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REVIEW

Feasibility, safety, and efficacy of endovascular treatment of anterior cranial fossa dural arteriovenous fistulas: a systematic review and meta-analysis with a subanalysis for Onyx

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Abstract

Dural Arteriovenous Fistulas (dAVFs) of the anterior cranial fossa (ACF) are uncommon but carry a high risk of hemorrhage and pose substantial treatment challenges. Recent advancements in endovascular treatment (EVT), including the introduction of novel liquid embolic agents, have markedly bolstered EVT's role in managing ACF-dAVFs, with notable series published in the last five years. We aimed to assess the feasibility, safety, and efficacy of EVT for ACF-dAVFs. We searched Medline, Scopus, Web of Science, and Cochrane Library databases following PRISMA guidelines. Eligible studies included those with ≥ 5 patients undergoing embolization of ACF-dAVFs, detailing both angiographic and clinical outcomes. We used single proportion analysis with 95% confidence intervals under a random-effects model, I^2 to assess heterogeneity, and Baujat and sensitivity analysis to address high heterogeneity. Publication bias was assessed by funnel-plot analysis and Egger's test. Outcomes included complete occlusion following embolization, unsuccessful endovascular embolization attempts, incomplete occlusion following embolization, symptom resolution or clinical improvement following embolization, recurrence; procedure-related complications, morbidity, and mortality. Additionally, a subanalysis for studies exclusively utilizing Onyx™ embolic system was done. Eighteen studies comprising 231 ACF-dAVF were included. Unsuccessful endovascular embolization attempts rate was 2%. Complete occlusion rate was 85%, with 4% of complications. Incomplete occlusion rate was 10%. Successfully embolized patients experienced either symptom resolution or clinical improvement in 94% of cases. Morbidity and mortality rates were 1% and 0%, respectively. Onyx subanalyses showed an overall rate of 0% for unsuccessful attempts, 95% for complete occlusion, and 5% for incomplete occlusion. Symptom resolution or clinical improvement was 98% and recurrence rate was 0%. EVT for ACF-dAVF is highly feasible, effective, and safe, with a low rate of complications, morbidity, and mortality. The subanalyses focusing on Onyx embolizations revealed superior efficacy and safety outcomes compared to the findings of the primary analyses involving all included studies.

Keywords Anterior cranial fossa · Ethmoidal · Dural arteriovenous fistula · Endovascular · Embolization · Onyx

Introduction

Dural arteriovenous fistulas (dAVFs) of the anterior cranial fossa (ACF) are rare and highly fragile lesions, comprising a minority of all dAVFs [1, 2]. Since there is no sinus in the ACF, the majority of these fistulas demonstrate venous drainage directly into cortical veins and typically have a high-grade Cognard classification (type III or IV) at the time of discovery [3, 4]. Compared to sinus walls, cortical veins have fragile walls, and the formation of venous varices is common, which often precedes hemorrhage [5]. Therefore, these fistulas are typically treated upon incidental discovery, as treatment outcomes are less favorable following a hemorrhagic presentation [6]. Available treatment options for

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ACF-dAVFs include surgical disconnection, radiosurgery, endovascular treatment (EVT), or a combination of these modalities [7].

ACF-dAVFs typically receive their arterial supply from the ophthalmic artery (OphA), specifically its ethmoidal branches. This connection puts transarterial embolization (TAE) at risk of causing visual complications [3]. Alternatively, ACF-dAVFs may be supplied by the Middle Meningeal Artery (MMA), or the pial branch of the Anterior Cerebral Artery, with potential anastomotic connections [8]. Additionally, the complex and tortuous venous anatomy makes transvenous embolization (TVE) challenging. However, the past decade has seen substantial advancements in endovascular techniques and the development of novel liquid embolic agents, greatly enhancing the effectiveness of EVT. Reports indicate occlusion rates reaching up to 100%, achieved with no major procedure-related complications [9–11]. Consequently, many centers favor the endovascular approach, especially when the angioarchitecture is favorable [4, 7, 10, 12]. Despite these advancements, there remains a scarcity of evidence regarding the safety and efficacy of EVT, with a notable lack of prospective, randomized controlled trials and comprehensive meta-analyses on the subject.

To date, the largest review on this topic reported outcomes from embolization in only 48 cases of ACF-dAVFs [13]. Herein, throughout a systematic review and meta-analysis, we aimed to synthesize data on the feasibility, safety, and efficacy of EVT in a larger cohort of 231 ACF-dAVFs. This effort aimed to provide a more robust understanding of EVT's role in managing these complex cases.

Methods

Eligibility criteria

The studies selected for this review met the following criteria: (1) they were either case series, prospective or retrospective cohorts, or randomized controlled trials (RCTs); (2) they provided data on clinical and angiographic outcomes on ACF-dAVFs treated with EVT as a primary approach; and (3) they included a cohort of five or more patients.

Search strategy, data extraction, and quality assessment

A comprehensive search on Medline, Scopus, Web of Science, and Cochrane from inception to 8 January 2024 with the following research strategy was done: ("dural arteriovenous fistula" OR "dural arteriovenous fistulas") AND ("anterior cranial fossa" OR "anterior fossa" OR "ethmoidal") AND (embolization OR endovascular OR "transarterial embolization" OR "transvenous embolization"). A modified version of the Newcastle-Ottawa Scale was adopted to evaluate the risk of bias in the included studies [14]. Two authors independently assessed the studies for data extraction and quality assessment (M.Y.F and A.G.), and any conflict was resolved by a third author (S.B.). Studies that had satisfactory angiographic and clinical follow-ups, along with clear outcome reports, were designated as having a "low risk of bias." Studies with unsatisfactory follow-ups were classified as "medium risk of bias." Those lacking both satisfactory follow-ups and clear outcome reports were categorized as "high risk of bias".

Endpoints, subanalysis, and definitions

Embolization outcomes included: (1) complete occlusion following embolization; (2) unsuccessful endovascular embolization attempts; (3) incomplete occlusion following embolization; and (4) recurrence.

Clinical outcomes included: (1) symptom resolution or clinical improvement following embolization; (2) procedure-related complications; (3) morbidity; (4) mortality.

Additionally, a subanalysis for studies exclusively utilizing Onyx (Medtronic, Irvine, CA, USA) as the embolization agent was conducted. Complete occlusion following embolization analysis did not include patients who underwent additional treatment after the first embolization as the aim of this analysis was to identify the rate of complete occlusion specifically in the first EVT attempt. An event was deemed an unsuccessful endovascular embolization attempt if reports indicated unsuccessful embolization, attributed to technical challenges like the inability to navigate to the arterial feeder, or any other factor contributing to the embolization attempt's failure. Conversely, fistulas that were embolized and did not achieve the expected occlusion were not classified as unsuccessful endovascular embolization attempts. Symptom resolution or clinical improvement analysis included patients who were successfully embolized. An event of morbidity was considered when complications resulted in permanent neurological or visual deficits. Incomplete occlusion following embolization event was considered when residual arterial feeding or venous drainage persisted after the procedure, resulting in partial, but not complete, elimination of the fistula.

Statistical analysis

The present systematic review and meta-analysis adhered to the updated PRISMA Guidelines 15. Single proportion analysis with 95% confidence intervals (CI) under a random-effects model was utilized to pool the data. Heterogeneity

was assessed using I^2 statistics, where $I^2 > 35\%$ was considered significant and Baujat analysis was used to identify outlier studies. Sensitivity analysis was performed to address high heterogeneity, systematically excluding one study at a time and recalculating the pooled results. Publication bias was evaluated through funnel plot analysis and Egger's regression test. The statistical analysis was performed using R Studio (version 4.2.3, R Foundation for Statistical Computing, Vienna, Austria), employing the inverse variance and the restricted maximum likelihood methods.

Results

Study selection

A total of 317 articles were identified from MEDLINE (92), Scopus (138), and Web of Science (87). After title and abstract screening, 33 articles underwent full-text review. Fifteen studies were excluded: five reported fewer than five cases, seven had overlapping series, and three were unrelated to ACF-dAVFs. Ultimately, 18 articles were included [3–7, 9–12, 16–24]. The search is illustrated in Fig. 1.

