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Factors Associated with Rescue Surgery After Middle Meningeal Artery Embolization for Chronic Subdural Hematoma: A Systematic Review and Meta-analysis.

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Systematic Review

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Abstract

Background and Objectives: Rescue surgery remains necessary in some patients with chronic subdural hematoma after middle meningeal artery embolization (MMAE), but factors associated with this outcome are incompletely characterized. We evaluated clinical, radiographic, and treatment-related predictors of rescue surgery after MMAE.

Methods: Rescue-surgery data were synthesized as unadjusted odds ratios (ORs) using DerSimonian–Laird random-effects models. Between-study heterogeneity was assessed using I^2. Sensitivity analyses included alternative model estimation, modified Hartung–Knapp confidence intervals, leave-one-out analyses, and exclusions for sparse or discrepant data. The Benjamini–Hochberg procedure was applied to account for multiple comparisons.

Results: Thirty-four study records contributed 70 study–predictor comparisons across 17 factors. The qualitative synthesis documented 790 rescue-surgery events among 9,414 study-reported outcome observations (8.4%). Anticoagulant use was associated with increased odds of rescue surgery (4 studies; OR, 2.25; 95% CI, 1.34–3.77; P = .002; I^2 = 0%; adjusted q = .037). MMAE before surgery (4 studies; OR, 0.57; 95% CI, 0.38–0.86; P = .007; q = .056) and liquid embolic agents (7 studies; OR, 0.65; 95% CI, 0.47–0.90; P = .010; q = .056) were associated with lower odds in primary analyses but did not meet the false-discovery threshold. The modified Hartung–Knapp interval for anticoagulant use crossed unity (95% CI, 0.97–5.21). No evaluated radiographic or demographic factor showed a statistically significant association.

Conclusion: Anticoagulant use emerged as the strongest candidate predictor of surgical rescue following MMAE, whereas associations with procedural timing and embolic agents require further validation. Unadjusted observational comparisons, heterogeneous outcome definitions, and unresolved denominator discrepancies limit clinical inference.

Introduction

Chronic subdural hematoma (cSDH) is an increasingly common cause of neurosurgical intervention in older adults. Although surgical evacuation is effective for symptomatic hematomas, recurrence necessitating additional treatment remains a substantial burden. [1] Inflammation and fragile neovascular membranes implicated in hematoma persistence provide the rationale for middle meningeal artery embolization (MMAE), now used as an adjunct to evacuation or, in selected patients, as standalone therapy.[2]

Randomized trials have strengthened the evidence supporting MMAE, but important differences persist in treatment strategies and outcome definitions. In EMBOLISE, adjunctive MMAE reduced hematoma recurrence or progression requiring reoperation from 11.3% to 4.1%.[3] STEM demonstrated a reduction in composite treatment failure,[4] whereas MAGIC-MT did not show a statistically significant reduction in its

primary outcome of symptomatic recurrence or progression.[5] More recently, EMMA-Can showed lower symptomatic recurrence on computed tomography after adjunctive embolization.[6] Despite these advances, some MMAE-treated patients ultimately require surgical intervention.

Predicting this need for surgical rescue is distinct from predicting radiographic recurrence or composite treatment failure. Patient-related factors, hematoma characteristics, and procedural decisions have been examined across heterogeneous cohorts; a recent risk-stratification study further highlighted the potential contribution of coagulation abnormalities, imaging findings, and neurological deficits.[7] However, the direction, magnitude, and consistency of individual associations remain uncertain. We therefore conducted a systematic review and meta-analysis to identify clinical, radiographic, and treatment-related factors associated with rescue surgery after MMAE for cSDH.

Materials and Methods

Review design and protocol

We conducted a systematic review and meta-analysis to identify clinical, imaging, and treatment-related factors associated with subsequent surgical intervention after middle meningeal artery embolization (MMAE) for chronic subdural hematoma (cSDH). We prospectively registered the review in PROSPERO on May 16, 2026 (CDR420251030165). We designed, conducted, and reported the review in accordance with the PRISMA 2020 statement and methodological guidance for systematic reviews of prognostic factors.[8,9]

Eligibility criteria and outcome definition

We included randomized and nonrandomized studies that enrolled adults 18 years or older with chronic or nonacute subdural hematoma treated with MMAE as standalone therapy or in conjunction with surgical evacuation. To enter the predictor-specific synthesis, a study had to report rescue-surgery outcomes according to an identifiable clinical, radiographic, demographic, or procedural factor, or provide enough information to reconstruct a 2 × 2 table. We did not require an MMAE-untreated control group. Instead, we compared patients or procedures with a given predictor against those without that predictor within MMAE-treated cohorts.

We defined rescue surgery as any subsequent operative evacuation, repeat evacuation, or surgical rescue after MMAE, according to each study's reported definition. We did not count radiographic recurrence, persistent hematoma, or broader composite treatment-failure endpoints as rescue events unless the study explicitly reported an additional surgical intervention. We retained differences in endpoint terminology, follow-up duration, and unit of analysis (patient, hematoma, or embolization) and addressed them as limitations during data validation and interpretation.

Information sources and search strategy

We searched MEDLINE/PubMed, CENTRAL, Scopus, and additional databases or registers identified in the protocol, supplemented by reference-list screening and forward-citation searching. We also considered conference material and unpublished or ongoing studies when available. We limited the review to English-language reports and did not apply date restrictions.

The MEDLINE strategy combined terms for chronic or nonacute subdural hematoma, MMA embolization, and prognostic or failure-related concepts. MEDLINE yielded 541 records. CENTRAL yielded 181 records, Scopus yielded 734 records, and other databases or registers yielded 17 records. Appendix A reproduces the exact MEDLINE strategy used for the review.

Study selection and data extraction

Two reviewers independently screened titles and abstracts, assessed full texts for eligibility, and extracted data. A third reviewer resolved disagreements. After deduplication, 914 records underwent title and abstract screening, and 351 full-text reports underwent eligibility assessment. We excluded 317 full-text reports, most commonly because they did not report usable rescue-surgery predictor data or did not allow reconstruction of 2 × 2 tables, evaluated the wrong outcome, used an ineligible design or publication type, or enrolled an ineligible population or intervention. The final dataset contained 34 eligible study records and 70 study–predictor comparisons across 17 rescue-surgery predictors.

