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REVIEW

Outcomes after middle meningeal artery embolization using coils alone for chronic subdural hematoma: A systematic review and single-arm meta-analysis

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Abstract

Coil-only middle meningeal artery embolization (MMAE) remains less well characterized in the literature compared to liquid or particulate embolization for chronic subdural hematoma (cSDH). This systematic review and single-arm meta-analysis summarized clinical, radiographic, procedural, and safety outcomes after coil-only MMAE for cSDH. This systematic review followed PRISMA guidelines. PubMed, Ovid MEDLINE, Web of Science Core Collection, and Scopus were searched for English-language studies evaluating coil-only MMAE for cSDH with ≥5 patients and ≥1 predefined endpoint. Risk of bias was assessed using ROBINS-I. Single-arm random-effects meta-analyses were performed for clinical and radiographic outcomes when sufficient data were available. Anesthetic approach was summarized descriptively. Ten studies comprising 397 patients and 502 embolizations were included. Recurrence was reported in 7 studies comprising 252 patients, with a pooled rate of 4.6% (95% CI, 1.7%–12.1%). Reintervention was reported in 9 studies comprising 345 patients, with a pooled rate of 7.5% (95% CI, 4.5%–12.3%). Procedure-related complications were reported in all 10 studies, with a pooled rate of 1.3% (95% CI, 0.5%–3.0%). Radiographic reduction > 50% was reported in 6 studies comprising 220 patients, with a pooled rate of 76.7% (95% CI, 55.0%–89.8%). Heterogeneity ranged from absent to substantial across outcomes, and 9 of 10 studies were judged to have serious risk of bias. In this meta-analysis based on studies with substantial risk of bias, coil-only MMAE for cSDH was associated with low pooled rates of recurrence, reintervention, and procedure-related complications; however, these estimates should be considered hypothesis-generating rather than definitive evidence. Most included studies were retrospective and nonrandomized, treatment contexts and outcome definitions were heterogeneous, and prediction intervals were wide for several endpoints. Coil-only MMAE may represent a potential anatomy-selective embolization strategy, but current evidence does not establish equivalence, noninferiority, or superiority relative to liquid or particulate embolic agents.

Keywords Chronic subdural hematoma · Middle meningeal artery embolization · Coil embolization · Embolic agent · Systematic review · Meta-analysis

Introduction

Chronic subdural hematoma (cSDH) is an increasingly common neurosurgical condition, with an annual incidence of 1.7–20.6 per 100,000 persons and up to 354.8 per 100,000 in men aged 85 years and older [1, 2]. A predicted 78% increase in prevalence from 2020 to 2040 highlights the need to optimize treatment strategies [3]. One-year mortality has been reported to be 32.9%, and standard surgical management with burr hole drainage or craniotomy is associated with recurrence rates of approximately 10%–11%

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[2, 4]. Middle meningeal artery embolization (MMAE) has emerged as an adjunctive, standalone, or alternative treatment strategy for cSDH [5]. MMAE targets branches of the middle meningeal artery that supply the dural border cell layer and outer hematoma membrane, reducing perfusion to fragile neomembrane neovessels implicated in recurrent bleeding, inflammation, and hematoma persistence [6]. Although several systematic reviews have evaluated MMAE broadly and compared liquid or particulate embolic agents, coil-only MMAE remains less well characterized [7]. Comparative studies suggest that coil embolization may be associated with shorter procedural times and may be useful in selected anatomies, including cases with dangerous anastomoses [8]. This systematic review and single-arm meta-analysis aimed to summarize the available evidence on coil-only MMAE for cSDH. Although comparative effectiveness between coil-only MMAE and liquid or particulate embolization is an important clinical question, the present study was not designed to establish equivalence, noninferiority, or superiority between embolic strategies. The primary outcome was cSDH recurrence after coil-only MMAE. Secondary outcomes included reintervention, procedure-related complications, radiographic hematoma reduction, procedural characteristics, and descriptively reported anesthetic approach.

Methods

In this meta-analysis, the authors followed the PRISMA checklist and the Cochrane Handbook for Systematic Reviews of Interventions, version 6.5 [9, 10]. Because this systematic review and meta-analysis relied exclusively on previously published aggregate data, ethics committee approval, Institutional Review Board approval, and patient informed consent were not required.

Search strategy and study inclusion criteria

A systematic search of PubMed, Ovid MEDLINE, Web of Science Core Collection, and Scopus was conducted on April 13th, 2026, to identify studies evaluating coil-only MMAE for cSDH. Search terms included combinations of “middle meningeal artery,” “MMA,” “embolization,” “coil,” “coil embolization,” “SwiftPAC,” “MicroPlex,” “Axium,” “Nester,” “Interlock,” “Concerto,” “Ruby,” “Target,” “chronic subdural hematoma,” “chronic subdural haematoma,” and “cSDH.” The complete database-specific search strategies are provided in Supplemental Table 1. Reference lists of included studies were manually reviewed for additional eligible studies. Eligible studies included English-language case series or cohort studies reporting clinical or radiographic outcomes after coil-only MMAE for cSDH, with at least five patients and at least one predefined endpoint. Case reports or case series with fewer than five patients, editorials, conference abstracts, review articles, non-English articles, and studies evaluating non-coil MMAE techniques were excluded. Grey literature and preprint servers were not systematically searched. Two reviewers screened titles and abstracts independently, followed by independent full-text review of potentially eligible studies. Disagreements were resolved through discussion with a third reviewer. To assess potential cohort overlap, we examined the included studies for shared author groups, institutions, and patient populations. We found no patient cohort overlaps among the studies.

Data extraction

Two reviewers independently extracted data from the included studies using a standardized template. Extracted baseline variables included study name, first author, publication year, study design, number of patients, number of embolizations, patient demographics, coil platform, vascular access approach, catheter positioning strategy, treatment context, anesthetic modality, and duration of radiographic follow-up. Sex distribution was calculated from studies reporting sex-specific data. Khorasanizadeh et al. did not provide an extractable sex distribution for 12 patients and were therefore excluded from this denominator [11]. Treatment context was categorized as standalone MMAE, adjunctive MMAE after surgical evacuation, prophylactic or upfront embolization, or salvage therapy for persistent or recurrent cSDH.

The predefined outcomes of interest included recurrence, reintervention, procedure-related complications, radiographic response, preoperative and postoperative SDH thickness, midline shift, number of coils deployed, procedural duration, and length of follow-up. Anesthetic variables were extracted as reported by each study, including the number of cases performed under general anesthesia, monitored anesthesia care, and local anesthesia or no general anesthesia. Recurrence was extracted according to each study’s reported definition, including radiographic enlargement or persistence of cSDH, symptomatic recurrence, or investigator-defined treatment failure. When no formal recurrence definition was provided, recurrence was extracted as reported by the original authors. Reintervention was defined as any subsequent procedure performed for persistent, recurrent, or worsening cSDH, most commonly repeat embolization or surgical evacuation. Throughout the manuscript, recurrence refers to study-defined recurrent or persistent cSDH, whereas reintervention refers only to subsequent procedural treatment. Radiographic response

was extracted as reported, including the number of patients achieving > 50% radiographic reduction, when available. Aggregate denominators were calculated only from studies that reported patient or embolization counts for the relevant variable.

Risk of bias assessment

Risk of bias was assessed using the Risk Of Bias In Non-randomized Studies of Interventions tool (ROBINS-I) [12]. Small-study effects were assessed visually using funnel plots. Egger regression and Begg rank correlation tests were performed only for outcomes with at least 10 contributing studies, given the limited reliability of these tests in smaller meta-analyses (Supplemental Fig. 1) [13, 14].