Baseline patient and study characteristics

All included studies were retrospective and comprised a total of 231 patients, and reported mean ages ranging between 49.5 and 62 years. Ten studies provided information regarding sex, comprising 33 females and 85 males. Twelve studies provided clinical presentation data, encompassing 68 cases of ruptured ACF-dAVFs among 142 patients (47.9%), and 27 incidental diagnoses among the same patient cohort (19%). Six of those studies, involving 45 patients, exclusively utilized Onyx as an embolic agent. Eleven studies brought data from a single center, while seven were multicentric. Thirteen articles were studies exclusively focused on EVT. The embolizing agents used were: coils, Onyx, PVA particles, NBCA (Glue), Squid (Balt, Montmorency, France), and Phil-4 (MicroVention, Aliso Viejo, CA, USA). Detailed information regarding baseline characteristics, embolization approach, and detailed follow-up with modality, outlined by each study, is available in Table 1. A comprehensive description of clinical presentation, grading, and procedure-related complications is available in Supplementary Table 1 (Online Resource 1).

Treatment efficacy

Summarized meta-analyzed findings are available in Table 2. The analysis of unsuccessful endovascular embolization attempts, complete occlusion following embolization, and incomplete occlusion following embolization included 18 studies encompassing 231 patients. For unsuccessful endovascular embolization attempts, an estimated rate of 2% (95% CI: 0–4%, $I^2 = 0\%$, Fig. 2A) was identified. The analysis for the complete occlusion following embolization identified an overall rate of 85% (95% CI: 77–93%, $I^2 = 64\%$, Fig. 2B). For incomplete occlusion following embolization, an estimated rate of 10% (95% CI: 4–15%, $I^2 = 54\%$, Fig. 3A) was identified. The analysis of symptom resolution or clinical improvement following embolization included 15 studies and 199 patients, resulting in an estimated rate of 94% (95% CI: 89–100%, $I^2 = 59\%$, Fig. 3B). Last, the analysis of the recurrence included 18 studies and 180 patients and revealed an estimated rate of 1% (95% CI: 0–4%, $I^2 = 0\%$), as shown in Supplementary Fig. 1 (Online Resource 2). A comprehensive description of incomplete occlusion cases and a comprehensive description of unsuccessful endovascular embolization attempts are available in Tables 3 and 4, respectively.

The analyses of the complete occlusion following embolization, incomplete occlusion following embolization, and symptom resolution or clinical improvement revealed significant heterogeneity. Therefore, a Baujat analysis and a sensitivity analysis were conducted. In the complete occlusion following embolization, Baujat identified Gross et al. [5] as the main contributor to the overall heterogeneity, as shown in Supplementary Fig. 2 (Online Resource 3), and in sensitivity analysis the estimated overall rates ranged from 83 to 89%, and sustained heterogeneity was identified in all scenarios, except when excluding Gross et al. [5], where the analysis identified an estimated rate of 89% (95% CI: 83–94%, $I^2 = 34\%$), as shown in Supplementary Fig. 3 (Online Resource 4). In the incomplete occlusion following embolization, Baujat identified Gross et al. [5] as the main contributor to the overall heterogeneity, as shown in Supplementary Fig. 4 (Online Resource 5), and in sensitivity analysis, the estimated overall rates ranged from 7 to 11%, and sustained heterogeneity was identified in all scenarios, except when excluding Gross et al. [5], where the analysis identified an estimated rate of 7% (95% CI: 3–11%, $I^2 = 0\%$), with noteworthy zero heterogeneity, as shown in Supplementary Fig. 5 (Online Resource 6). In the symptom resolution or clinical improvement evaluation, Baujat analysis identified Sanchez et al. [21] and Trivelato et al. [20] as the main contributors, as shown in Supplementary Fig. 6 (Online Resource 7), and in the sensitivity analysis, the estimated overall rates ranged from 93 to 97%. Notably, when excluding Sanchez et al. [21], the overall rate was 97% (95% CI: 82–94%, $I^2 = 0\%$), with noteworthy zero heterogeneity, as shown in Supplementary Fig. 7 (Online Resource 8).