For each included study, we extracted the first author, publication year, country or study setting, numbers of participants and embolizations, sex distribution, total rescue-surgery events, and predictor-specific event counts. For each binary predictor, F and S represented rescue-surgery events and nonevents in the predictor-exposed group, whereas FC and SC represented the corresponding counts in the comparator group. When potentially overlapping institutional cohorts were present, we handled them conservatively. Specifically, we did not treat earlier Ma datasets as independent when the consolidated Ma et al. 2026 record captured the same cohort structure.

Risk of bias and certainty of evidence

The registered protocol prespecified Cochrane RoB 2 for randomized trials, ROBINS-I for nonrandomized intervention-effect studies, and GRADE for certainty assessment. For prognostic-factor research, however, QUIPS more directly addresses bias in prognostic studies than ROBINS-I.[10,11] We therefore framed the present review as a prognostic-factor synthesis and interpret the findings accordingly. Formal study-level risk-of-bias ratings and certainty-of-evidence judgments were not completed as part of the supplied extraction-based analysis and are not presented in this manuscript draft.

Statistical analysis

We calculated study-specific odds ratios (ORs) and 95% confidence intervals (CIs) from 2 × 2 tables. When a table contained at least 1 zero cell, we added 0.5 to all 4 cells before calculating the log OR and inverse-variance weight. We performed a separate meta-analysis for each eligible predictor using DerSimonian–Laird random-effects models. We quantified heterogeneity with Cochran Q, I^2, and the between-study variance (τ^2). We used 2-sided tests, defined nominal statistical significance as $P < .05$, and applied the Benjamini–Hochberg procedure across 17 predictor-specific analyses to account for multiple testing.

We tested model robustness with fixed-effect and restricted maximum likelihood (REML) random-effects estimates, modified Hartung–Knapp 95% CIs with variance inflation constrained to at least 1, leave-one-out analyses when informative, and sensitivity analyses that excluded zero-cell contrasts. Because no predictor was represented by 10 or more studies, we did not perform funnel-plot asymmetry testing. We summarized the quantitative findings in predictor-specific forest plots and grouped them thematically by medication-related, radiologic, procedural, and demographic factors rather than combining unrelated predictors into a single pooled effect.

In the qualitative synthesis, we also summarized rescue-surgery events descriptively across included reports (790/9,414; 8.4%). We interpreted this figure as a descriptive ratio rather than a pooled incidence estimate because the included studies analyzed different units (patients, hematomas, or procedures) and may have included overlapping source populations.

Appendix A. MEDLINE search strategy

((("Hematoma, Subdural, Chronic"[Mesh] OR "chronic subdural hematoma*" OR cSDH OR "nonacute subdural hematoma*" OR "subacute and chronic subdural hematoma*")) AND (("middle meningeal artery embolization" OR "middle meningeal artery embolisation" OR "MMA embolization" OR "MMA embolisation" OR MMAE OR ("embolization, therapeutic"[Mesh] AND "middle meningeal")))) AND ((predict* OR prognos* OR factor* OR determinant* OR associated OR risk OR failure OR recurrence OR reoperation OR "rescue surgery" OR "subsequent intervention" OR "radiographic failure" OR nonresolution OR "delayed resolution"))).

Result

Study-level evidence

The qualitative synthesis documented 790 rescue-surgery events among 9,414 study-reported outcome observations (8.4%). Thirty-four study records contributed 70 valid study–predictor comparisons encompassing 17 prespecified rescue-surgery predictors. All reported associations were unadjusted **(Table 1 and Figure 2).**

Medication and antithrombotic exposures

Anticoagulant use was associated with greater odds of rescue surgery across four comparisons (odds ratio [OR], 2.25; 95% CI, 1.34–3.77; P = .002; I^2 = 0%). It was the only association to meet the Benjamini–Hochberg false-discovery threshold after testing 17 predictors (q = .037). The modified Hartung–Knapp 95% CI was wider (0.97–5.21), crossing the null. Neither antithrombotic therapy at admission (four studies; OR, 1.58; 95% CI, 0.92–2.71) nor antithrombotic resumption (seven studies; OR, 0.95; 95% CI, 0.61–1.47) showed a clear association. Similarly, statin use (four studies; OR, 1.22; 95% CI, 0.85–1.75) and steroid exposure (two studies; OR, 1.48; 95% CI, 0.70–3.13) were not associated with rescue surgery on the primary analysis **(Table 2 and Figure 3).**

Radiologic and hematoma characteristics

No radiologic feature was associated with rescue surgery on the primary analyses **(Figure 4).** The estimated effects were imprecise for midline shift of at least 5 mm (three studies; OR, 1.84; 95% CI, 0.81–4.18), a hyperdense or acute hematoma component (two studies; OR, 1.79; 95% CI, 0.88–3.65), and hematoma septation (three studies; OR, 0.70; 95% CI, 0.10–4.63). Bilateral cSDH (seven studies; OR, 0.93; 95% CI, 0.66–1.29) and axial thickness of at least 15 mm (four studies; OR, 0.78; 95% CI, 0.31–1.95) likewise showed no association. Between-study heterogeneity was moderate for septation (I^2 = 58.2%) and otherwise negligible for these imaging variables.

Treatment and procedural characteristics

MMAE performed before surgery was associated with lower rescue-surgery odds in the four-study primary analysis (OR, 0.57; 95% CI, 0.38–0.86; P = .007; I^2 = 0%). however, the association did not meet the false-discovery threshold (q = .056). Liquid embolic agents were also associated with lower odds in seven studies (OR, 0.65; 95% CI, 0.47–0.90; P = .010; I^2 = 0%; q = .056). Standalone MMAE (five studies; OR, 2.10; 95% CI, 0.94–4.70), femoral access (three studies; OR, 0.81; 95% CI, 0.58–1.14), and general anesthesia (three studies; OR, 1.05; 95% CI, 0.66–1.69) showed no clear association **(Figure 5).**

Demographic characteristics

Female sex (five studies; OR, 1.21; 95% CI, 0.75–1.94) and White race (three studies; OR, 1.50; 95% CI, 0.91–2.48) were not associated with rescue surgery **(Figure 6).**

Model robustness and sensitivity analyses

Primary models showed low heterogeneity for most predictors **(Table 2).** Moderate heterogeneity was observed for hematoma septation (I^2 = 58.2%) and steroid exposure (I^2 = 50.5%). Fixed-effect and restricted maximum likelihood (REML) estimates were generally comparable to the DerSimonian–Laird estimates. Modified Hartung–Knapp intervals crossed the null for anticoagulant use (0.97–5.21) and

MMAE before surgery (0.29–1.10); the corresponding interval for liquid embolic agents was 0.43–0.98. Excluding zero-cell comparisons yielded an anticoagulant OR of 2.18 and a standalone MMAE OR of 2.04. Across 17 analyses, the limited number of studies per predictor precluded reliable funnel-plot asymmetry tests.