Statistical analysis

All analyses were conducted in R version 4.5.3 (2026-03-11) using the meta package version 8.3.0 and metafor package version 4.8.0 within RStudio version 2026.01.2+418. Analyses were outcome-specific, and studies without extractable data were excluded only from the relevant analysis. Single-arm proportional meta-analyses were performed for recurrence, reintervention, procedure-related complications, and radiographic reduction > 50%; mortality was summarized descriptively. Proportions were modeled using random-effects generalized linear mixed models with a logit link via the metaprop function in the meta package, allowing inclusion of zero-event studies without continuity correction. Pooled estimates were reported with 95% confidence intervals, and prediction intervals were generated when possible. Heterogeneity was assessed using τ^2, χ^2, and I^2 statistics.

Continuous outcomes, including preoperative and postoperative SDH thickness, coils deployed per case, and procedure duration, were analyzed using random-effects models when at least two studies provided extractable means, standard deviations, and sample sizes. Means were pooled using metamean, with between-study variance estimated by restricted maximum likelihood. For studies reporting both pre- and postoperative SDH thickness, mean change was calculated as postoperative minus preoperative thickness. Because paired change-score standard deviations were not reported, they were estimated using a within-patient correlation coefficient of 0.5, with sensitivity analyses using 0.3 and 0.7 (Supplemental Fig. 2A&B). Forest plots were generated using the meta package in R.

Between-study variance in the generalized linear mixed models was estimated by maximum likelihood, as required by the GLMM implementation. Leave-one-out influence analyses were performed for recurrence and reintervention by sequentially omitting each study and refitting the model, with pooled estimates, τ^2, and I^2 recorded at each iteration.

Results

The search identified 160 records, of which 103 were duplicates. After title and abstract screening of 57 records, 30 full-text articles were reviewed and 20 were excluded, leaving 10 studies for final inclusion (Fig. 1) [8, 11, 15–22].

Characteristics of included studies of meta-analysis

The final review included 10 studies published between 2021 and 2026, comprising 397 patients and 502 embolization procedures (Table 1). Included studies were case series or retrospective cohort studies, with cohort sizes ranging from 10 to 91 patients. Coil platforms and treatment contexts varied across studies, including standalone MMAE, adjunctive MMAE after surgery, prophylactic postoperative embolization, salvage therapy, and targeted branch embolization. Reported mean radiographic follow-up ranged from 52 to 170 days.

Radiographic and clinical outcome reporting was heterogeneous (Table 2). Recurrence was available in 7 studies comprising 252 patients, reintervention in 9 studies comprising 345 patients, procedure-related complications in all 10 studies comprising 397 patients, and mortality in 3 studies comprising 163 patients. Procedural variables are summarized in Table 3. Anesthetic approach was reported in 8 studies comprising 333 patients, and coil deployment was reported in 4 studies (Table 4).

Clinical outcomes

Random-effects single-arm meta-analyses examined recurrence, mean number of coils used per procedure, reintervention, and any procedure-related complications (Fig. 2). Recurrence was documented in 7 studies with 252 patients, resulting in 21 recurrence events. The pooled recurrence rate was 4.6% (95% CI, 1.7%–12.1%), with a 95% prediction interval of 0.4%–34.5%. Moderate heterogeneity was observed ($\tau^2 = 0.6698$; $\chi^2 = 10.59$, df = 6, $p = 0.1019$; $I^2 = 43.3\%$) (Fig. 2A). Mortality was reported in 3 studies comprising 163 patients, with 9 total deaths or hospice transitions. Seven of these events were reported by Iyer et al. and were described by the original authors as unrelated to the treated cSDH or MMAE procedure [18]. Given the influence of a single cohort, we did not interpret all-cause mortality as a procedure-specific safety endpoint. Reintervention was reported in 9 studies with 345 patients, with 29 events. The pooled reintervention rate was 7.5% (95% CI, 4.5%–12.3%),

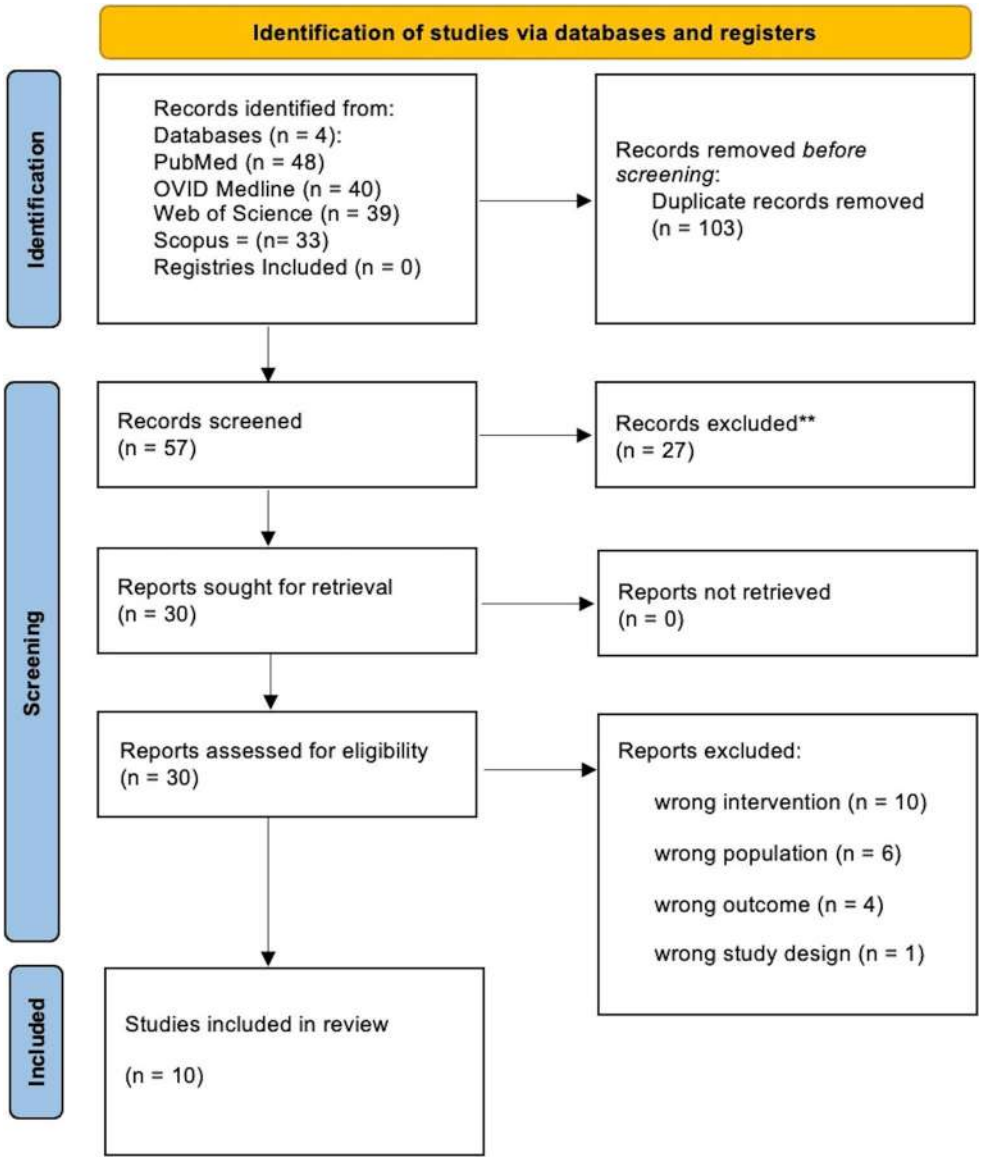


Fig. 1 PRISMA 2020 flow diagram for study identification, screening, eligibility assessment, and inclusion. Searches of PubMed, Ovid MEDLINE, Web of Science Core Collection, and Scopus identified 160 records; no records were identified from registries. After removal of 103 duplicate records, 57 records underwent title and abstract screening, of which 27 were excluded. Thirty full-text reports were sought and assessed for eligibility; none were unavailable. Twenty unique reports were excluded for reasons related to intervention, population, outcome, or study design; one report met two exclusion criteria and is represented in two exclusion categories. Ten studies were included in the systematic review and meta-analysis

with a prediction interval of 2.8%–18.6%. No significant heterogeneity was detected ($\tau^2 = 0.1233$; $\chi^2 = 7.78$, df = 8, $p = 0.4554$; $I^2 = 0.0\%$), although the confidence interval around I^2 is likely wide given the small number of included studies (Fig. 2C). While Ashraf et al. observed a higher crude reintervention rate compared to other cohorts, the statistical heterogeneity was low ($I^2 = 0\%$). This probably indicates that the estimates at the study level, especially in smaller cohorts with few events, are imprecise. This leads to a small Cochran Q relative to its degrees of freedom. Therefore, an I^2 of 0% does not necessarily indicate clinical homogeneity. All 10 studies, including 397 patients with 5 events, reported on any procedure-related complication. The pooled complication rate was 1.3% (95% CI, 0.5%–3.0%), with a prediction interval of 0.5%–3.4%. Heterogeneity was absent ($\tau^2 = 0$; $\chi^2 = 2.13$, df = 9, $p = 0.9893$; $I^2 = 0.0\%$) (Fig. 2D).

