 95% CI 1.10 to 3.15), and stent-assisted adjunctive technique (OR 1.79, 95% CI 1.18 to 2.73) were independent predictors of device- or procedure-related AEs. Full results of the univariate and multivariate predictive analyses are available in online supplemental table 3.

DISCUSSION

The SMART registry is one of the largest prospective coiling studies to date and includes ruptured aneurysm patients with severe Hunt and Hess scores. Aneurysm data from this registry provides a detailed understanding of bare metal platinum coils' complications and efficacy in routine clinical practice and may serve as a useful comparison for studies involving other aneurysm treatment modalities (eg, clipping, flow diversion, intrasaccular devices). In the ruptured aneurysm cohort, rates of periprocedural thromboembolic events and RRP were 8.3% (22/264) and 3.4% (9/264), respectively. In the unruptured aneurysm cohort, these rates were 3.6% (21/587) and 2.7% (16/587), respectively.

We used the CLARITY[9] and ATENA[10] studies as a historical comparison for the ruptured and unruptured cohorts of the SMART registry, respectively. CLARITY and ATENA are chosen due to their large sample sizes and inclusion of subjects based on on-site routine practice – which is a similar design to the SMART registry. However, study design differences make direct comparison imprecise. Most notably, the CLARITY and ATENA studies excluded aneurysms>15 mm in size and/or patients outside the ages of 18–80. In contrast, SMART did not restrict enrollment by age or size;: ages ranged from 20 to 93 years' old and large or giant aneurysms comprised 13.4% of the population.

The CLARITY trial (a multicenter prospective ruptured aneurysm GDC coils study) had a thromboembolic event rate of 13.3% (54/405) and an RRP rate of 3.7% (15/405).[9] The ATENA study (an international multicenter prospective unruptured aneurysm coiling study) reported a thromboembolic event rate of 7.1% (50/700) and an RRP rate of 2.6% (18/700).[10] Lower rates of thromboembolic events were observed in the SMART registry despite the registry's higher rate of stent assistance (37.6%) as compared with CLARITY (0.5%) and ATENA (7.8%). Optimization of antiplatelet regimens, updated embolization techniques, advances in guide catheter technology, improved coil conformability, and reduced coil protrusion may contribute to the SMART registry's lower thromboembolic event rate.

Two notable contemporary studies involving bare platinum coils are the TARGET registry, and a single-center series investigating Barricade coils.[11 12] The TARGET registry limited enrollment to patients with pre-morbid mRS ≤3 and Hunt and Hess≤3, while neither SMART nor the Barricade series had this restriction. Approximately 20.4% of the ruptured aneurysm cases in the SMART registry had Hunt and Hess scores of 4 or 5. All three studies were of prospective design and included ruptured and unruptured aneurysms. The rates of periprocedural thromboembolic events and RRP were similar across these trials. For periprocedural thromboembolic events, rates were 4.7%, 5.6%, and 5.1%, and for RRP, rates were 2.7%, 6.3%, and 2.9% in the TARGET, Barricade, and SMART studies, respectively.

Risk factors for periprocedural complications

We found that the risk of RRP increased with balloon assistance. This association has been previously studied and yielded mixed results – some authors have reported that balloon assistance is associated with increased risk while others determined not.[15–19] These differences may be partly due to technique variations between operators. An inflated balloon may reduce microcatheter tip deflection during coil deployment. By increasing construct rigidity, force transfer to the dome could occur during coil introduction and therefore increase the likelihood of RRP. Alternatively, balloon placement before coiling can be useful for rapidly controlling hemorrhage if a rupture does occur.

Thromboembolic event occurrence was observed to be higher with bifurcation and ruptured aneurysms. Using routine diffusion weighting MRI, Altay et al also found that thromboembolic events are significantly more likely with ruptured aneurysms (vs unruptured) regardless of the coiling technique used.[20] Procedure- or device- related AEs were more likely with bifurcation aneurysms, and in cases using balloon or stent assistance. This may be because increasing the number of devices increases procedural complexity. Similarly, procedural complexity is higher with bifurcation aneurysms than with simple sidewall aneurysms.[21] Day of the procedure (weekend vs weekday) was not predictive of any of the investigated complications, including procedure- or device-related AEs. This may be a reflection of general trends toward increased coiling case volume and therefore coiling proficiency.[22]

Limitations and strengths of the SMART registry

The SMART registry's primary limitation is a function of its design, the lack of a randomized controlled comparison. Additionally, there was no independent core laboratory to review imaging endpoints and emergent cases could be enrolled up to 1 day after the procedure, allowing for potential selection bias. Strengths of this study include the prospective nature, and large sample size. Data was monitored via on-site visits to ensure consistency and accuracy of reported information. The registry was designed to follow site routine standards of care in order for the results to reflect real-world clinical practice.