A formal risk-of-bias assessment was not conducted.

Table 1: Qualitative synthesis of rescue-surgery predictors after MMAE

Author, country, and year	Participants (N)	MMAEs (N)	Female (%)	Rescue-surgery predictors	Rescue surgery N (%)
Salem et al., USA, 2023	530	636	27.2	Antithrombotic therapy at admission: 18/178 (10.1%) Anticoagulant use: 16/128 (12.5%) Bilateral cSDH: 14/189 (7.4%) MMAE before surgery: 18/284 (6.3%) Female sex: 14/164 (8.5%) Femoral access: 26/410 (6.3%) Liquid embolic agents: 11/239 (4.6%)	43/563 (7.6%)
Martinez-Gutierrez et al., USA, 2025	80	99	20.0	Hematoma septation: 1/32 (3.1%)	5/96 (5.2%)
Martinez-Gutierrez et al., USA, 2023	57	66	21.1	Antithrombotic resumption: 2/23 (8.7%)	4/66 (6.1%)
Maciaszek et al., Australia, 2025	13	17	15.4	Bilateral cSDH: 1/6 (16.7%)	2/13 (15.4%)
Sioutas et al., USA, 2025	237	266	26.2	MMAE before surgery: 4/85 (4.7%)	8/141 (5.7%) 17/266 (6.4%)
Khorasanizadeh et al., USA, 2022	45	52	42.2	Bilateral cSDH: 1/14 (7.1%) Hematoma septation: 2/9 (22.2%) Midline shift ≥5 mm: 3/21 (14.3%) Female sex: 2/23 (8.7%) Axial thickness ≥15 mm: 3/29 (10.3%)	5/52 (9.6%)
Salim et al., multicenter, 2025	338	338	24.6	MMAE before surgery: 12/169 (7.1%)	42/338 (12.4%)
Sioutas et al., USA, 2024	84	109	20.2	MMAE before surgery: 7/64 (10.9%)	12/109 (11.0%)
Palumbo et al., USA, 2023	35	NR	28.6	Anticoagulant use: 3/20 (15.0%)	3/35 (8.6%)

Author, country, and year	Participants (N)	MMAEs (N)	Female (%)	Rescue-surgery predictors	Rescue surgery N (%)
				Axial thickness ≥15 mm: 1/16 (6.2%)	
Shehabeldin et al., USA, 2023	97	97	26.8	Liquid embolic agents: 5/49 (10.2%)	13/97 (13.4%)
Lim et al., USA, 2026	114	134	35.1	Hyperdense/acute hematoma: 5/47 (10.6%)	10/134 (7.5%)
Gomez-Paz et al., USA/Canada, 2025	557	663	74.0	White race: 48/323 (14.9%)	73/557 (13.1%)
Fuentes et al., USA, 2023	322	NR	29.2	Anticoagulant use: 5/19 (26.3%)	55/322 (17.1%)
Bastianon Santiago et al., USA, 2025	49	61	34.4	Antithrombotic therapy at admission: 2/16 (12.5%) White race: 4/26 (15.4%) Female sex: 3/11 (27.3%)	4/32 (12.5%)
Thakur et al., multinational, 2025	438	NR	NR	Steroid exposure: 14/219 (6.4%)	28/438 (6.4%)
Salem et al., North America, 2024	872	1070	27.1	Femoral access: 48/575 (8.3%) Liquid embolic agents: 49/594 (8.2%)	97/1065 (9.1%)
Krothapalli et al., USA, 2023	116	116	31.1	Liquid embolic agents: 1/48 (2.1%)	2/116 (1.7%)
Salem et al., North America, 2024	778	956	26.8	Bilateral cSDH: 30/356 (8.4%) General anesthesia: 26/280 (9.3%)	86/956 (9.0%)
Ban et al., South Korea, 2018	72	72	33.3	Bilateral cSDH: 0/19 (0.0%) Axial thickness ≥15 mm: 0/33 (0.0%)	1/72 (1.4%)
Gomez-Paz et al., USA, 2021	23	27	56.5	Midline shift ≥5 mm: 1/12 (8.3%)	3/27 (11.1%)
Chaliparambil et al., USA, 2024	111	111	27.9	Antithrombotic resumption: 3/32 (9.4%)	11/111 (9.9%)

Author, country, and year	Participants (N)	MMAEs (N)	Female (%)	Rescue-surgery predictors	Rescue surgery N (%)
				Standalone MMAE: 8/55 (14.5%)	
Sioutas et al., USA, 2023	669	669	NR	Steroid exposure: 25/372 (6.7%) Statin exposure: 27/391 (6.9%)	39/669 (5.8%)
Keil et al., Germany, 2026	38	47	23.4	Statin exposure: 0/18 (0.0%) Standalone MMAE: 1/15 (6.7%)	3/47 (6.4%)
Scoville et al., USA, 2022	NR	208	44.7	Liquid embolic agents: 1/54 (1.9%) Standalone MMAE: 8/131 (6.1%)	10/206 (4.9%)
Saway et al., USA, 2023	100	136	32.0	Bilateral cSDH: 0/32 (0.0%)	2/100 (2.0%)
Chaliparambil et al., USA, 2025	28	56	35.7	Antithrombotic therapy at admission: 2/11 (18.2%) Antithrombotic resumption: 2/7 (28.6%) White race: 5/24 (20.8%) Female sex: 2/10 (20.0%) Standalone MMAE: 5/23 (21.7%) General anesthesia: 5/22 (22.7%)	5/28 (17.9%)
Housley et al., USA, 2022	46	50	NR	Statin exposure: 2/18 (11.1%)	4/50 (8.0%)
Weinberg et al., USA, 2023	99	117	28.0	Hematoma septation: 1/31 (3.2%) Standalone MMAE: 5/75 (6.7%)	7/65 (10.8%)
Salim et al., multicenter, 2025	1132	1132	NR	Statin exposure: 46/566 (8.1%)	88/1132 (7.8%)
Patel et al., USA, 2025	128	NR	NR	Antithrombotic resumption: 3/66 (4.5%) Liquid embolic agents: 4/53 (7.5%)	12/127 (9.4%)
Essibayi et al., multinational,	326	NR	NR	Antithrombotic resumption: 12/163	29/326 (8.9%)