Radiographic outcomes

Six studies comprising 220 patients reported radiographic reduction > 50%, with 139 patients reaching this endpoint (Fig. 3A). The combined proportion was 76.7% (95% CI, 55.0%–89.8%), and the 95% prediction interval ranged from 14.3% to 98.5%. Heterogeneity was significant ($\tau^2 = 1.0878$; $\chi^2 = 15.41$, df = 5, $p = 0.0088$; $I^2 = 67.6\%$) (see Fig. 3A). Preoperative SDH thickness was pooled from 8 studies including 368 patients, with an average of 15.6 mm (95% CI, 14.0–17.1 mm) and a prediction interval of 10.7–20.4 mm. Heterogeneity was substantial ($\tau^2 = 3.6761$; $\chi^2 = 26.02$, df = 7, $p = 0.0005$; $I^2 = 73.1\%$) (see Fig. 3B). Postoperative SDH thickness was pooled from 3 studies with 65 patients, showing an average of 6.0 mm (95% CI, 3.0–9.0 mm). Given the small number of contributing studies

Table 1 Characteristics of the studies included in the coil-only middle meningeal artery embolization (MMAE) review. The table details study design, cohort size, number of embolizations, coil platform(s) employed, laterality of treated arteries, therapeutic context (up-front, prophylactic after surgery, salvage, or isolated MMAE), and mean radiological follow-up. Abbreviations: L = left, NR = not reported, R = right, MMA = middle meningeal artery, SDH = subdural hematoma

Study	Design	Patients (*n*)	Embolization (*n*)	Coil Type	Laterality (*R* / L / Bilateral)	Treatment	Follow-up (days)
Wei et al. 2021	Case series	10	10	MicroPlex & Axium	0/0 /10	Bilateral MMA embolization + bilateral burr-hole drainage	170
Webb et al. 2025	Case series	23	31	SwiftPAC	10/5/8	MMAE alone: 7(30.43%) Surgery+MMAE: 16(69.56%)	54
Khorasanizadeh et al. 2022	Case series	12	12	Helical	NR	Upfront MMAE: 11/12 (91.7%)	84.5
Abramyan et al. 2025	Cohort	52	71	Stryker Target Tetra/Nano; Penumbra Ruby; Kaneka i-ED	NR	Upfront: 34/71 (48%) Prophylactic post-surgery: 31/71 (44%) Salvage: 6/71 (8%)	91
Iyer et al. 2023	Case Series	45	45	Nester coils & Axium coils	11/8/23	Coil-only MMAE	158
Perng et al. 2024	Case series	27	27	Interlock (Boston Scientific) & MicroNester (Cook)	NR	Coil-only MMAE of main trunk	NR
Fecker et al. 2025	Cohort	88	88	Conerto (Medtronic) & Stryker Target Tetra/Nano	16/46/26	Coil-only MMAE	52
Boulter et al. 2025	Cohort	19	25	Stryker Target Tetra/Nano & Phenox-Wallaby Pico	NR	Proximal MMAE with coils	97
Ashraf et al. 2025	Cohort	91	150	MicroNester (Cook)	24/28/38	proximal MMA trunk or more distal branch including frontal or parietal branch	70
Hoffman et al. 2026	Cohort	30	43	Detachble coils (Smartcoils Extra Soft)	unilateral − 10 bilateral − 20	Coil-only MMAE targeting proximal frontal and parietal MMA branches with detachable coils	165

Table 2 Radiographic status at baseline and after coil-only middle meningeal artery embolization (MMAE), with key clinical outcomes. Columns list pre-operative subdural hematoma (SDH) thickness and midline shift (MLS), corresponding post-operative values, number of cases achieving ≥ 50% radiographic improvement, and counts of recurrence, re-intervention, any procedure-related complication, and mortality reported by each study. NR = not reported; mm = millimeters

Study	Preop SDH thickness (mm)	Preop MLS (mm)	Postop SDH Thickness (mm)	Post Procedure Midline Shift mm	Partial (> 50%) Radiographic Improvement	Recurrence	Reintervention	Any complication	Mortality
Wei et al. 2021	NR	NR	NR	NR	NR	0	0	0	NR
Webb et al. 2025	18.6	3.7	5.24	0.25	19	1	1	0	NR
Khorasanizadeh et al. 2022	14.5	2.7	8.7	NR	10	0	1	0	NR
Abramyan et al. 2025	15.52	NR	1.92	NR	NR	2	NR	0	NR
Iyer et al. 2023	20	6	NR	NR	22	1	3	0	7
Perng et al. 2024	14.1	3.5	NR	NR	NR	NR	3	1	NR
Fecker et al. 2025	15	NR	5	NR	NR	NR	5	1	1
Boulter et al. 2025	NR	NR	NR	NR	19	1	1	1	NR
Ashraf et al. 2025	16	4	NR	NR	46	16	14	1	NR
Hoffman et al. 2026	12	NR	3.6	NR	23	NR	1	1	1

and high heterogeneity, this estimate should be interpreted descriptively rather than as a stable pooled radiographic benchmark. Heterogeneity was high ($\tau^2 = 6.1902$; $\chi^2 = 20.74$, df = 2, $p < 0.0001$; $I^2 = 90.4\%$) (see Fig. 3C). The mean change in SDH thickness was assessed in 3 studies and should be considered exploratory. Because paired change-score standard deviations were not reported, the primary analysis assumed a within-patient correlation coefficient of 0.5. Change was calculated as postoperative minus preoperative thickness, so negative values indicated reductions. The pooled mean change was −9.1 mm (95% CI, −13.5 to −4.8 mm; $p < 0.0001$), with a prediction interval of −27.7 to 9.4 mm. Heterogeneity was significant ($\tau^2 = 13.6887$; $\chi^2 = 26.91$, df = 2, $p < 0.0001$; $I^2 = 92.6\%$) (Fig. 3D). Given the

Table 3 Procedural details reported in studies of coil-only middle meningeal artery embolization (MMAE). Listed are the number of patients treated, anesthetic modality used—general anesthesia (GA), monitored anesthesia care (MAC), or local anesthesia without GA—together with the mean number of coils deployed per case and the average procedure duration when available. NR = not reported

Study	Patients	GA	MAC	No-GA (local)	Mean coils per case	Time of Procedure (min)
Wei et al. 2021	10	0	0	10	NR	52.9
Webb et al. 2025	23	21	2	0	2.5	37
Khorasanizadeh et al. 2022	12	NR	NR	NR	NR	NR
Abramyan et al. 2025	52	NR	NR	NR	1.96	NR
Iyer et al. 2023	45	12	31	2	3	52.3
Perng et al. 2024	27	0	0	27	NR	NR
Fecker et al. 2025	88	35	53	0	NR	NR
Boulter et al. 2025	19	0	19	0	NR	NR
Ashraf et al. 2025	91	14	77	0	NR	36
Hoffman et al. 2026	30	30	0	0	3	NR

small number of studies and wide prediction interval, this analysis should be interpreted descriptively rather than as a definitive estimate of radiographic treatment effect.