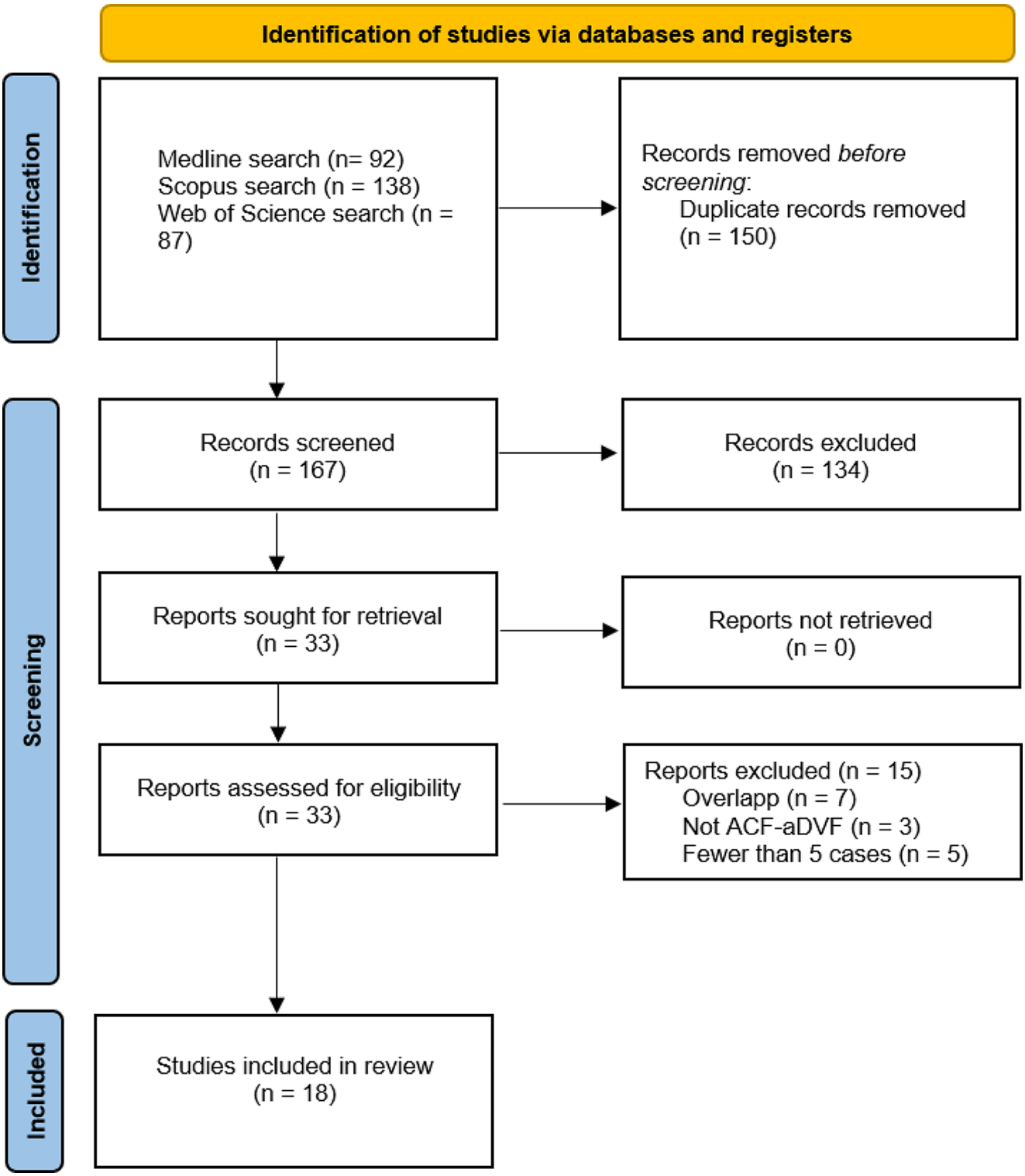


Fig. 1 PRISMA flow diagram

Table 1 Baseline patient and study characteristics

Author	Design	No patients	Sex F/M	Mean age (range)	No of EVT DAVFs	No of ruptured DAVFs	Embolization approach	No.-Embolizing agent	No.-Access artery	FU modality	Length fu clinical (mean)	Length fu imaging (mean)
Abud 2011 [24]	RS	6	NR	NR	6	NR	6-TAE	6-Onyx	5-OphA 1-OphA + MMA	DSA	6 mo	5.5 mo
Agid 2009 [3]	RMS	11	NS	NR	11	NR	11-TAE	9-NBCA 1-NBCA + PVA-particles 1-NBCA + PVA-particles + ONYX 18	11-OphA	DSA	15.8 mo	2.3 mo
Cannizzaro 2016 [16]	RMS	6	5/1	57.1 ± 13	6	2/6	4-TAE; 2-TVE	4-Onyx 2-Coils	NS	DSA and MRA	12 mo	NR
Dabus 2020 [19]	RMS	23	5/18	53	23	12/23	4-TAE 14-TVE 5-TAE failed followed by TVE	19-Onyx 4- Phil, 4-Coils, 1-Onyx + Coil	7-OphA 2-MMA 19-TVE	DSA	25 mo	25 mo
Deng 2013 [9]	RS	5	2/3	56.8	5	4/5	5 - TAE	5-Onyx	5-MMA	DSA	7–18 mo	NR
Gross 2016 [5]	RS	9	NS	62	9	NS	8 - TAE 1 - TVE	7-Onyx 2-Onyx + NBCA	8-OphA 1-ACA dural branch 1-IMA	NR	19 mo	20.5 mo
Kulan-thaivelu 2020 [17]	RS	6	4/2	59.3	6	4/6	4 - TAE 1-TVE 1-TAE failed followed by TVE	5-Onyx or Squid 1-Coil	5-MMA 1-OphA	DSA	6 mo	6 mo
Kular 2022 [11]	RMS	5	3/2	59	5	3/5	5-TAE	6-Squid	5-OphA	MRA	6	6
Li 2012 [7]	RS	11	1/10	49.5 (37–68)	11	9/11	11-TAE	11-Onyx	11-OphA	DSA	18.5 mo	6 mo
Li 2013 [4]	RS	6	0/6	55 (38–68)	6	5/6	6-TAE	6-Onyx	2-OphA 2-Bilateral OphA 1-MMA + OphA 1-MMA + orbitofrontal A	4-DSA 1-MRA	7.1 mo	7.4 mo
Mayercik 2020 [18]	RMS	10	8/2	59.7 ± 9.5	10	4/10	12-TAE	1-NBCA 8-Onyx	10-OphA	NR	3 mo	NS
Piergallini 2019 [12]	RS	6	1/5	60	6	3/6	6-TAE	6-Onyx 18	4-OphA 2-Bilateral OphA	DSA and MRI	24 mo	DSA – 12 mo; MRI – 24 mo
Puylaert 2024 [23]	RS	14	NS	59 ± 11	15	3/14	12-TAE 1-TVE 1-TAE + TVE	14-NBCA	12-OphA -MMA 1-Orbitofrontal A	NR	13 mo	13 mo

Table 1 (continued)

Author	Design	No patients	Sex F/M	Mean age (range)	No of EVT DAVFs	No of ruptured DAVFs	Embolization approach	No.-Embolizing agent	No.-Access artery	FU modality	Length fu clinical (mean)	Length fu imaging (mean)
Sanchez 2023 [21]	RMS	17	NS	61 ± 12	17	NR	14-TAE 2-TVE 1-TAE + TVE	6-Onyx 2-Phil 3-NBCA 1-Coil	NS	DSA	22 mo	13 mo
Su 2023 [6]	RS	40	4/36	55.6 ± 7.4	40	14/40	40-TAE	54-Onyx 10-NBCA	18-MMA 24-OphA 15-Sphenopalatin A 9-ACA	MRA/CTA or DSA	NR	29,7 mo (DSA); 41 mo (CTA/MRA)
Trivelato 2022 [20]	RMS	35	NS	58.4 ± 12.3	35	NS	19-TAE; 12-TVE; 4-TAE + TVE	31-Liquid 2-Liquid + coils 1-coils	19-OphA 5-MMA 1-IMA artery 1-Facial artery	DSA	6 mo	6 mo
Voldrich 2023 [10]	RS	10	NR	NR	10	5/10	10 -TAE	8-Onyx 1-NBCA + Coil 1-Onyx + NBCA	6-OphA 4-MMA	NR	NR	NR
Zhang 2023 [22]	RS	11	NR	NR	11	NR	9-TAE 2 - TVE	11-Onyx	5-OphA 3 MMA 1-Combined OphA + MMA 2-NS	DSA	11.3 ± 6.1 (3–23)	11.3 ± 6.1 (3–23)

Abbreviations ACA: Anterior Cerebral Artery; A: Artery; DSA: Digital Subtraction Angiogram; EVT: Endovascular Treatment; IMA: Internal Maxillary Artery; MMA: Middle Meningeal Artery; MRA: Magnetic Resonance Angiography; MRI: Magnetic Resonance Imaging; NBCA: N-butyl cyanoacrylate; NR: Non-reported; OphA: Ophthalmic Artery; NS: Not specified for anterior cranial fossa dural arteriovenous fistulas treated by endovascular treatment; RMS: Retrospective Multi-Center Study; RS: Retrospective Study; RSS: Retrospective Single-Center Study; TAE: Transarterial Embolization; TVE: Transvenous Embolization

Table 2 Summary of meta-analysis findings

		Outcomes	Estimate (95% CI)	I^2 (%)	No. of studies	No. of events / total
Main analyses	Embolization Outcomes	Unsuccessful endovascular embolization attempts	2% (0–4)	0	18	11 / 231
		Complete occlusion following embolization	85% (77–93)	64	18	189 / 231
		Incomplete occlusion following embolization	10% (4–15)	54	18	29 / 231
		Recurrence of ACF-dAVFs	1% (0–4)	0	18	3 / 180
	Clinical Outcomes	Procedure-related complications	4% (2–7)	0	18	19 / 231
		Symptom resolution or clinical improvement	94% (89–100)	59	15	181 / 199
		Morbidity	1% (0–4)	0	18	6 / 231
		Mortality	0% (0–2)	0	18	1 / 231
Onyx sub-analyses	Embolization Outcomes	Unsuccessful endovascular embolization attempts	0% (0–6)	0	6	0 / 45
		Complete occlusion following embolization	95% (87–100)	0	6	41 / 45
		Incomplete occlusion following embolization	5% (0–13)	0	6	4 / 45
		Recurrence of ACF-dAVFs	0% (0–7)	0	6	0 / 40
	Clinical Outcomes	Procedure-related complications	11% (1–20)	0	6	7 / 45
		Symptom resolution or clinical improvement	98% (91–100)	0	5	38 / 39
		Morbidity	0% (0–6%)	0	6	0 / 45
		Mortality	0% (0–6%)	0	6	0 / 45

Abbreviations CI: Confidence interval; No.: Number

Procedure-related complications, morbidity, and mortality

The analyses for procedure-related complications, morbidity, and mortality included data from 18 studies and 231 patients. The procedure-related complications assessment resulted in an overall rate of 4% (95% CI: 2–7%, $I^2 = 0\%$, Fig. 4A); while the analysis of morbidity showed an overall rate of 1% (95% CI: 0–4%, $I^2 = 0\%$, Fig. 4B); and the evaluation of mortality revealed an overall rate of 0% (95% CI: 0–2%, $I^2 = 0\%$, Fig. 4C).

Onyx embolization subanalysis

A subanalysis focusing on Onyx was done for the following outcomes: unsuccessful endovascular embolization attempts, complete occlusion following embolization, symptom resolution or clinical improvement following embolization, and recurrence of ACF-dAVFs. The subanalyses of unsuccessful endovascular embolization attempts, complete occlusion following embolization, incomplete occlusion following embolization, procedure-related complications, morbidity, and mortality included data from 6 studies comprising 45 patients. An overall rate of 0% (95% CI: 0–6%, $I^2 = 0\%$, Fig. 5A) was identified for unsuccessful endovascular embolization attempts, 95% (95% CI: 87–100%, $I^2 = 0\%$, Fig. 5B) for complete occlusion following embolization, 5% (95% CI: 0–13%, $I^2 = 0\%$, Fig. 5C) for incomplete occlusion following embolization, 11% (95% CI: 1–20%, $I^2 = 0\%$) for procedure-related complications, and 0% (95% CI: 0–6%, $I^2 = 0\%$) for both morbidity and mortality. The subanalysis of symptom resolution or clinical improvement included data from 5 studies comprising 39 patients and revealed an estimated rate of 98% (95% CI: 91–100%, $I^2 = 0\%$, Fig. 6A). Lastly, the analysis of the recurrence included data from 6 studies comprising 40 patients and identified an estimated rate of 0% (95% CI: 0–7%, $I^2 = 0\%$, Fig. 6B).