Author, country, and year	Participants (N)	MMAEs (N)	Female (%)	Rescue-surgery predictors	Rescue surgery N (%)
2026				(7.4%)	
Ma et al., USA, 2026	NR	298	34.2	Antithrombotic therapy at admission: 6/58 (10.3%) Antithrombotic resumption: 16/141 (11.3%) Anticoagulant use: 3/18 (16.7%) Bilateral cSDH: 13/134 (9.7%) Midline shift ≥5 mm: 6/38 (15.7%) Hyperdense/acute hematoma: 20/180 (11.1%) Female sex: 10/102 (9.8%) Axial thickness ≥15 mm: 5/77 (6.5%) Femoral access: 5/48 (10.4%) General anesthesia: 0/9 (0.0%)	28/298 (9.4%)
Lakhani et al., multinational, 2026	801	NR	NR	Antithrombotic therapy resumption: 6/143 (4.2%)	34/801 (4.2%)
Christie et al., USA, 2026	268	NR	NR	Liquid embolic agents: 3/50 (6.0%)	13/100 (13.0%)
Total (descriptive)	**—**	**—**	**—**	**—**	**790/9414(8.4%)**

Table 2: Selected clinically relevant associations

Predictor	Studies	Pooled OR (95% CI)	P value	BH q	I^2
Anticoagulant use	4	2.25 (1.34–3.77)	0.002	0.037	0.0%
MMAE before surgery	4	0.57 (0.38–0.86)	0.007	0.056	0.0%
Liquid embolic agents	7	0.65 (0.47–0.90)	0.010	0.056	0.0%
Antithrombotic therapy at admission	4	1.58 (0.92–2.71)	0.095	0.269	0.0%
Antithrombotic resumption	7	0.95 (0.61–1.47)	0.803	0.831	10.0%
Midline shift ≥5 mm	3	1.84 (0.81–4.18)	0.144	0.306	0.0%
Standalone MMAE	5	2.10 (0.94–4.70)	0.070	0.269	0.0%
Bilateral cSDH	7	0.93 (0.66–1.29)	0.652	0.792	0.0%

OR, odds ratio; BH q, Benjamini–Hochberg false-discovery rate–adjusted P value. Each row represents a separate predictor-specific random-effects meta-analysis

Table 3: Model checks and heterogeneity analyses

Predictor	Q (P)	I^2	τ^2	Fixed OR	REML OR	Modified HK 95% CI	LOO OR range
Antithrombotic therapy at admission	0.54 (0.910)	0.0%	0.000	1.58	1.58	0.66–3.78	1.48–1.63
Antithrombotic resumption	6.66 (0.353)	10.0%	0.036	0.95	0.95	0.55–1.64	0.79–1.07
Anticoagulant use	0.90 (0.826)	0.0%	0.000	2.25	2.25	0.97–5.21	2.13–2.40
Bilateral cSDH	0.55 (0.997)	0.0%	0.000	0.93	0.93	0.61–1.40	0.90–0.96
Hematoma septation	4.79 (0.091)	58.2%	1.634	0.75	0.70	0.01–44.61	0.27–1.46
Steroid exposure	2.02 (0.155)	50.5%	0.148	1.50	1.48	0.01–190.36	k=2
Statin use	2.41 (0.491)	0.0%	0.000	1.22	1.22	0.68–2.19	1.09–1.51
MMAE before surgery	2.89 (0.410)	0.0%	0.000	0.57	0.57	0.29–1.10	0.51–0.72
Midline shift ≥5 mm	0.89 (0.640)	0.0%	0.000	1.84	1.84	0.30–11.13	1.46–2.10
Hyperdense/acute hematoma	0.03 (0.872)	0.0%	0.000	1.79	1.79	0.02–182.26	k=2
White race	0.25 (0.883)	0.0%	0.000	1.50	1.50	0.50–4.53	1.48–2.57
Female sex	2.45 (0.654)	0.0%	0.000	1.21	1.21	0.62–2.36	1.12–1.29
Axial thickness ≥15 mm	0.46 (0.928)	0.0%	0.000	0.78	0.78	0.18–3.45	0.68–0.83
Femoral access	1.92 (0.383)	0.0%	0.000	0.81	0.81	0.38–1.72	0.78–1.03
Liquid embolic agents	4.88 (0.560)	0.0%	0.000	0.65	0.61	0.43–0.98	0.47–0.71
Standalone MMAE	0.97 (0.914)	0.0%	0.000	2.10	2.10	0.67–6.58	1.75–2.43
General anesthesia	0.97 (0.614)	0.0%	0.000	1.05	1.05	0.37–2.96	1.02–1.44

Q, Cochran Q; τ^2, between-study variance; HK, modified Hartung–Knapp; LOO, leave-one-out; REML, restricted maximum likelihood. The HK intervals use a t distribution with k − 1 degrees of freedom and

variance scaling constrained to at least 1.