Anesthetic approach and coil-use

Eight studies involving 333 patients reported on an anesthetic approach. General anesthesia was used in 112/333 patients, while non-general anesthesia was used in 221/333 patients, including monitored anesthesia care in 182/333 and local anesthesia or no general anesthesia in 39/333. Because anesthetic approach likely reflects institutional practice patterns, operator preference, patient selection, and procedural workflow rather than a treatment effect, these data were summarized descriptively rather than interpreted as a pooled treatment effect. Overall, the available data suggest that coil-only MMAE was frequently performed without general anesthesia, although anesthesia selection varied substantially across studies. Coil deployment was reported descriptively across 4 studies, ranging from 1.96 to 3.0 coils per case. Only 2 studies, comprising 68 patients, provided extractable means, standard deviations, and sample sizes required for quantitative pooling (Fig. 2B). Among these studies, the pooled mean number of coils deployed per case was 2.8 (95% CI, 2.3–3.3). However, heterogeneity was substantial ($\tau^2 = 0.1030$; $\chi^2 = 5.68$, df = 1, $p = 0.0171$; $I^2 = 82.4\%$), and the prediction interval was wide (−2.3 to 7.9), reflecting substantial uncertainty. Given the small number of contributing studies and between-study variability, this estimate should be interpreted descriptively rather than as a stable pooled procedural benchmark.

Risk of bias and publication bias

The risk-of-bias assessment identified important methodological limitations across the included studies (Fig. 4). Overall risk of bias was judged to be serious in 9 of 10 studies, with one study rated as moderate. The most common concerns were bias due to confounding and participant selection, reflecting the retrospective, observational, and nonrandomized nature of the available evidence.

Funnel plots were generated for recurrence, reintervention, radiographic improvement > 50%, and any complication (Supplemental Fig. 1). Formal testing for funnel plot asymmetry was performed only on complications reported in all 10 studies. Egger regression did not demonstrate significant funnel plot asymmetry ($p = 0.392$), and Begg rank correlation testing was also nonsignificant (Kendall's tau = 0.244; $p = 0.381$). However, these findings should be interpreted cautiously because funnel plot asymmetry tests have limited power when few studies are included. In addition, the available evidence consisted predominantly of small retrospective case series and observational cohorts.

Leave-one-out analyses are summarized in Supplemental Tables 2 & 3. Omission of any single study other than Ashraf et al. changed the pooled recurrence rate by less than 1% point (range, 4.3%–5.5%) and the pooled reintervention rate by less than 1% point (range, 7.0%–8.2%). Omission of Ashraf et al. reduced the pooled recurrence rate to 3.1% (95% CI, 1.3%–7.2%) and the pooled reintervention rate to 5.9% (95% CI, 3.6%–9.6%), with τ^2 falling to zero for both outcomes. Ashraf et al. reported the highest study-level event rates, and their exclusion lowered rather than raised the pooled estimates.

Discussion

In this systematic review and single-arm meta-analysis, coil-only MMAE for cSDH was associated with low pooled clinical event rates. Recurrence occurred in 21 of 252 patients, with a pooled rate of 4.6% (95% CI, 1.7%–12.1%); reintervention occurred in 29 of 345 patients, with a pooled rate of 7.5% (95% CI, 4.5%–12.3%); and procedure-related complications occurred in 5 of 397 patients, with a pooled rate of 1.3% (95% CI, 0.5%–3.0%). However, because the

Table 4 Aggregate patient- and procedure-level characteristics across the 10 included coil-only MMAE studies. Data are presented as totals or means among patients with available information. Variables include total embolizations, sex distribution, mean age, presenting symptoms, proportion receiving anticoagulation or antiplatelet therapy, vascular access site, laterality of treatment, anesthetic modality, mean coils deployed per case, and average procedural duration. Denominators (n/N) indicate the number of patients or embolizations contributing data for each variable

Characteristics (no. of patients who for whom information was avaliable)	Value (among patients with available data)
Total embolizations	502
Total patients (n)	397
Male (n)	275/385
Female (n)	110/385
Mean age, range (years)	72 (63–78)
Symptoms	Total, n/N (%)
Headache	46/124 (37)
Weakness in limbs	8/124 (6)
Altered Mental Status	26/124 (21)
Gait	45/124 (36)
Seizures	5/124 (4)
Anticoagulation/Antiplatelet use (n/N)	133/322
Access category	Embolizations, n/N (%)
Femoral a. only	109/228 (48)
Radial a. only	116/228 (51)
Ulnar	3/228 (1)
Laterality	Total embolizations, n/N (%)
Left	87/298 (29)
Right	61/298 (20)
Bilateral	150/298 (50)
Anesthesia data available, n	Total Patients, n/N (%)
General anesthesia, n/N (%)	112/333 (34%)
MAC, n/N (%)	182/333 (55%)
Local anesthesia, n/N (%)	39/333 (12%)
Non-GA anesthesia, n/N (%)	221/333 (66%)
Coils per case, mean (range)	2.56 (1.96–3.0)
Time of Procedure (min) ($n = 169$), mean (range)	44.6 (36-52.9)

Total patient count reflects studies with reported patient denominators only. One included study did not report patient number and was excluded from aggregate patient-level totals. GA = General anesthesia; MAC = Monitored anesthesia care

available evidence is single-arm and heterogeneous, these findings should be interpreted as hypothesis-generating rather than comparative evidence of equivalence to liquid or particulate embolics. Rather than positioning coil-only MMAE as a universal alternative, the available evidence supports its potential role as an anatomy-selective strategy when controlled proximal occlusion is preferred, including cases with dangerous anastomoses, tortuous anatomy, or concern for unintended distal embolization.The present analysis should not be interpreted as evidence that coil-only MMAE is equivalent or noninferior to liquid or particulate embolization; these findings should instead be viewed as a descriptive summary of coil-only MMAE outcomes and as a basis for future prospective comparative studies.

Coil-only recurrence, reintervention, and safety outcomes in context

Contemporary MMAE evidence is increasingly supported by randomized trials, although these studies largely evaluate liquid or particulate embolics rather than coil-only embolization. EMBOLISE and STEM showed reduced recurrence, progression, or treatment failure with adjunctive liquid MMAE, whereas MAGIC-MT showed similar 90-day symptomatic recurrence or progression and EMPROTECT showed a nonsignificant reduction in 6-month recurrence after particle embolization [5, 6, 23, 24]. These trials support the broader role of MMAE in cSDH management but should not be interpreted as direct evidence for coil-only MMAE, because liquid and particulate embolics aim to achieve more distal penetration of the MMA branches and neomembrane vascular supply. In contrast, coil-only MMAE primarily provides mechanical proximal or branch-level occlusion and may be selected when distal embolization is less desirable, such as in cases with dangerous anastomoses or concern for unintended embolic migration. In a meta-analysis of these four trials, Xi et al. reported that MMAE reduced treatment failure compared with conventional management (RR 0.55, 95% CI, 0.41–0.74; $P < 0.001$), without significant differences in serious adverse events, mortality, or imaging-based outcomes [25]. While randomized MMAE data elucidate the effectiveness of embolization as a treatment strategy for cSDH, these randomized trials do not establish the comparative effectiveness of coil-only embolization.