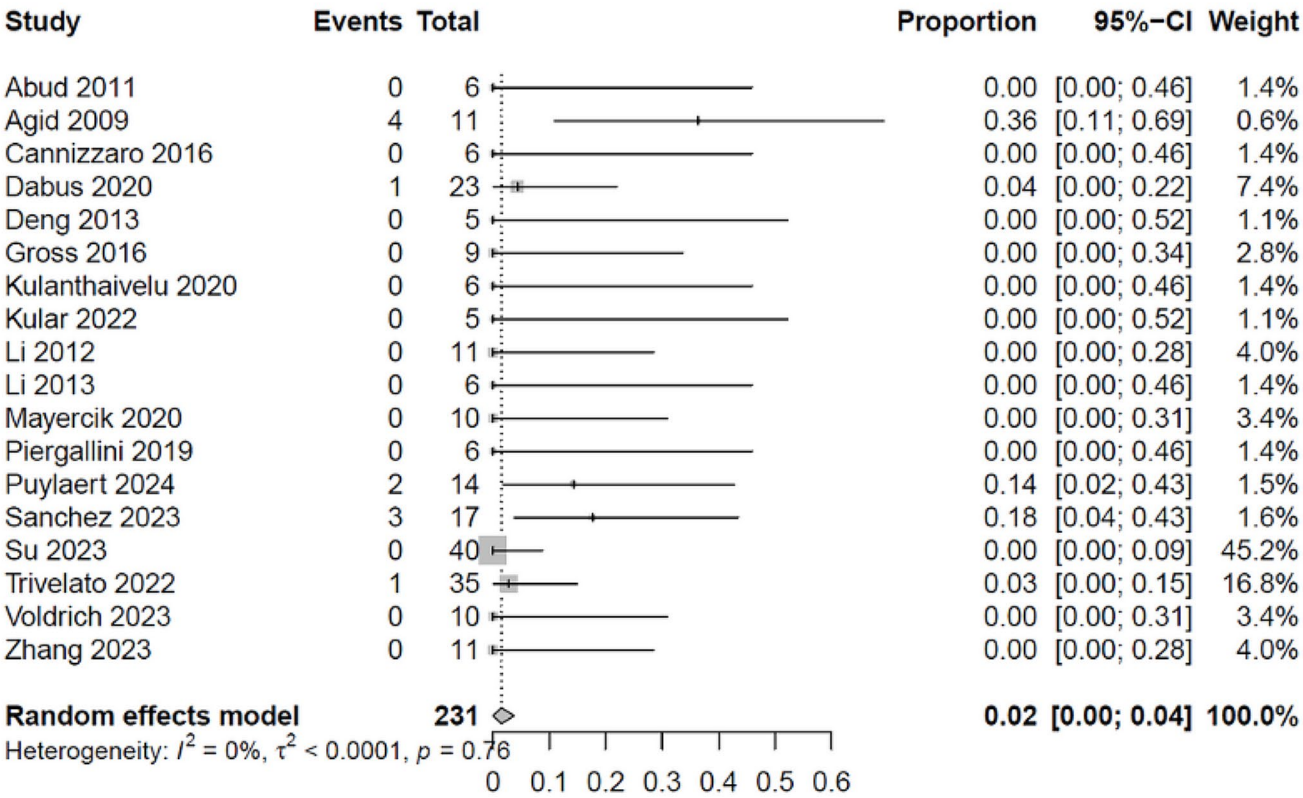
Quality assessment and publication bias assessment

All the included studies were classified as a low risk of bias, study-specific results of the quality assessment are disclosed in Supplementary Table 2 (Online Resource 9). By visual analysis of the funnel plot in the complete occlusion following embolization, there was asymmetry suggestive of a small study effect, as shown in Supplementary Fig. 8 (Online Resource 10). However, Egger's regression test did not confirm publication bias ($p = 0.06$). The same scenario was identified in the symptom resolution or clinical improvement following embolization analysis ($p = 0.15$) and incomplete occlusion following embolization analysis ($p = 0.1$). In the funnel plot of recurrence, morbidity, mortality, and procedure-related complications there was no asymmetry observed in each respective analysis.

Discussion

This meta-analysis, encompassing 231 cases of ACF-dAVFs treated with EVT, reveals several critical findings. Despite previous concerns about the technical challenges and potential risks associated with EVT for ACF-dAVFs, the results indicate a high success rate for EVT. The procedures resulted in an 85% rate of complete occlusion

2A Unsuccessful endovascular embolization attempts



2B Complete occlusion following embolization

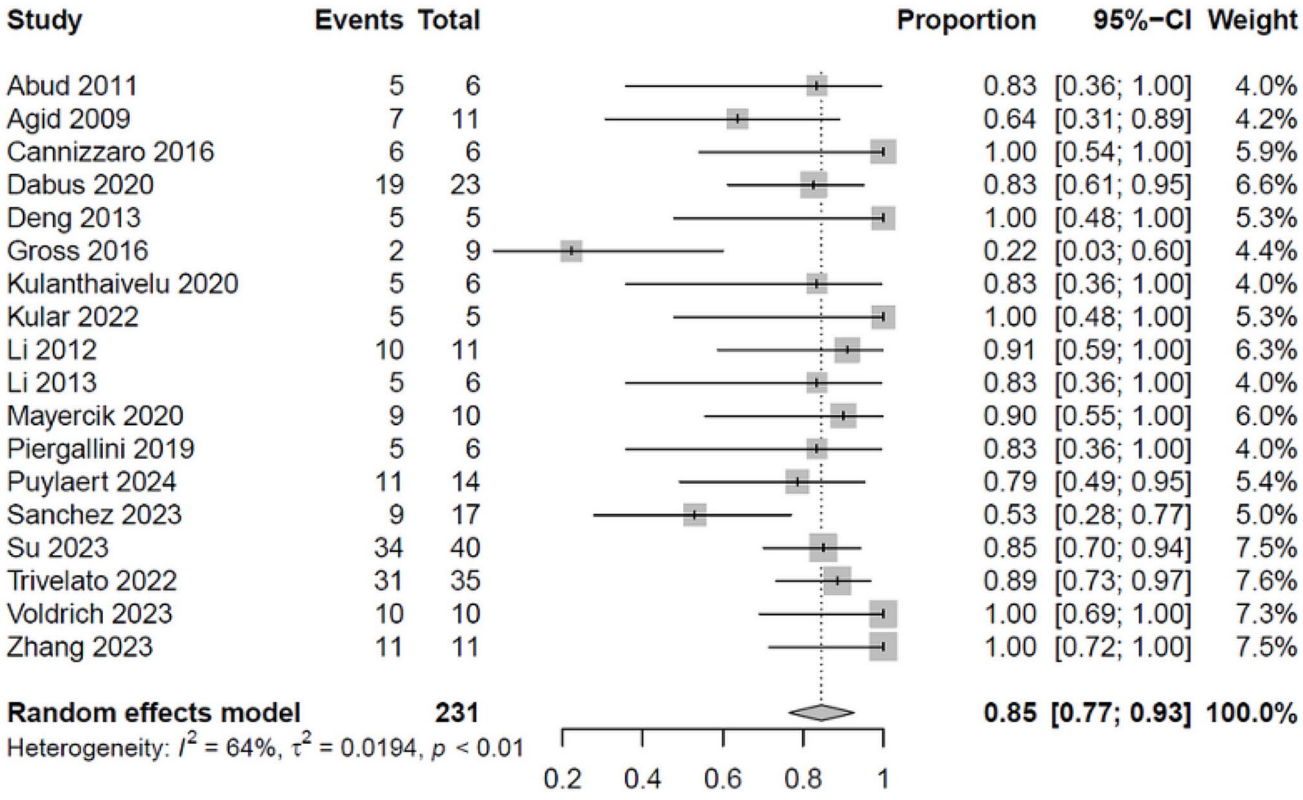


Fig. 2 (**A**) - Unsuccessful endovascular embolization attempts rate in 231 Anterior Cranial Fossa Dural Arteriovenous Fistulas (ACF-dAVFs) treated with endovascular embolization. (**B**) – Complete Occlusion rate in 231 Anterior Cranial Fossa Dural Arteriovenous Fistulas (ACF-dAVFs) following embolization

following embolization with complications arising in only 4% of cases, a 10% rate of incomplete occlusion following embolization, and minimal unsuccessful embolization attempts in only 2% of cases. Furthermore, 94% of successful embolized patients experienced either symptom resolution or clinical improvement at follow-up attributable to the fistula following EVT. The procedure-related morbidity rate was 1%, and death occurred in a single case out of the 231 patients treated, underscoring the feasibility, safety, and efficacy of EVT in the management of ACF-dAVFs.