Table 4: Sparse-event, and timing sensitivity

Predictor	Zero-cell contrasts	OR without zero-cell comparisons
Anticoagulant use	1	2.18
Bilateral cSDH	2	0.94
Steroid exposure	0	—
Statin use	1	1.25
Axial thickness ≥15 mm	1	0.83
Femoral access	0	—
Standalone MMAE	1	2.04

Discussion

Principal Findings

In this synthesis of 34 study records and 70 predictor-specific comparisons, anticoagulant exposure emerged as the most consistent marker of rescue surgery following middle meningeal artery embolization (MMAE) for chronic subdural hematoma (cSDH). The association persisted after correction for 17 comparisons (odds ratio [OR], 2.25; 95% CI, 1.34–3.77; q = .037), although a more conservative confidence interval included no association. Embolization before surgical evacuation and the use of liquid embolic agents were each associated with lower odds of subsequent surgery in the primary analyses, but neither met the multiple-testing threshold. No individual radiographic or demographic variable demonstrated a statistically significant association. Together, these findings suggest that surgical rescue reflects a combination of patient vulnerability and treatment context rather than any single readily measurable feature.

The Persistent Need for Surgical Rescue

The qualitative synthesis documented 790 rescue-surgery events among 9,414 study-reported outcome observations (8.4%). This is a descriptive ratio—not a meta-analytically pooled incidence—because studies differed in their unit of analysis, outcome definition, and treatment strategy, and some cohorts may overlap. Nevertheless, it emphasizes a clinically important limitation of an otherwise promising therapy: embolization does not fully eliminate the need for later decompression. An earlier systematic review reported a pooled surgical-rescue rate of 4.4% after MMAE, but its older study mix and different definitions preclude a direct comparison with the present aggregate.[12] Likewise, randomized trials have

demonstrated benefits on reoperation or broader recurrence and treatment-failure outcomes without establishing that rescue surgery is uniformly prevented.[3–6]

The distinction matters to patients. Radiographic persistence may be acceptable during gradual hematoma resorption, whereas worsening weakness, cognition, gait, or consciousness may demand prompt surgery regardless of angiographic success. Future reports should therefore distinguish unplanned evacuation after standalone MMAE from repeat evacuation after an index operation, and separate clinical deterioration from imaging-only failure.

Anticoagulant Exposure: Hemorrhagic Risk Versus Thromboembolic Necessity

Anticoagulant use was associated with approximately twice the odds of rescue surgery in the primary analysis (OR, 2.25; 95% CI, 1.34–3.77; I^2 = 0%). This observation is biologically plausible: continued bleeding from fragile vascularized membranes could counteract the gradual reduction in hematoma supply achieved by MMAE.[2] However, the estimate is based on four unadjusted comparisons, and the modified Hartung–Knapp interval (0.97–5.21) crossed unity. Anticoagulation may also identify patients with greater cardiovascular comorbidity, frailty, or competing clinical risks, rather than exerting an isolated treatment-failure effect.

Importantly, anticoagulant exposure should not be conflated with all antithrombotic therapy or with its resumption after treatment. Neither antithrombotic use at admission (OR, 1.58; 95% CI, 0.92–2.71) nor antithrombotic resumption (OR, 0.95; 95% CI, 0.61–1.47) showed a clear association. A separate systematic review likewise found no statistically significant increase in cSDH recurrence after antithrombotic resumption following MMAE, although the evidence was limited to three retrospective studies.[13] These findings do not justify routine continuation or withdrawal of anticoagulation. The decision must balance recurrent hemorrhage against preventable thromboembolism and reflect the indication for treatment, timing, agent, hematoma stability, and neurological status. Multidisciplinary guidance similarly favors individualized decisions in patients receiving antithrombotics.[14]

Timing of Embolization: A Signal Vulnerable to Treatment Selection

MMAE before surgical evacuation was associated with lower rescue-surgery odds across four comparisons (OR, 0.57; 95% CI, 0.38–0.86; P = .007. The association was consistent in direction across leave-one-out analyses, yet failed to reach the Benjamini–Hochberg threshold (q = .056); its modified Hartung–Knapp interval also included unity (0.29–1.10). The finding should therefore be regarded as exploratory rather than evidence that preoperative embolization itself prevents failure.

The direction of selection bias is clinically intuitive. Patients with severe mass effect or evolving neurological deficits often require immediate decompression, leaving embolization to be performed later; more stable patients may be candidates for embolization first. In a multicenter study, Sioutas and colleagues found no significant difference in reoperation after propensity matching between MMAE before and after surgery (4/48 vs 4/93, respectively).[15] Those matched data are not interchangeable with the unadjusted comparison extracted for our analysis, but they temper a causal interpretation. Timing should remain subordinate to the urgency of decompression until prospective studies account for neurological severity, baseline hematoma characteristics, and treatment indication.

Embolic Material: A Promising Association, Not a Preferred Agent

Use of liquid embolic agents was associated with lower odds of rescue surgery in seven comparisons (OR, 0.65; 95% CI, 0.47–0.90; P = .010), with no measurable heterogeneity; however, the adjusted q value was .056. Greater distal penetration and durable occlusion of the membrane microvasculature offer a mechanistic explanation, but this hypothesis cannot be established from nonrandomized material selection. Agent choice is entangled with operator experience, vascular anatomy, extent of embolization, treatment era, and case complexity.[2,5]

Notably, a multicenter propensity score–matched investigation involving 1,070 embolization procedures found no significant differences in surgical rescue between particles and liquid embolic materials, nor between individual liquid agents.[16] The contrast with our unadjusted pooled finding underscores why embolic choice should not be prescribed on the basis of the current association. Comparisons that standardize the outcome, embolization completeness, adjunctive surgery, and safety events are needed before one material can be favored on clinical grounds.

Radiographic Features: Why Nonsignificance Is Not Reassurance

No individual imaging characteristic showed a statistically significant association with rescue surgery. This included midline shift of at least 5 mm (OR, 1.84; 95% CI, 0.81–4.18), hyperdense or acute hematoma components (OR, 1.79; 95% CI, 0.88–3.65), bilateral hematomas, and thickness of at least 15 mm. These results should not be interpreted as evidence that imaging severity is clinically unimportant. Most analyses included only two to seven studies, and the estimates for septation were particularly unstable (OR, 0.70; 95% CI, 0.10–4.63; I^2 = 58.2%). Differences in lesion morphology, reporting thresholds, and decisions to operate may conceal meaningful patient-level relationships.

The recently proposed CSDH grading scheme by Ma et al. combines hematologic abnormalities, scan findings, neurological deficits, and the need for antithrombotic treatment; in its institutional series,

surgical-rescue risk increased across higher grades.[7] That approach illustrates a plausible direction for research: interactions between vulnerability, mass effect, and symptoms may be more informative than one isolated CT measurement. Our findings cannot validate or refute the grading system, because the present pooled analyses evaluated individual unadjusted predictors rather than calibrated multivariable models.