Although direct comparison is not possible from the present single-arm analysis, Gupta et al. reported pooled recurrence rates of 7% for PVA, 5% for nBCA, and 7% for EVOH embolization [7]. The 4.6% pooled recurrence rate observed in the present coil-only analysis is numerically similar, but cross-study comparisons are limited by differences in patient selection and treatment context. More directly relevant are comparative observational studies of coil-only MMAE. Ashraf et al. compared Nester pushable coils with Onyx in a multicenter propensity score-matched cohort, and Fecker et al. compared coil-only MMAE with particle or liquid embolic agents [8, 20]. Both studies reported broadly comparable safety and effectiveness signals across embolic strategies, although treatment selection remained nonrandomized and likely reflected anatomy, operator preference, and institutional practice. These findings align with the low recurrence, reintervention, and complication rates observed in the present single-arm analysis but should be interpreted

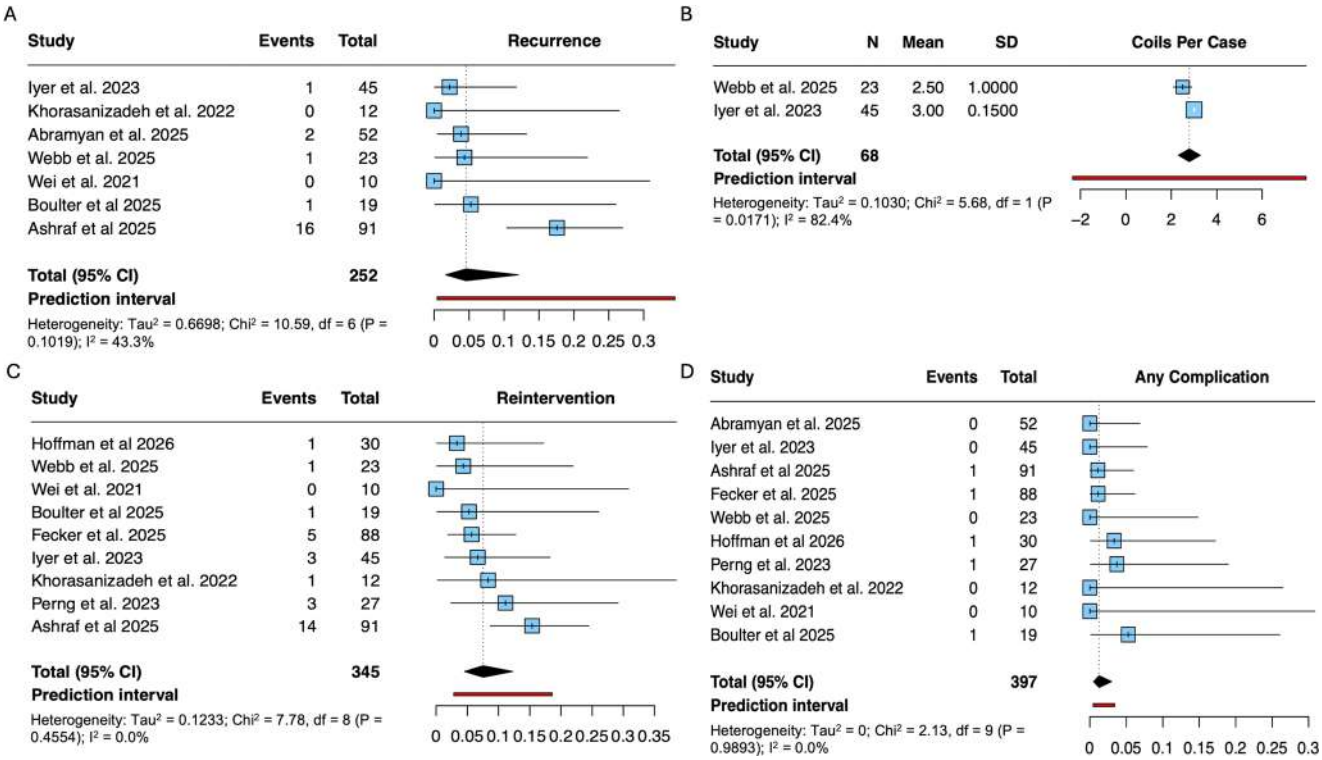


Fig. 2 Random-effects meta-analyses of clinical and procedural outcomes after coil-only middle meningeal artery embolization (MMAE) for chronic subdural hematoma. (**A**) Recurrence (7 studies, $n = 252$); (**B**) pooled mean number of coils deployed per case (2 studies, $n = 68$); (**C**) reintervention (9 studies, $n = 345$); and (**D**) any procedure-related complication (10 studies, $n = 397$). For proportional outcomes, study-level proportions are displayed as blue squares scaled to inverse-variance weight, with horizontal lines representing 95% confidence intervals. For the continuous coil-use outcome, study-level means are displayed with corresponding 95% confidence intervals. Pooled random-effects estimates are shown as black diamonds, with red bars indicating 95% prediction intervals where applicable. τ^2, χ^2, and I^2 values beneath each plot quantify between-study heterogeneity

as hypothesis-generating rather than evidence of equivalence or noninferiority.

Reintervention may be more clinically reliable than recurrence in the available literature. Recurrence definitions varied across studies and included radiographic enlargement, symptom recurrence, or clinician-judged failure, whereas reintervention reflects a concrete escalation of care. In this analysis, reintervention showed no meaningful heterogeneity, while recurrence showed moderate heterogeneity and a broad prediction interval. Treatment context is also important because standalone MMAE, adjunctive postoperative embolization, prophylactic or upfront embolization, and salvage therapy likely involve different baseline risks and should not be interpreted as interchangeable settings.

The pooled procedure-related complication rate was low at 1.3% (95% CI, 0.5%–3.0%; $I^2 = 0.0\%$), with 5 events among 397 patients. Coil-only MMAE should be viewed as a selective strategy rather than a replacement for liquid or particle embolization. Coils may be useful when controlled proximal occlusion is preferred, such as in patients with dangerous anastomoses, tortuous anatomy, or concern for unintended distal embolization. Liquid or particle agents may remain preferable when distal penetration is safe and technically feasible. Therefore, embolic choice should be individualized based on vascular anatomy, treatment context, operator experience, and device availability.

Radiographic response and hematoma resolution

Coil-only MMAE was associated with substantial radiographic hematoma reduction in this review. Among 6 studies comprising 220 patients, the pooled proportion achieving > 50% radiographic reduction was 76.7% (95% CI, 55.0%–89.8%). In studies with extractable thickness data, the pooled mean SDH thickness was 15.6 mm preoperatively and 6.0 mm postoperatively. In an exploratory paired change analysis limited to 3 studies, mean SDH thickness decreased by 9.1 mm; however, this estimate should be interpreted cautiously because paired change-score standard deviations were not directly reported and were estimated using an assumed within-patient correlation. These findings are broadly consistent with prior MMAE literature showing frequent hematoma reduction