ACF-dAVFs are also referred to as ethmoidal DAVFs or cribriform plate DAVFs. These vascular anomalies are well-known for their propensity to drain directly into cortical veins and have a malignant natural history with a high risk of hemorrhage [5, 13, 25]. Also, a male predominance is noted [16, 26]. This meta-analysis confirms a male predominance, aligning with the literature on ACF-dAVFs. The most common presentation identified was intracranial hemorrhage, which is consistent with prior reports [13]. Incidental discovery was presented in 19% of cases in a cohort of 142 patients in our study. ACF-dAVFs carry a rebleeding risk of up to 35% post-rupture, necessitating treatment whether found incidentally or secondary to rupture [7, 27].

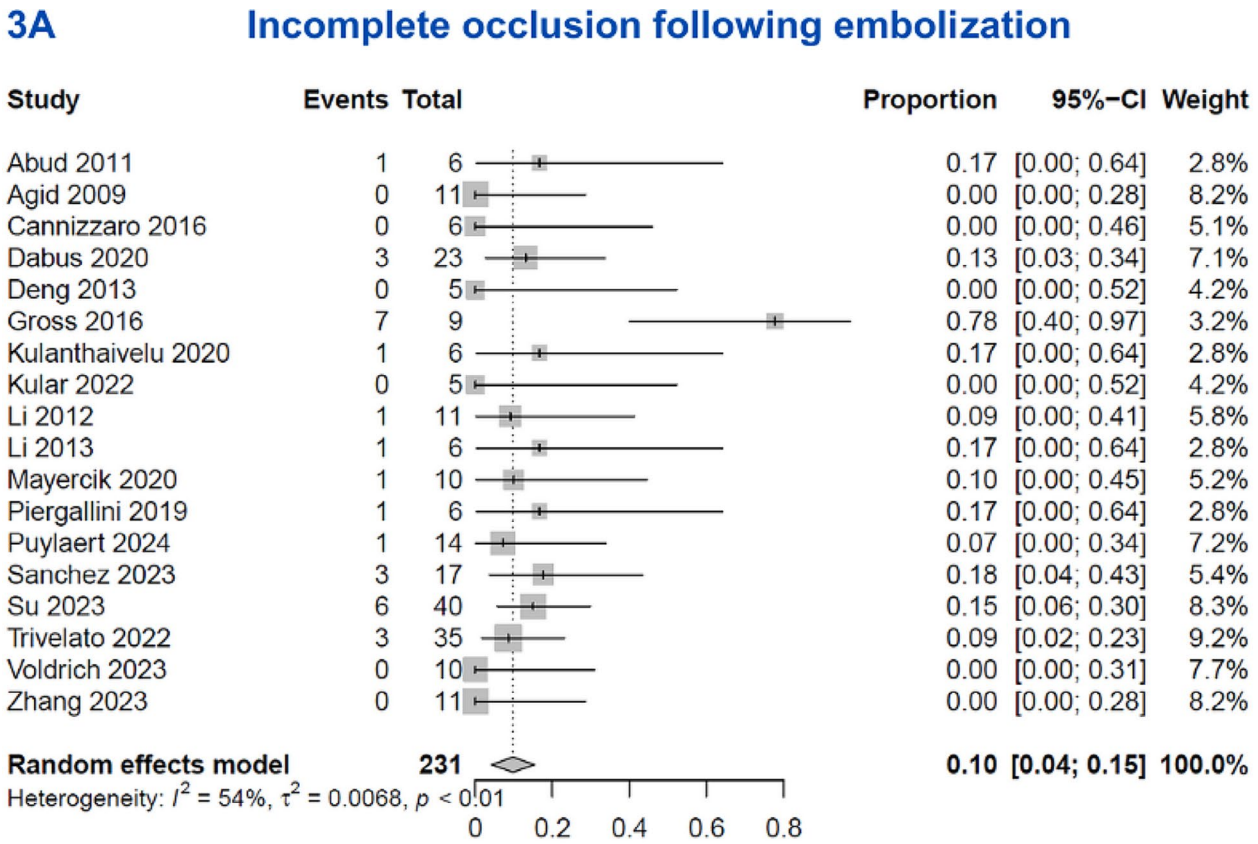
The efficacy of surgical treatment for ACF-dAVFs is notably high, with a pooled analysis of 92 cases reporting a 100% total occlusion rate [5]. A comparative meta-analysis between endovascular and surgical treatment for ACF-dAVF indicated that a surgical approach was superior in achieving complete occlusion, with a success rate of 100% compared to 47% for EVT [26]. It is important to note, however, that, the endovascular cohort in this analysis included just 32 cases, and the most current study considered was published in 2016, likely limiting the relevance of these findings to the current state of endovascular techniques.

A review focusing on EVT, which was primarily based on 48 cases, reported a complete occlusion rate of 91.7% [13]. More recent publications from the past five years have demonstrated a wider range of complete occlusion rates for EVT, varying from 52.9 to 100% [6, 10, 11, 17–23]. The findings from the present study, involving a larger cohort of 231 cases, identified a complete occlusion following embolization rate of 85% with EVT. While surgery remains a highly effective treatment option for ACF-dAVFs, it is now typically reserved for instances where EVT does not achieve desired outcomes [10, 17, 28], a scenario that occurred in only 2% in the analysis of unsuccessful endovascular attempts cases and in 10% in the analysis of the incomplete occlusion following embolization in this study. The majority of these cases underwent successful surgical treatment as described in Tables 3 and 4.

The primary goal of EVT for ACF-dAVFs is to completely occlude the fistulous connection [29]. Depending on the angioarchitecture, EVT of ACF-dAVFs may be performed with TAE, TVE, or a combination of both. TAE was the predominant approach in the included studies, with the OphA and the MMA being the most frequently utilized access arteries. TAE via the OphA is often the preferred strategy when access is achievable [11, 12]. Deng et al. [9] documented a 100% occlusion rate for TAE performed through the MMA. The anastomoses between the MMA's frontal branches and the ethmoidal arteries' anterior falcine branches may enable successful embolization of ACF-dAVFs with MMA access [9, 17]. On the other hand, Piergallini et al. [12] reported an 83.3% occlusion rate through OphA, emphasizing the importance of targeting the arterial route with the highest flow to enhance the achievement of complete occlusion. Additionally, they also observed enlargement of the OphA due to fistula flow, which facilitated its catheterization. Li et al. [7] reported a technique involving balloon-assisted temporary ICA occlusion distal to OphA, enhancing OphA inflow to aid catheterization.

TVE may offer a superior alternative in some cases, particularly when the draining vein is short and non-tortuous, and when transarterial access may be challenging. Dabus et al. [19] observed higher occlusion rates with TVE compared to TAE in treating ACF-dAVFs. Despite this, recent publications have explored a range of strategies, including both TAE, TVE, and their combinations, reflecting a tailored approach to each case based on the individual angioarchitecture [17, 19–23]. Trivelato et al. [20] documented four cases treated with a TAE and TVE combination. Dabus et al. [19] reported five successful TVEs after failed TAE attempts. Our study, which we believe captures the contemporary real-world experience, showcases a marked improvement in treatment outcomes, with a complete occlusion rate of 85% with only a 1% recurrence rate. This contrasts sharply with previous meta-analyses reporting a 47% occlusion rate [26], underscoring the evolving efficacy of EVT in the treatment of ACF-dAVFs.