Treatment Strategy and the Need to Preserve Clinical Judgment

Standalone MMAE showed a numerically higher—but statistically uncertain—association with rescue surgery (OR, 2.10; 95% CI, 0.94–4.70), while femoral access and general anesthesia showed no clear association. Patients receiving embolization alone are not necessarily comparable with those selected for adjunctive embolization: operative contraindications, antithrombotic requirements, neurological stability, and prior recurrence can influence treatment selection. Conversely, adjunctive cohorts may define rescue as reoperation after an initial evacuation. Existing consensus statements recognize standalone MMAE as an option in selected patients for whom surgery carries prohibitive risk and support adjunctive MMAE in recurrent cSDH.[14] Our findings neither establish the inferiority of standalone treatment nor support delaying urgent surgical decompression.

Strengths, Limitations, and Implications for Future Research

A strength of this synthesis is its focus on the patient-important endpoint of surgical rescue rather than the less specific construct of radiographic recurrence. We assessed 17 predefined predictors, reported predictor-specific data, corrected for multiplicity, and examined alternative meta-analytic models and data-integrity exclusions. Most pooled estimates showed low measured heterogeneity, although this does not imply comparable clinical populations when few studies are available.

Several limitations constrain interpretation. First, the estimates are unadjusted, predominantly observational comparisons, leaving confounding by indication and disease severity unresolved. Second, outcomes described as rescue surgery, reoperation, or repeat surgery were not uniformly defined; denominator units varied among patients, hematomas, and procedures. Third, the 8.4% aggregate is not a pooled incidence estimate, and potential cohort overlap limits simple aggregation. Fourth, sparse events and small study counts yield unstable confidence intervals, especially under conservative small-sample inference.

Prospective multicenter cohorts should prespecify rescue surgery as an unplanned operative intervention after MMAE, report timing and clinical indications, use patient-level denominators, and distinguish adjunctive from standalone treatment. Individual-patient-data studies could assess

interactions among anticoagulant exposure, functional status, imaging findings, and treatment strategy, while adjusted comparisons of embolic materials and procedure timing could reduce confounding. Equally important is external validation of risk tools that identify who can safely await hematoma resorption—and who may be harmed by waiting.

Conclusion

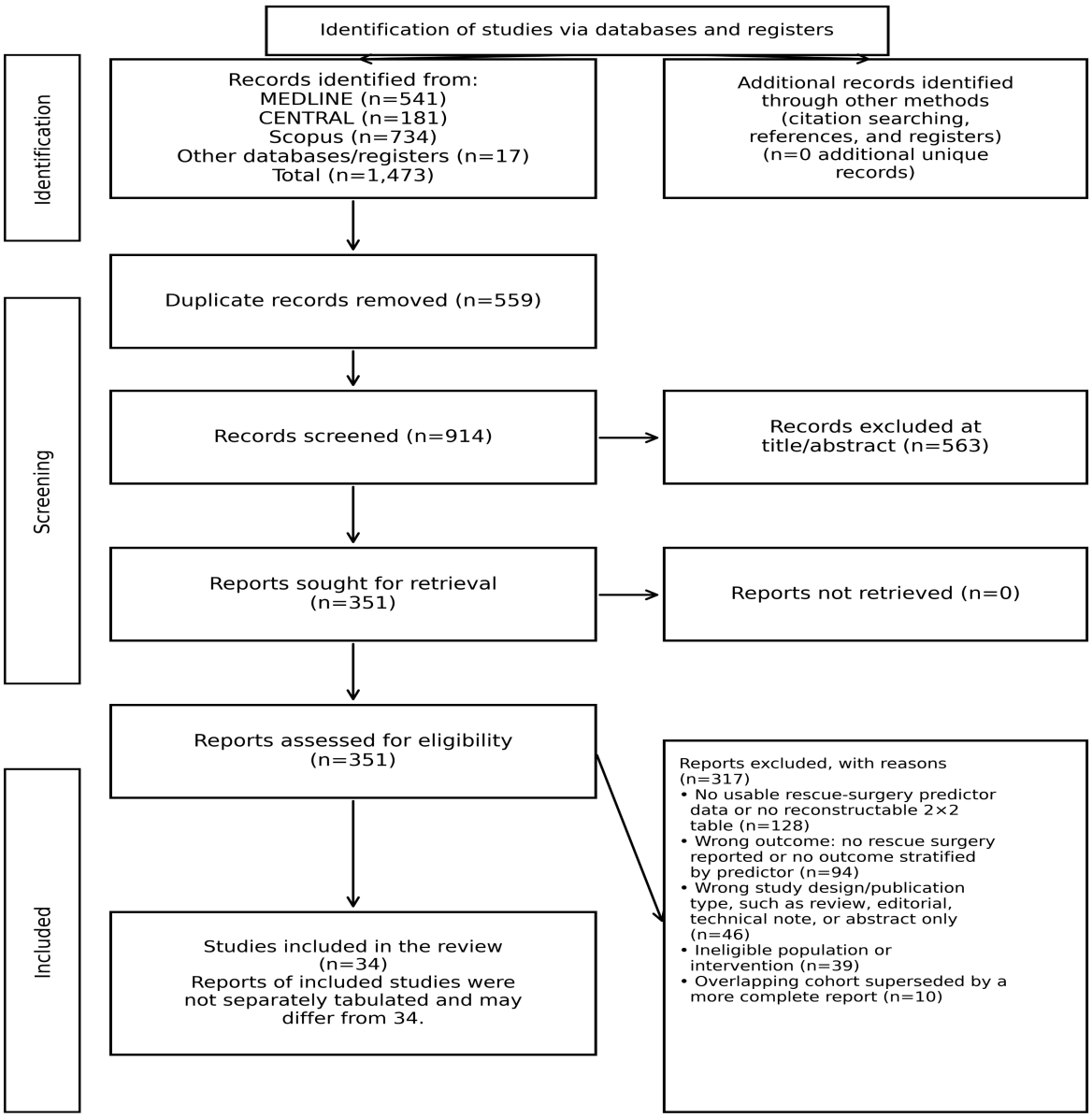
Rescue surgery remains a meaningful outcome after MMAE for cSDH. Anticoagulant exposure emerged as the strongest candidate risk marker, while the apparent associations with preoperative embolization and liquid agents were less robust after accounting for multiple testing and model uncertainty. Current evidence supports careful, individualized surveillance rather than deterministic prediction from any single factor. Better-standardized and prospectively validated data are needed to translate these signals into safer patient selection and follow-up.