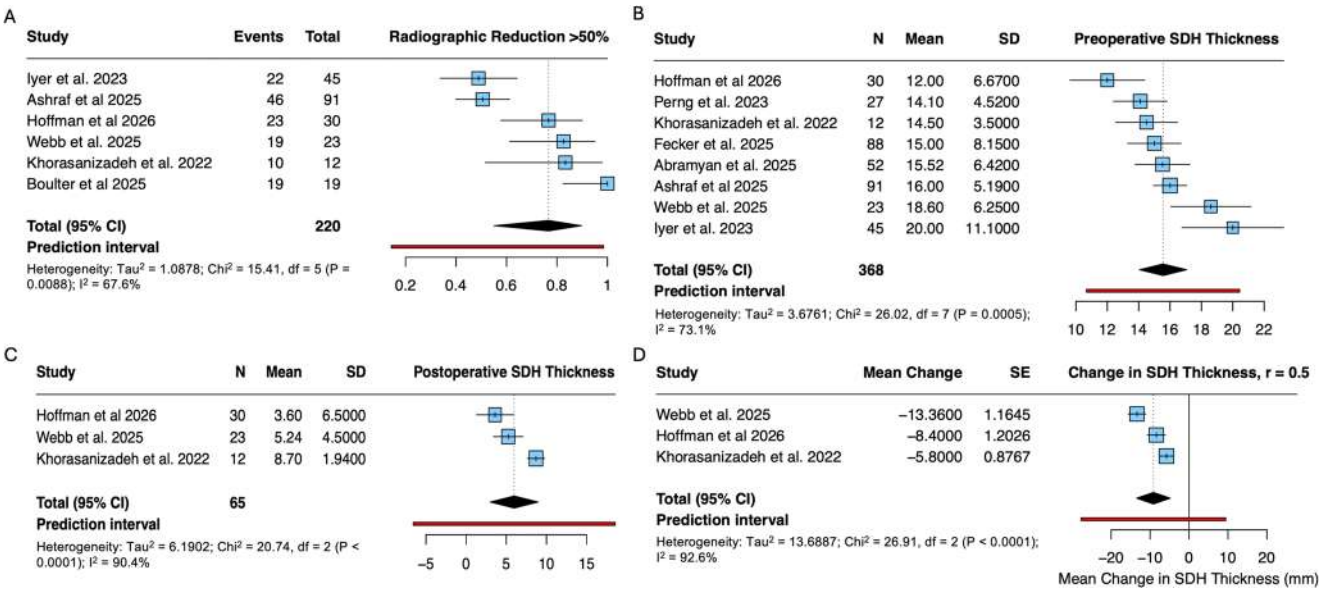


Fig. 3 Random-effects meta-analysis of radiographic outcomes after coil-only middle meningeal artery embolization (MMAE) for chronic subdural hematoma. (**A**) Proportion of patients achieving > 50% radiographic reduction at follow-up (6 studies, $n = 220$). (**B**) Pooled mean preoperative subdural hematoma (SDH) thickness (8 studies, $n = 368$). (**C**) Pooled mean postoperative SDH thickness (3 studies, $n = 65$). (**D**) Mean change in SDH thickness, calculated as postoperative minus preoperative thickness, using an assumed within-patient correlation coefficient of 0.5 to estimate change-score standard deviations (3 studies, $n = 65$ paired observations). Negative values indicate reduction in SDH thickness after treatment. Study-level estimates are shown as weighted blue squares with 95% confidence intervals, and pooled random-effects estimates are shown as black diamonds. Red horizontal bars indicate 95% prediction intervals where estimable. τ^2, χ^2, and I^2 statistics quantify between-study heterogeneity

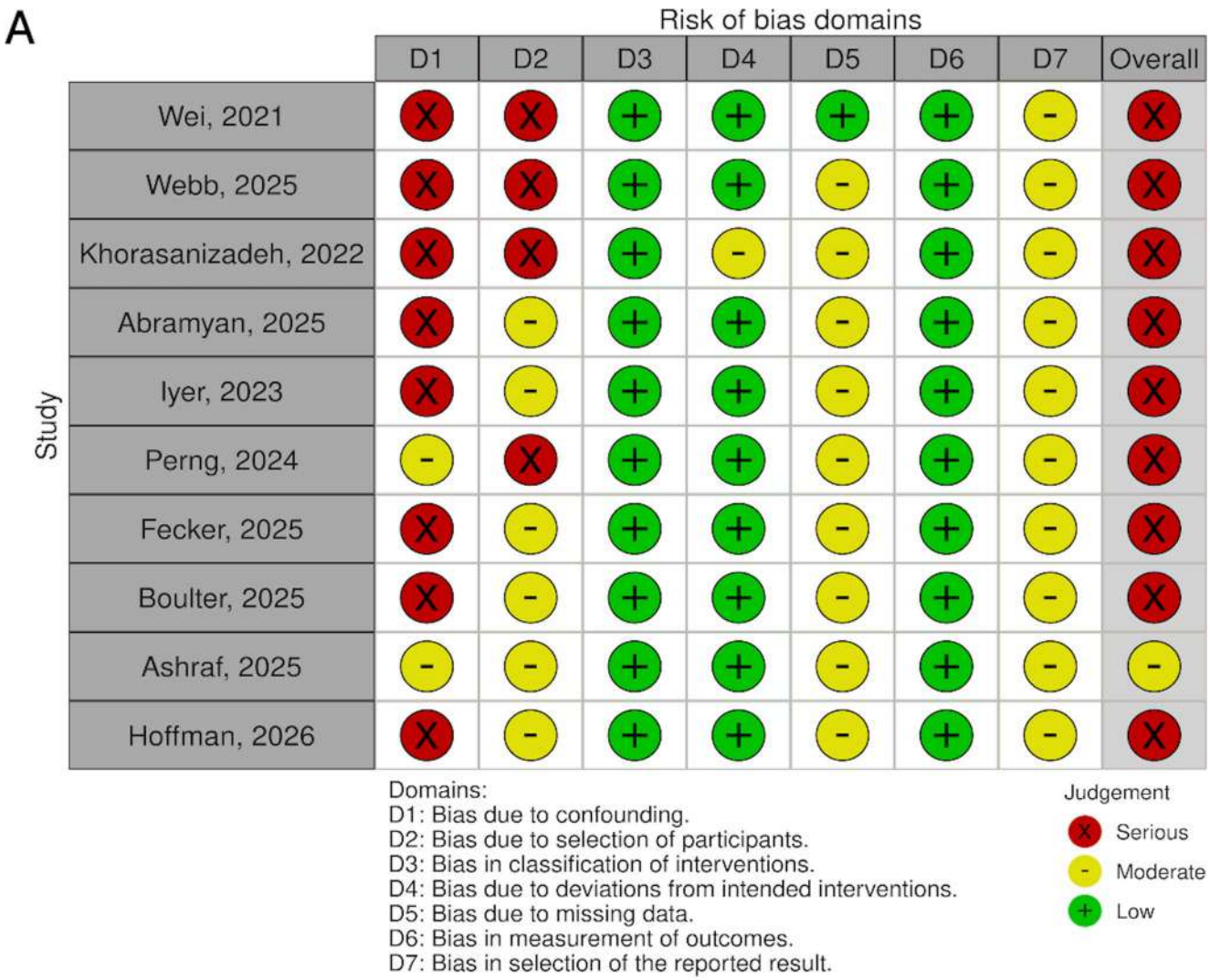
after embolization. In a multicenter mixed-agent cohort, Kan et al. reported that 70.8% of patients achieved > 50% imaging improvement, with median hematoma thickness decreasing to 4 mm at last follow-up [26]. Khorasanizadeh et al. similarly reported ≥ 50% volumetric reduction in 79.6% of hematomas after upfront MMAE [11]. Available comparative data also suggest that coil-only MMAE can produce radiographic resorption comparable to liquid or particle embolization in selected cohorts, although these findings remain observational and subject to selection bias [20]. Therefore, the present results support a favorable radiographic signal after coil-only MMAE but do not establish radiographic equivalence or superiority compared with other embolic agents.

Radiographic outcomes were heterogeneous. For > 50% reduction, I^2 was 67.6%, and the prediction interval ranged from 14.3% to 98.5%. Mean change in SDH thickness showed even greater heterogeneity (I^2 = 92.6%; prediction interval, − 27.7 to 9.4 mm). This variability likely reflects differences in imaging follow-up duration. Imaging endpoints following MMAE are time-dependent [27]. The present findings indicate that the mean-change estimate should be interpreted cautiously, as it was based on only three studies, and the paired change-score standard deviations were estimated assuming a within-patient correlation coefficient of 0.5 rather than directly reported.

Radiographic improvement should not be interpreted in isolation. In the Kan et al. multicenter series, imaging improvements were observed more often than documented clinical improvements, highlighting that hematoma reduction and symptomatic recovery are connected but not clinically synonymous [26].