Onyx solidifies slower than n-BCA (glue), allowing the operator to create a plug by pausing during embolization, which enables further distal penetration and prevents reflux, thereby improving angiographic outcomes from single arterial feeders [4, 29, 30]. A meta-analysis assessing TAE of 463 dAVFs with Onyx demonstrated a complete occlusion rate of 82%, with a recurrence rate of 2% [31]. Voldrich et al. [10] compared the results of patients treated in the Onyx era versus the pre-Onyx era, reporting a higher complete occlusion rate with Onyx compared to other embolic



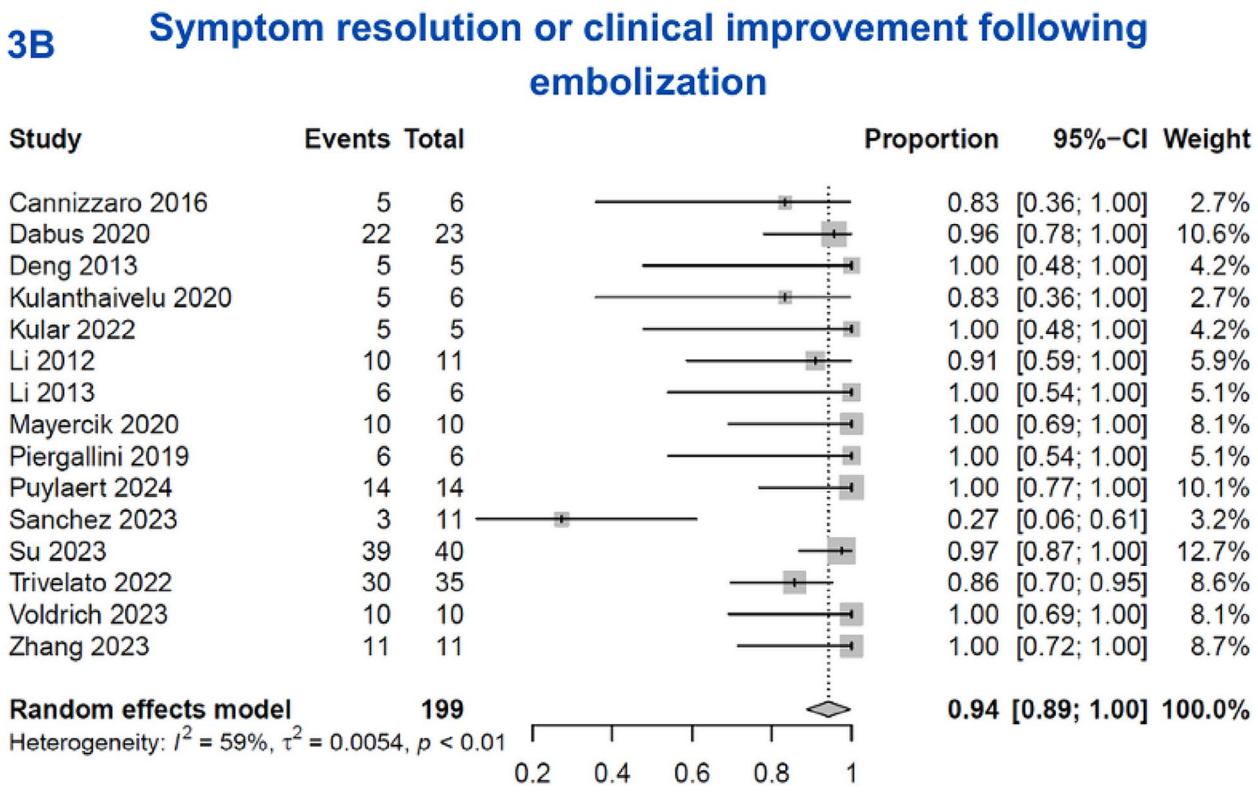


Fig. 3 (**A**) - Incomplete Occlusion rate in 231 Anterior Cranial Fossa Dural Arteriovenous Fistulas (ACF-dAVFs) following embolization. (**B**) - Symptom Resolution or Clinical Improvement rate in 199 Anterior Cranial Fossa Dural Arteriovenous Fistulas (ACF-dAVFs) following embolization

Table 3 Comprehensive description of incomplete occlusion cases

Study	TAE or TVE (specifically for incomplete occlusion cases)	Access artery or vein	Embolic agent	No. of incomplete occlusion cases / no. of embolized cases	Subsequent re-treatment approach	Final outcomes
Abud 2011 [24]	TAE	NR	Onyx	1/6	Surgical Treatment	Complete occlusion following Surgical Treatment
Dabus 2020 [19]	2 TAEs 1 TVE	NR	NR	3/23	2 TAEs: Surgical Treatment 1 TVE: Refused additional treatment	2 TAEs: Complete occlusion following Surgical Treatment 1 TVE: Asymptomatic at 3-year clinical FU.
Gross 2016 [5]	TAE	NR	Onyx or Onyx + NBCA	7/9	6 Patients underwent Surgical Treatment 1 Patient refused additional treatment	6 TAEs: Complete occlusion following Surgical Treatment 1 TAE: The patient who refused additional treatment remained neurologically intact at 39-month clinical FU, with normal MR imaging.
Kulanthaivelu 2020 [17]	TAE	MMA	Coil	1/6	No additional treatment	No treatment: fistula spontaneously disappeared 6 months later
Li 2012 [7]	TAE	OphA	Onyx	1/11	The fistula was re-embolized 3 months later	Near-complete occlusion was observed after re-embolization. The patient refused further angiographic FU or additional treatment
Li 2013 [4]	TAE	OphA and MMA	Onyx	1/6	Gamma Knife treatment 4 months later	NR
Mayercik 2020 [18]	TAE	OphA	NS	1/10	Surgical Treatment	Complete occlusion following Surgical Treatment
Piergallini 2019 [12]	TAE	NR	Onyx	1/6	The fistula was re-embolized 1 month later	Complete occlusion following re-embolization
Puylaert 2024 [23]	TAE	NR	NBCA	1/14	Surgical Treatment	Complete occlusion following Surgical Treatment
Sanchez 2023 [21]	NR	NR	Onyx	3/17	Surgical Treatment	Complete occlusion following Surgical Treatment
Su 2023 [6]	NR	NR	Onyx or NBCA	6/40	2 Patients underwent Surgical Treatment 3 Patients refused additional treatments 1 Patient did not receive additional treatment	2 patients that underwent Surgical Treatment: NR 3 Patients that refused additional treatment: NR 1 No treatment: fistula spontaneously disappeared 3 months later
Trivelato 2022 [20]	NR	NR	NR	3/35	Surgical Treatment	NR

Abbreviations no.: number; NR: non-reported; TAE: Transarterial Embolization; TVE: Transvenous Embolization

materials (88% vs. 35%). Similarly, Gross et al. [30] reported on 173 patients in the Onyx era and 87 patients in the pre-Onyx era, with initial complete occlusion rates via TAE-only approaches at 43% versus 23%, respectively, and cure rates via TAE treatment from a single arterial feeder at 29% versus 11%. The findings of the present sub-analysis focusing on studies that exclusively used Onyx mirrored these reports, with a better complete occlusion rate than the overall results of the primary analysis (95% vs. 85%). Notably, in our sub-analysis, 11% of procedure-related complications were identified. However, we observed a 0% rate for both morbidity and mortality, indicating that none of these complications resulted in permanent neurological or visual deficits or death.