CONCLUSION

The low rates of thromboembolic complications and RRP events demonstrate the adequate safety profile of the SMART Coil System to treat cerebral aneurysms in routine clinical practice.

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REFERENCES

1 Hui FK, Fiorella D, Masaryk TJ, *et al*. A history of detachable coils: 1987–2012. *J Neurointerv Surg* 2014;6:134–8.
2 Thompson BG, Brown RD, Amin-Hanjani S, *et al*. Guidelines for the management of patients with unruptured intracranial aneurysms: a guideline for healthcare professionals from the American Heart Association/American Stroke Association. *Stroke* 2015;46:2368–400.
3 Molyneux AJ, Kerr RSC, Yu L-M, *et al*. International subarachnoid aneurysm trial (ISAT) of neurosurgical clipping versus endovascular coiling in 2143 patients with ruptured intracranial aneurysms: a randomised comparison of effects on survival, dependency, seizures, rebleeding, subgroups, and aneurysm occlusion. *Lancet* 2005;366:809–17.
4 Brisman JL, Song JK, Newell DW. Cerebral aneurysms. *N Engl J Med* 2006;355:928–39.
5 Sokolowski JD, Ilyas A, Buell TJ, *et al*. SMART coils for intracranial aneurysm embolization: follow-up outcomes. *J Clin Neurosci* 2019;59:93–7.
6 Ilyas A, Buell TJ, Chen C-J, *et al*. SMART coils for intracranial aneurysm embolization: initial outcomes. *Clin Neurol Neurosurg* 2018;164:87–91.
7 Spiotta AM, Fargen KM, Lena J, *et al*. Initial technical experience with the SMART coil for the embolization of intracranial aneurysms. *World Neurosurg* 2017;97:80–5.
8 Daniel B, Henrik S, Ioannis T, *et al*. SMART coils for intracranial aneurysm repair – a single center experience. *BMC Neurol* 2020;20:38–9.
9 Cognard C, Pierot L, Anxionnat R, *et al*. Results of embolization used as the first treatment choice in a consecutive nonselected population of ruptured aneurysms: clinical results of the clarity GDC study. *Neurosurgery* 2011;69:837–41.
10 Pierot L, Spelle L, Vitry F, *et al*. Immediate clinical outcome of patients harboring unruptured intracranial aneurysms treated by endovascular approach: results of the ATENA study. *Stroke* 2008;39:2497–504.
11 Zaidat OO, Castonguay AC, Rai AT, *et al*. TARGET intracranial aneurysm coiling prospective multicenter registry: final analysis of peri-procedural and long-term safety and efficacy results. *Front Neurol* 2019;10:737.
12 Guerreiro-Simoes R, Soize S, Gawlitza M, *et al*. Intracranial aneurysms treatment with Barricade coils: safety and 1-year efficacy in a prospective, single-center series. *J Neuroradiol* 2019;46:331–5.
13 Roy D, Milot G, Raymond J. Endovascular treatment of unruptured aneurysms. *Stroke* 2001;32:1998–2004.
14 Hunt WE, Hess RM. Surgical risk as related to time of intervention in the repair of intracranial aneurysms. *J Neurosurg* 1968;28:14–20.
15 Levy E, Koebbe CJ, Horowitz MB, *et al*. Rupture of intracranial aneurysms during endovascular coiling: management and outcomes. *Neurosurgery* 2001;49:807–11.
16 Lubicz B, Lefranc F, Bruneau M, *et al*. Balloon-assisted coiling of intracranial aneurysms is not associated with a higher complication rate. *Neuroradiology* 2008;50:769–76.
17 Santillan A, Gobin YP, Mazura JC, *et al*. Balloon-assisted coil embolization of intracranial aneurysms is not associated with increased periprocedural complications. *J Neurointerv Surg* 2013;5 Suppl 3:iii56–61.
18 Sluzewski M, van Rooij WJ, Beute GN, *et al*. Balloon-assisted coil embolization of intracranial aneurysms: incidence, complications, and angiography results. *J Neurosurg* 2006;105:396–9.
19 Santillan A, Gobin YP, Greenberg ED, *et al*. Intraprocedural aneurysmal rupture during coil embolization of brain aneurysms: role of balloon-assisted coiling. *AJNR Am J Neuroradiol* 2012;33:2017–21.
20 Altay T, Kang HI, Woo HH, *et al*. Thromboembolic events associated with endovascular treatment of cerebral aneurysms. *J Neurointerv Surg* 2011;3:147–50.
21 Pierot L, Wakhloo AK. Endovascular treatment of intracranial aneurysms: current status. *Stroke* 2013;44:2046–54.
22 Piazza M, Nayak N, Ali Z, *et al*. Trends in resident operative teaching opportunities for treatment of intracranial aneurysms. *World Neurosurg* 2017;103:194–200.