Anesthetic considerations

Anesthetic approach is an important consideration in MMAE because cSDH disproportionately affects older patients with frailty and multimorbidity [28]. Salem et al. found no significant differences in complications, surgical rescue, radiographic, or functional outcomes between general and nongeneral anesthesia for MMAE [29]. In our review, anesthesia data were available in 8 studies comprising 333 patients: general anesthesia was used in 112 patients, monitored anesthesia care in 182, and local anesthesia or no general anesthesia in 39. These data suggest that coil-only MMAE was frequently performed without general anesthesia, although anesthesia selection likely reflected institutional workflow, operator preference, patient selection, and procedural context. Because coils provide mechanical occlusion and do not require DMSO-compatible delivery systems or distal liquid embolic penetration, coil-only MMAE may be technically practical in selected anatomic or institutional settings.



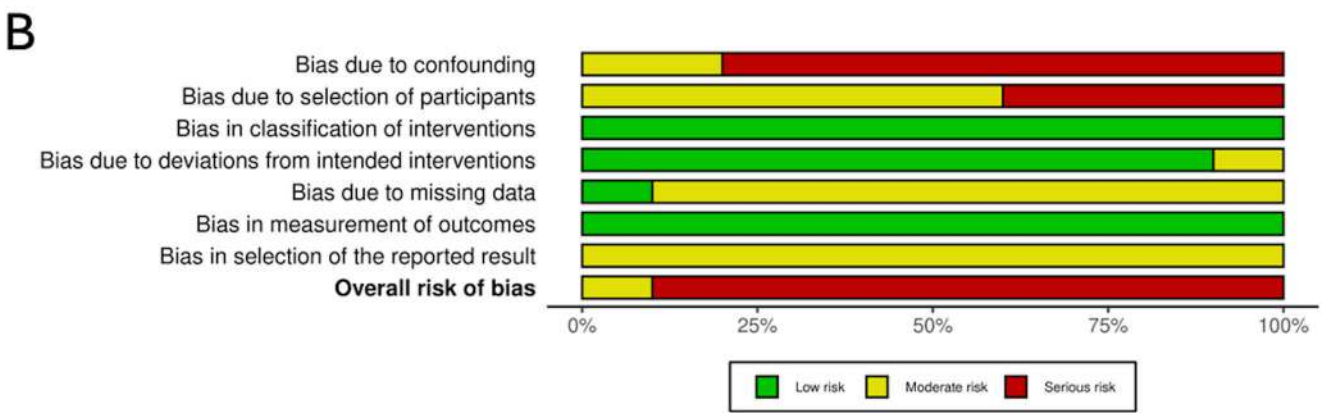


Fig. 4 Risk-of-bias assessment using ROBINS-I. Risk of bias was assessed for included nonrandomized studies using the ROBINS-I tool. (**A**) Traffic-light plot showing domain-level and overall risk-of-bias judgments for each included study. Domains assessed included bias due to confounding, selection of participants, classification of interventions, deviations from intended interventions, missing data, measurement of outcomes, and selection of the reported result. (**B**) Weighted summary plot showing the proportion of studies rated as low, moderate, or serious risk of bias across each domain and overall. Most studies were judged to have serious overall risk of bias, primarily due to confounding and selection-related concerns inherent to retrospective observational designs

Caution regarding certainty of evidence

The certainty of evidence supporting coil-only MMAE remains limited. Nine of the ten included studies were judged to have serious overall risk of bias, primarily because of confounding, participant selection, retrospective design, and nonrandomized treatment selection. These limitations are clinically important because coil-only embolization may have been selected based on vascular anatomy, dangerous anastomoses, operator preference, institutional workflow, patient comorbidity, or treatment context rather than random allocation.

Therefore, the pooled estimates in this review should be interpreted as low-certainty, hypothesis-generating evidence rather than definitive estimates of treatment effect. Current data should not independently guide embolic agent selection or be interpreted as evidence of equivalence or noninferiority compared with liquid or particulate embolization. Instead, these findings should inform the design of future prospective registries and comparative studies with standardized endpoints, stratification by treatment context, and careful adjustment for anatomic and clinical selection factors.

Limitations

This study has several limitations. The available evidence for coil-only MMAE remains limited, retrospective, nonrandomized, and at serious risk of bias; therefore, pooled estimates should be interpreted as descriptive and hypothesis-generating rather than evidence of comparative efficacy. Confounding by indication is likely because coils may have been selected based on vascular anatomy, high-risk anastomoses, operator preference, anesthesia considerations, institutional workflow, patient comorbidity, or treatment context. Clinical heterogeneity was also substantial, as included studies evaluated coil-only MMAE across diverse settings, including standalone embolization, adjunctive treatment after surgical evacuation, prophylactic postoperative embolization, and salvage therapy for recurrent or persistent cSDH. These populations likely differ in baseline risks of recurrence, reintervention, and hematoma progression, and most studies did not report outcomes separately by indication, precluding meaningful subgroup analysis. Outcome reporting was heterogeneous. Recurrence definitions varied across studies and included radiographic enlargement, persistence, symptom recurrence, or investigator-defined treatment failure, whereas reintervention likely represented a more reproducible escalation-of-care endpoint. Outcomes were also limited by small numbers of studies, sparse events, variable denominators, and inconsistent reporting of procedural and patient-level variables, which prevented identification of patients most likely to benefit from coil-only MMAE. Mortality was reported in only 3 studies, was dominated by one medically complex cohort, and included deaths or hospice transitions not necessarily attributable to cSDH or MMAE; therefore, mortality should not be interpreted as a procedure-specific safety endpoint. Continuous radiographic analyses were constrained by incomplete reporting of means, standard deviations, and paired change scores, requiring estimation of change-score variance. Assessment of publication bias and small-study effects was limited by the small number of studies, sparse events, and predominance of retrospective case series; therefore, publication bias, selective reporting, and unpublished negative experiences cannot be excluded. Formal certainty assessment using GRADE was not performed.

Conclusions

In this systematic review and single-arm meta-analysis based on studies with substantial risk of bias, coil-only MMAE for cSDH was associated with low pooled rates of recurrence, reintervention, and procedure-related complications; however, these estimates should be considered hypothesis-generating rather than definitive evidence. The available evidence is limited by retrospective study designs, serious risk of bias, heterogeneous treatment contexts, inconsistent outcome definitions, sparse event data, variable follow-up, and limited ability to assess publication bias. Coil-only MMAE should therefore be considered a potential anatomy-selective embolization strategy when controlled proximal occlusion is preferred, rather than an established equivalent, noninferior, or superior alternative to liquid or particulate embolics. Future prospective registries and comparative studies should standardize clinical, radiographic, procedural, and patient-centered endpoints while stratifying outcomes by embolic agent, treatment context, coil strategy, and anatomic risk features.

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Author contributions MT and SS made substantial contributions to the conception and design of the work, acquisition of data, data analysis, interpretation of results, and drafting of the manuscript. MT prepared Figs. 1, 2, 3 and 4 of the manuscript. BDL contributed to interpretation of findings and manuscript drafting and revision. KB and BG critically reviewed the work for important intellectual content and provided methodological and substantive feedback. HS served as the primary supervisor for the project and contributed to study conception, interpretation of results, and critical revision of the manuscript. All other authors contributed to review and revision of the final submission. All authors approved the final manuscript and agree to be accountable for all aspects of the work, including the accuracy and integrity of the study.

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Data availability All data analyzed in this study were extracted from previously published studies cited in the manuscript. The extracted dataset and analytic code are available from the corresponding author upon reasonable request.

Declarations

Ethics approval Not applicable. This systematic review and meta-analysis used previously published aggregate data and did not involve direct interaction with human participants, collection of individual patient-level data, access to identifiable private information, or use of human biological material. Therefore, ethics committee approval and Institutional Review Board approval were not required.

Registration and protocol This systematic review and meta-analysis was registered in PROSPERO (CRD420261389320). A formal review protocol was prepared and is available through PROSPERO.

Consent to participate Not applicable. This study used previously published aggregate data and did not involve enrollment of human participants.

Consent to publish Not applicable. This manuscript does not contain identifiable individual-level data, images, or personal information requiring consent for publication.