In this study, procedure-related complications analysis identified an overall rate of 4%. Visual complications occurred in five patients, of whom only two suffered permanent visual deficits due to retinal ischemia. This finding indicates that the rate of visual complications is overall very low. One patient died due to venous perforation following a TVE approach [17]. Intracranial hemorrhage secondary to venous perforation occurred in two other cases [12, 19]. The overall permanent morbidity and mortality rates secondary to EVT were 1% and 0% respectively. Previous reviews

Table 4 Comprehensive description of unsuccessful endovascular embolization attempts cases

Study	TAE or TVE (specifically for unsuccessful cases)	Access artery or vein	Embolic agent	No. of unsuccessful endovascular attempts / no. of patients	Reason	Subsequent management	Final outcomes
Agid 2009 [3]	TAE	OphA	NBCA or NBCA + PVA or NBCA + Onyx	4/11	One case: Failure to achieve proper positioning of the microcatheter. Three cases: NR	NR	NR
Dabus 2020 [19]	NR	NR	NR	1/23	Venous perforation	Decompressive hemicraniectomy and Surgical Treatment	mRS 1 at 2-month FU Fistula outcome: complete occlusion following surgical treatment
Puylaert 2024 [23]	NR	NR	NR	2/14	The microcatheter could not be navigated to a position safe enough beyond the origin of the central retinal artery, which would allow embolization without risking reflux into the retinal artery.	Surgical Treatment	Complete occlusion following Surgical Treatment for both cases
Sanchez 2023 [21]	NR	NR	NR	3/17	Inability to access the target arterial feeder	Surgical Treatment or Radiosurgery or no additional treatment	NR
Trivelato 2022 [20]	NR	OphA	NR	1/35	The microcatheter could not be navigated beyond the origin of the central retinal artery	NR	NR

Abbreviations NR: non-reported; TAE: Transarterial Embolization; TVE: Transvenous Embolization

found a procedure-related complication rate of 8.3–9.3% [13, 26]. For surgical treatment complication rates ranging from 6.7 to 10% have been reported in small multicentric studies [3, 32]. For morbidity and mortality, 4% and 1.2%, respectively [32].

It is noteworthy that the present study identified low heterogeneity among most analyses, and for those with high heterogeneity, efforts were made to address it. The Baujat analysis identified outlier studies; however, given the observational nature of all included studies, there was no reasonable justification for excluding those studies [33]. Therefore, heterogeneity was explored through leave-one-out sensitivity analysis, revealing 0% heterogeneity when omitting Sanchez et al. [21] in the symptom resolution or clinical improvement analysis, 0% heterogeneity when omitting Gross et al. [5] in the incomplete occlusion following endovascular embolization, and a moderate heterogeneity of 34% when omitting Gross et al. [5] in complete occlusion analysis. Additionally, funnel plot analysis was conducted to assess the potential for publication bias, and no bias was confirmed in any of the explored outcomes, and the quality assessment revealed a low risk of bias in all included studies. To date, this study represents the largest synthesis of the EVT of ACF- dAVFs.

Limitations

Despite low heterogeneity and the exclusion of publication bias, the present study has limitations. The included studies were all observational, mostly from small single-institution experience. Additionally, a small number of cases were included in Onyx subgroup analyses, and different embolizing agents and different approaches were included in the analysis. Also, despite our attempt to qualitatively describe information related to unsuccessful endovascular embolization attempts and incomplete occlusion following embolization cases, it was not possible to statistically analyze whether there were treatment-related, anatomical/grading-related, or embolic agent-related characteristics more or less associated with the undesirable outcomes. Furthermore, the expertise of the physicians may be related to the outcomes included in the analysis. Lastly, despite attempts, subanalyses for each of the included embolizing agents and different approaches were not possible. All these limitations should be considered when interpreting the present study's findings.

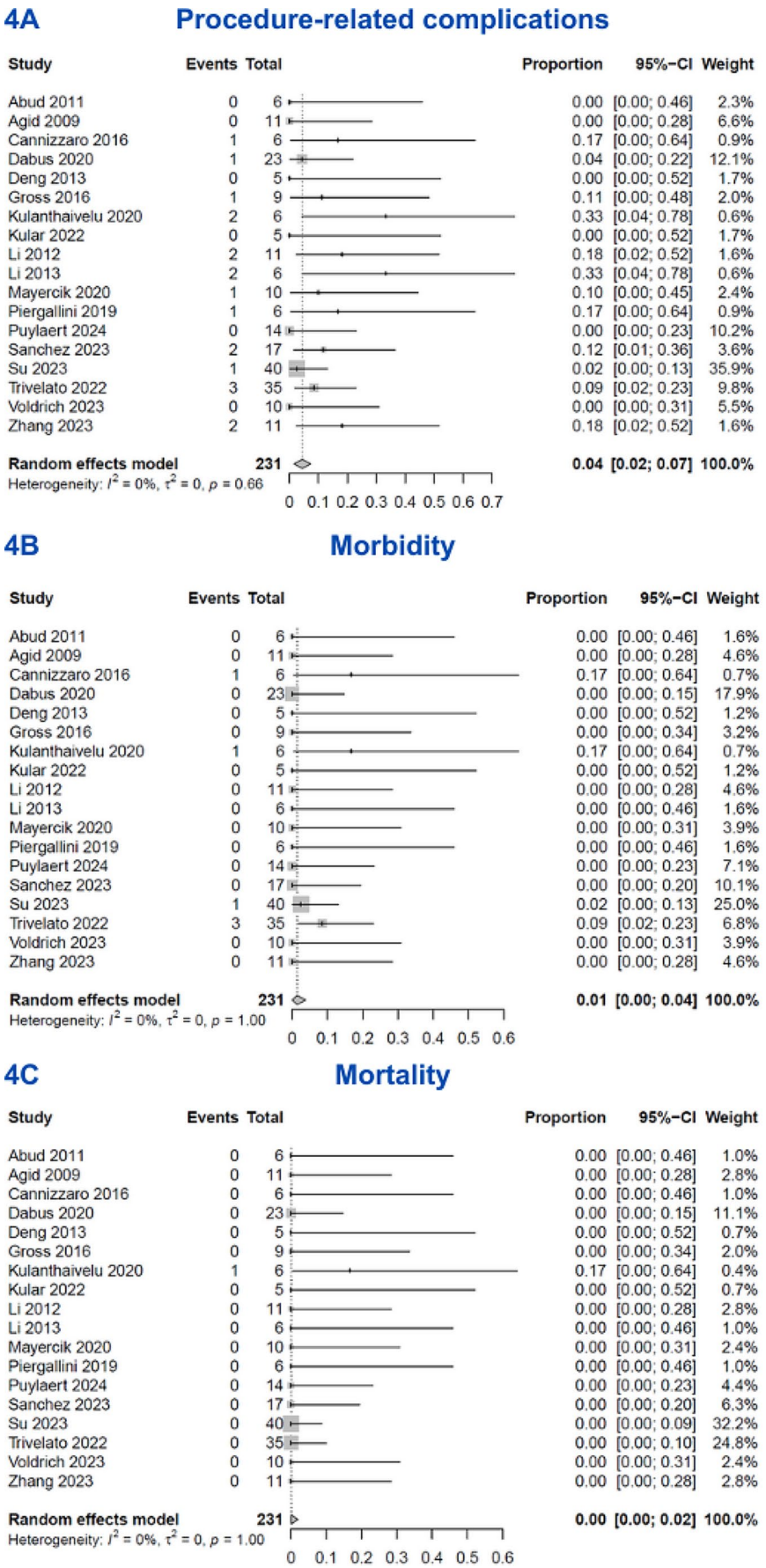


Fig. 4 (**A**) - Procedure-Related Complications in 231 Anterior Cranial Fossa Dural Arteriovenous Fistulas (ACF-dAVFs) following embolization. (**B**) - Morbidity rate in 231 patients with Anterior Cranial Fossa Dural Arteriovenous Fistulas (ACF-dAVFs) following embolization. (**C**) – Mortality rate in 231 patients with Anterior Cranial Fossa Dural Arteriovenous Fistulas (ACF-dAVFs) following embolization

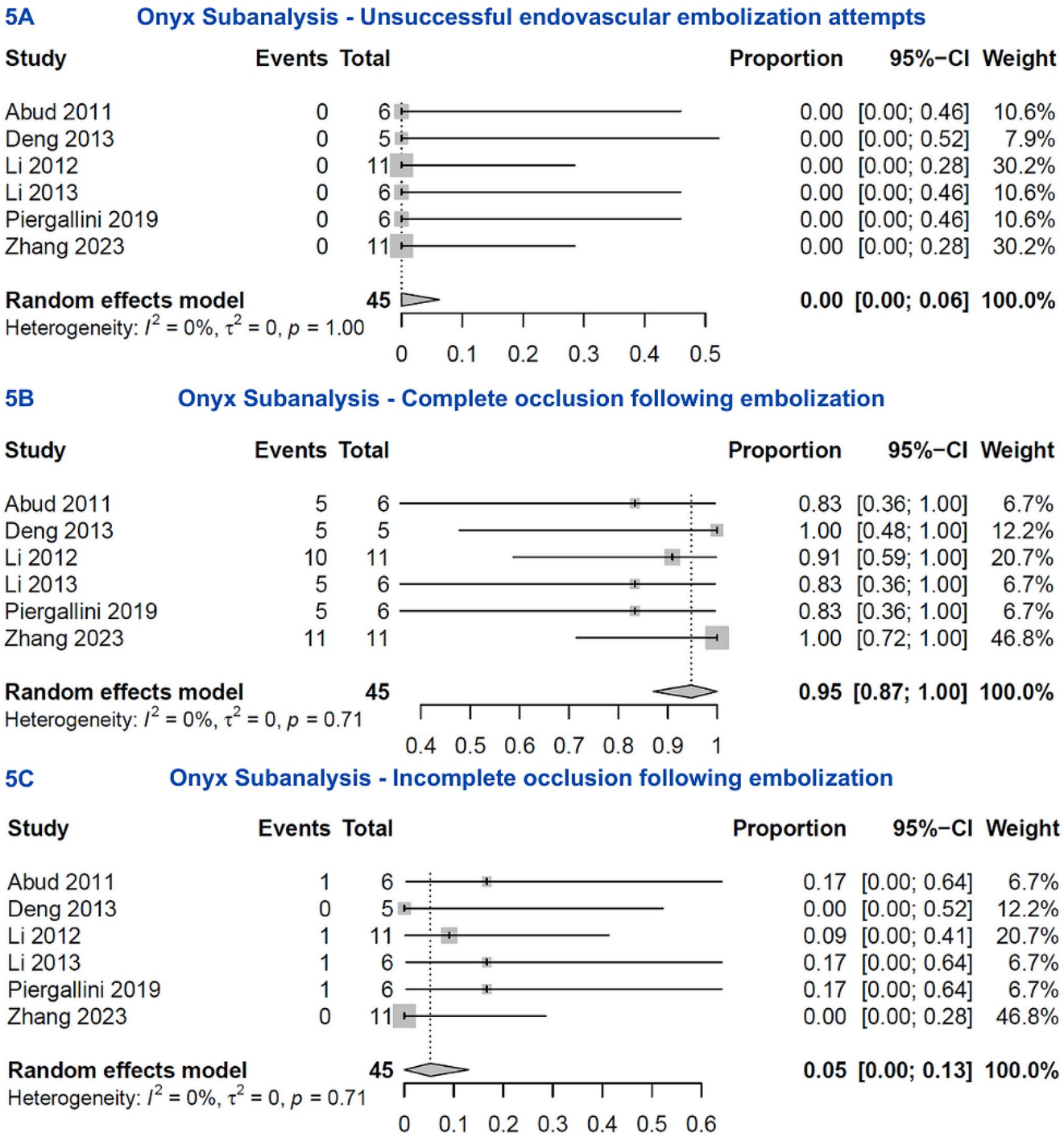


Fig. 5 (**A**) - Unsuccessful endovascular embolization attempts rate in 45 Anterior Cranial Fossa Dural Arteriovenous Fistulas (ACF-dAVFs) treated with Onyx as embolic agent for endovascular embolization showing zero unsuccessful events. (**B**) - Complete Occlusion rate in 45 Anterior Cranial Fossa Dural Arteriovenous Fistulas (ACF-dAVFs) following embolization with Onyx. (**C**) - Incomplete Occlusion rate in 45 Anterior Cranial Fossa Dural Arteriovenous Fistulas (ACF-dAVFs) following embolization with Onyx

Conclusion

This systematic review and meta-analysis revealed that EVT for ACF-dAVFs is highly feasible, effective, and safe, with a low rate of complications and low procedure-related morbidity and mortality. Furthermore, the sub-analyses focusing on studies exclusively utilizing Onyx for embolization demonstrated higher efficacy and safety compared to the findings of the primary analyses involving all included studies.

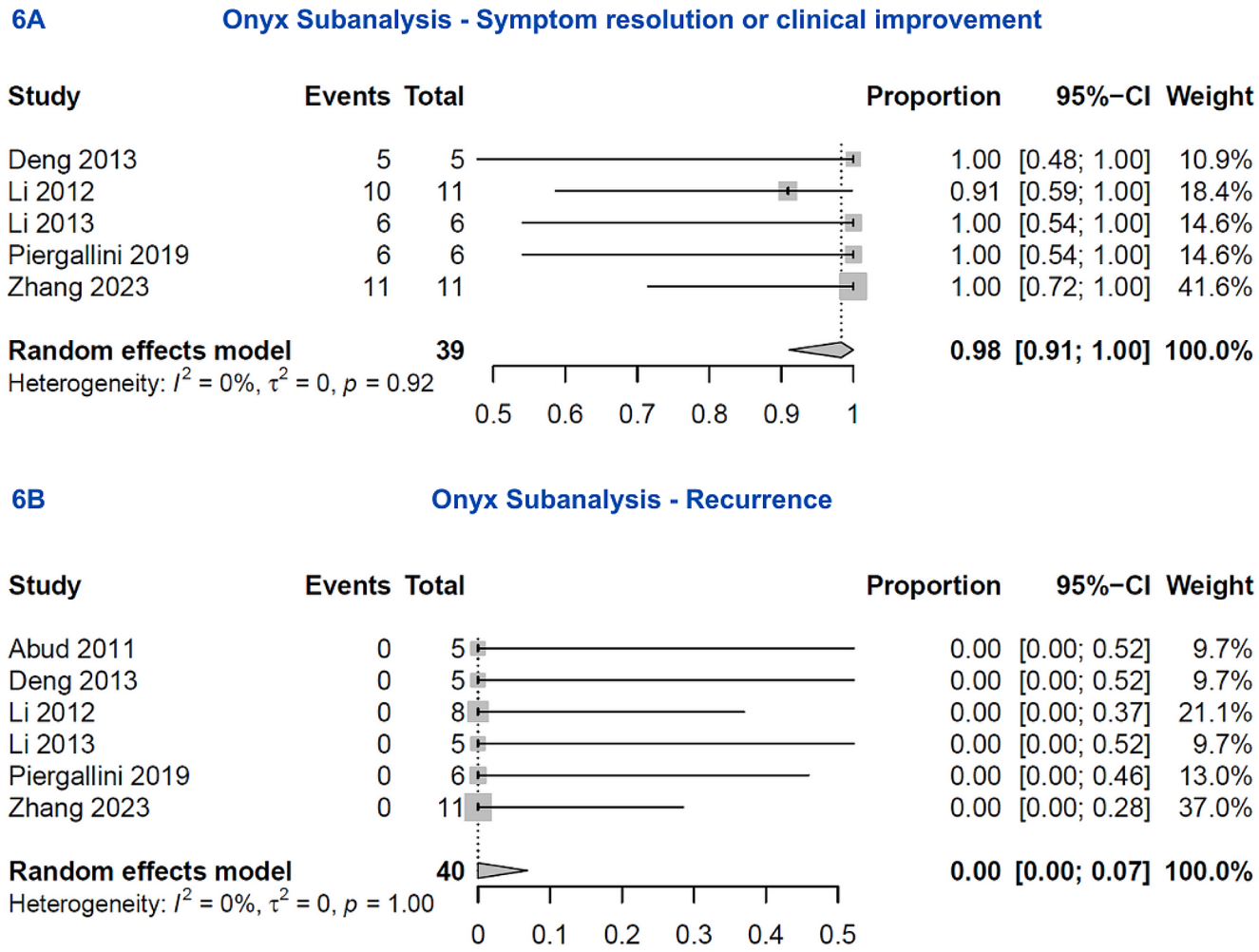


Fig. 6 (**A**) - Symptom Resolution or Clinical Improvement rate in 39 patients with Anterior Cranial Fossa Dural Arteriovenous Fistulas (ACF-dAVFs) following embolization with Onyx. (**B**) - Recurrence rate in 40 Anterior Cranial Fossa Dural Arteriovenous Fistulas (ACF-dAVFs) that were completely occluded following endovascular embolization with Onyx showing zero recurrence events

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Declarations

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