Human ethics and consent to participate Not applicable.

Clinical trial number Not applicable. This study is not a clinical trial.

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References

1. Mehmandoost M, Bahri A, Hasheminejad A, Sharifi H, Oveisi S, Fahim F (2025) Prevalence, etiology, risk factors, management options, and outcomes in chronic subdural hematoma (cSDH): A comprehensive literature review of recent advances. Brain Disorders 19:100271 2025/09/01/. https://doi.org/10.1016/j.dscb.2025.100271
2. Robinson D, Ding L, Stanton RJ et al (2026) Incidence and Mortality of Chronic Subdural Hematomas: A Population-Based Study. Stroke 57(2):459–466. https://doi.org/10.1161/STROKEAHA.125.053396
3. Neifert SN, Chaman EK, Hardigan T et al (2020) Increases in Subdural Hematoma with an Aging Population—the Future of American Cerebrovascular Disease. *World Neurosurgery*. 2020/09/01/. ;141:e166-e174. https://doi.org/10.1016/j.wneu.2020.05.060
4. Zolnourian A, Manivannan S, Edwards B et al (2025) Factors affecting outcomes following burr hole drainage of chronic subdural hematoma: a single-center retrospective study. J Neurosurg Jun 1(6):1606–1615. https://doi.org/10.3171/2024.9.Jns24370
5. Shotar E, Mathon B, Salle H et al (2025) Meningeal Embolization for Preventing Chronic Subdural Hematoma Recurrence After Surgery: The EMPROTECT Randomized Clinical Trial. JAMA 334(2):127–135. https://doi.org/10.1001/jama.2025.7583
6. Liu J, Ni W, Zuo Q et al (2024) Middle Meningeal Artery Embolization for Nonacute Subdural Hematoma. N Engl J Med 391(20):1901–1912. https://doi.org/10.1056/NEJMoa2401201
7. Gupta M, Saha A, Gupta A et al (2025) Material Matters: A Systematic Review and Meta-Analysis of the Effectiveness of Different Embolic Agents in Middle Meningeal Artery Embolization. J Vasc Interv Radiol Sep 26:107859. https://doi.org/10.1016/j.jvir.2025.09.030
8. Ashraf O, Musmar B, Fargen KM et al (2025) Middle meningeal artery embolization for chronic subdural hematoma using Nester pushable coils versus Onyx: a multicenter propensity score-matched analysis. J Neurointerv Surg Jan 30. https://doi.org/10.1136/jnis-2025-024746
9. Page MJ, McKenzie JE, Bossuyt PM et al (2021) The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Bmj Mar 29:372:n71. https://doi.org/10.1136/bmj.n71
10. Higgins JPT, Thomas J, Chandler J, Cumpston M, Li T, Page MJ (2024) Cochrane Handbook for Systematic Reviews of Interventions version 6.5, 6.5 edn. Cochrane
11. Khorasanizadeh M, Shutran M, Garcia A et al (2022) Middle Meningeal Artery Embolization with Isolated Use of Coils for Treatment of Chronic Subdural Hematomas: A Case Series. World Neurosurg Sep 165:e581–e587. https://doi.org/10.1016/j.wneu.2022.06.099
12. Sterne JA, Hernán MA, Reeves BC et al (2016) ROBINS-I: a tool for assessing risk of bias in non-randomised studies of interventions. Bmj Oct 12 355:i4919. https://doi.org/10.1136/bmj.i4919
13. Begg CB, Mazumdar M (1994) Operating characteristics of a rank correlation test for publication bias. Biometrics Dec 50(4):1088–1101
14. Egger M, Davey Smith G, Schneider M, Minder C (1997) Bias in meta-analysis detected by a simple, graphical test. Bmj Sep 13(7109):629–634. https://doi.org/10.1136/bmj.315.7109.629
15. Wei Q, Fan G, Li Z et al (2021) Middle Meningeal Artery Embolization for the Treatment of Bilateral Chronic Subdural Hematoma. Front Neurol 12:651362. https://doi.org/10.3389/fneur.2021.651362
16. Webb M, Luo A, Naratadam GT et al (2025) Middle meningeal artery embolization with SwiftPAC coils for the treatment of chronic subdural hematomas. Interv Neuroradiol Aug 28:15910199251370824. https://doi.org/10.1177/15910199251370824
17. Abramyan A, Afridi M, Soliman A et al (2025) Standalone short-coil embolization of the middle meningeal artery for subdural hematomas: Efficient, safe, and radiation-sparing. Clin Neurol Neurosurg. https://doi.org/10.1016/j.clineuro.2025.109226. /12/01/ 2025;259:109226
18. Iyer AM, Venkataraman SS, Kittel CA, Fargen KM (2023) Coil embolization alone appears sufficient for middle meningeal artery embolization. Interventional Neuroradiol. 0(0):15910199231217144. https://doi.org/10.1177/15910199231217144
19. Perng P-S, Chuang M-T, Wong C-E et al (2024) Simple coiling of middle meningeal artery embolization for chronic subdural hematoma: An inverse probability of treatment weighting matched cohort study. Interventional Neuroradiol. 0(0):15910199241234407. https://doi.org/10.1177/15910199241234407
20. Fecker A, McIntyre MK, Chen H et al (2025) Coil only middle meningeal artery embolization versus particles or liquid embolic agents for chronic subdural hematoma. J Neurointerv Surg Aug 22. https://doi.org/10.1136/jnis-2025-023848
21. Boulter JH, Schuette AJ, Viaggio K et al (2025) Comparison of proximal coil embolization versus distal middle meningeal artery embolization for the treatment of chronic subdural hematomas. Surg Neurol Int Dec 05:16:510. https://doi.org/10.25259/SNI_733_2025
22. Hoffman T, Bokhari R, Echelman I et al (2026) Middle Meningeal Artery Embolization Using Coils for Subdural Hematoma in Patients with Cancer: Safety and Effectiveness. J Vasc Interv Radiol May 37(5):108562. https://doi.org/10.1016/j.jvir.2026.108562

23. Davies JM, Knopman J, Mokin M et al (2024) Adjunctive Middle Meningeal Artery Embolization for Subdural Hematoma. N Engl J Med 391(20):1890–1900. https://doi.org/10.1056/NEJMoa2313472
24. Fiorella D, Monteith SJ, Hanel R et al (2025) Embolization of the Middle Meningeal Artery for Chronic Subdural Hematoma. N Engl J Med 392(9):855–864. https://doi.org/10.1056/NEJMoa2409845
25. Xi Y, Liu C, Shen Z, Luo W, Zhang H (2025) Meta-analysis of four phase III, Multicenter, randomized trials assessing the efficacy and safety of middle meningeal artery embolization for subdural hematoma. Neuroradiology Nov 67(11):3303–3311. https://doi.org/10.1007/s00234-025-03792-x
26. Kan P, Maragkos GA, Srivatsan A et al (2021) Middle Meningeal Artery Embolization for Chronic Subdural Hematoma: A Multi-Center Experience of 154 Consecutive Embolizations. Neurosurgery Jan 13(2):268–277. https://doi.org/10.1093/neuros/nyaa379
27. Kniep H, Gellissen S, Bechstein M et al (2026) Middle Meningeal Artery Embolization for Subdural Hematoma: CT/MRI End Points of the EMBOLISE Trial. Radiology Jan 318(1):e251746. https://doi.org/10.1148/radiol.251746
28. Rickard F, Gale J, Williams A, Shipway D (2023) New horizons in subdural haematoma. Age Ageing Dec 1(12). https://doi.org/10.1093/ageing/afad240
29. Salem MM, Sioutas GS, Khalife J et al (2024) General Versus Nongeneral Anesthesia for Middle Meningeal Artery Embolization for Chronic Subdural Hematomas: Multicenter Propensity Score Matched Study. Neurosurgery Feb 27. https://doi.org/10.1227/neu.0000000000002874

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