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Figures



PRISMA indicates Preferred Reporting Items for Systematic Reviews and Meta-Analyses.

The final review included 34 study records. The number of reports corresponding to those records was not separately tabulated.

Figure 1

PRISMA flow diagram

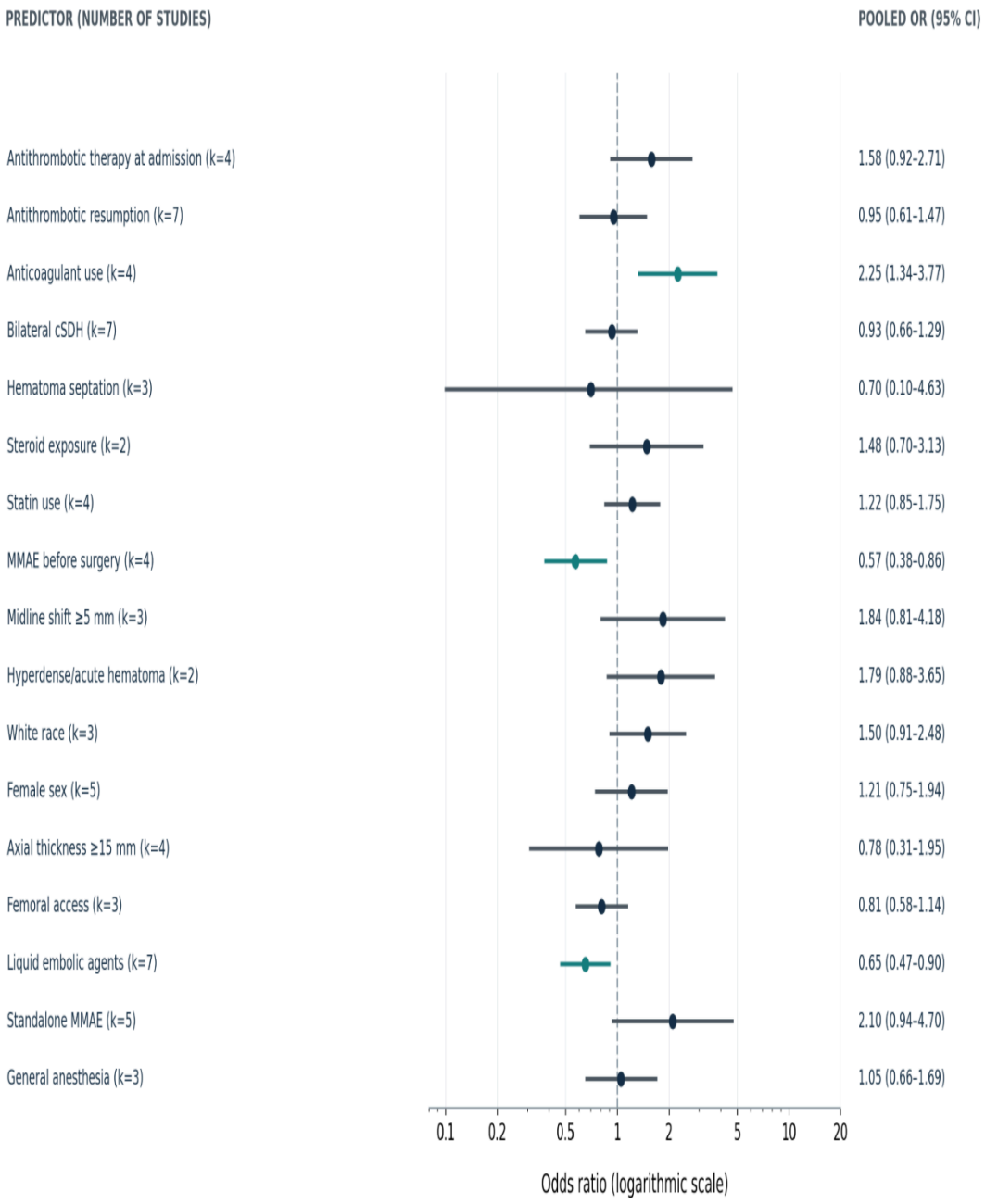


Figure 2

Overview of all 17 rescue-surgery predictors

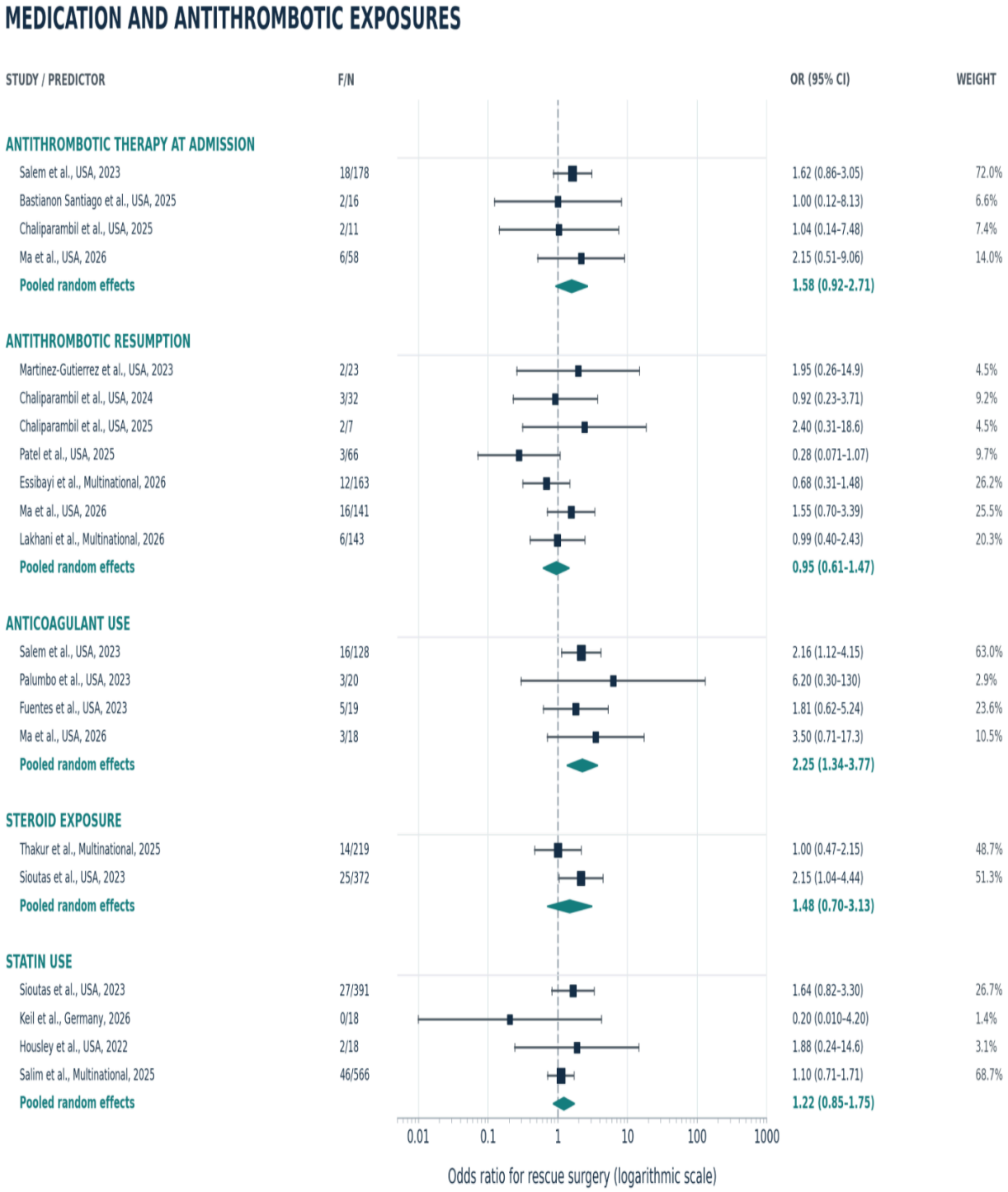


Figure 3

Medication and antithrombotic exposures

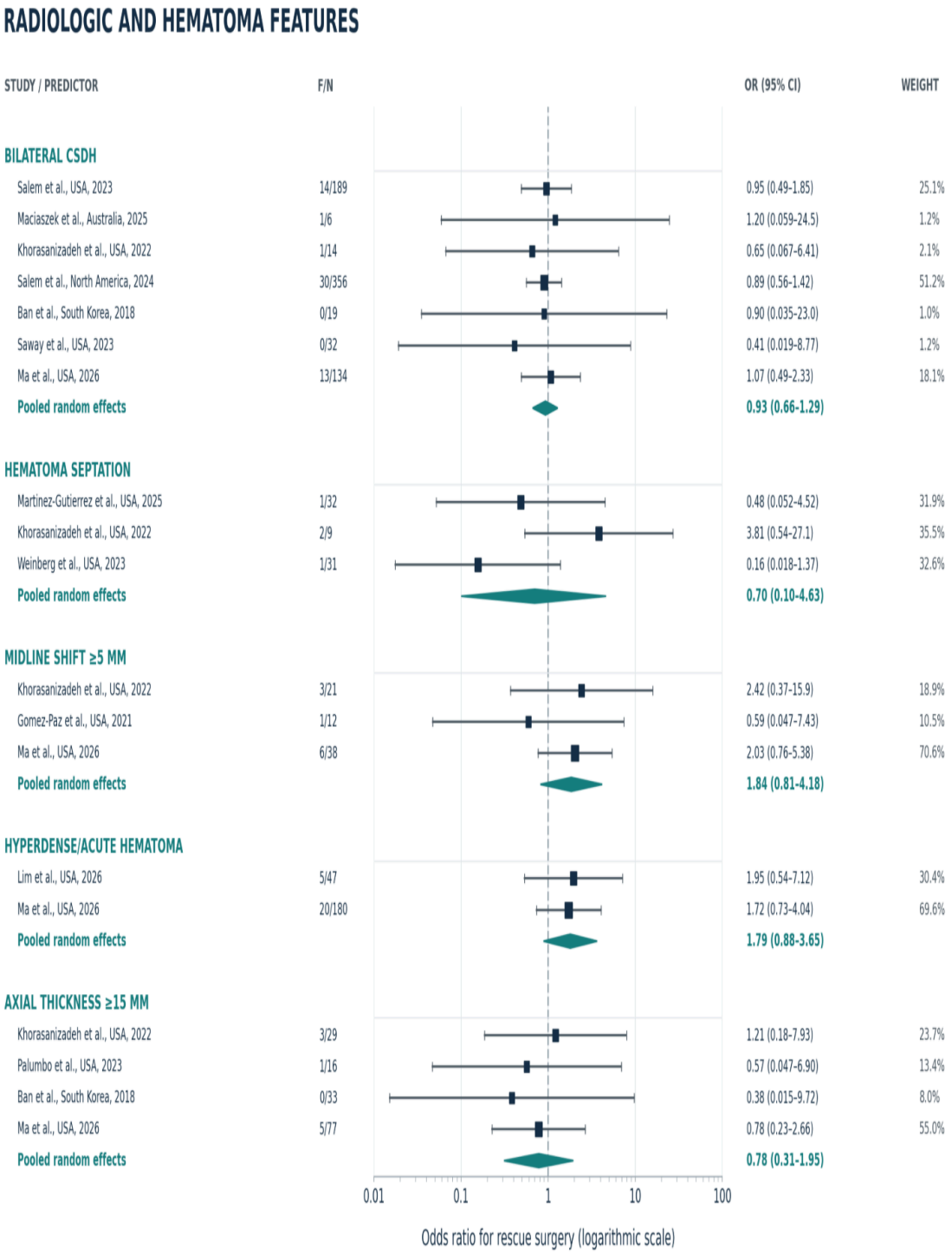


Figure 4

Radiologic and hematoma features

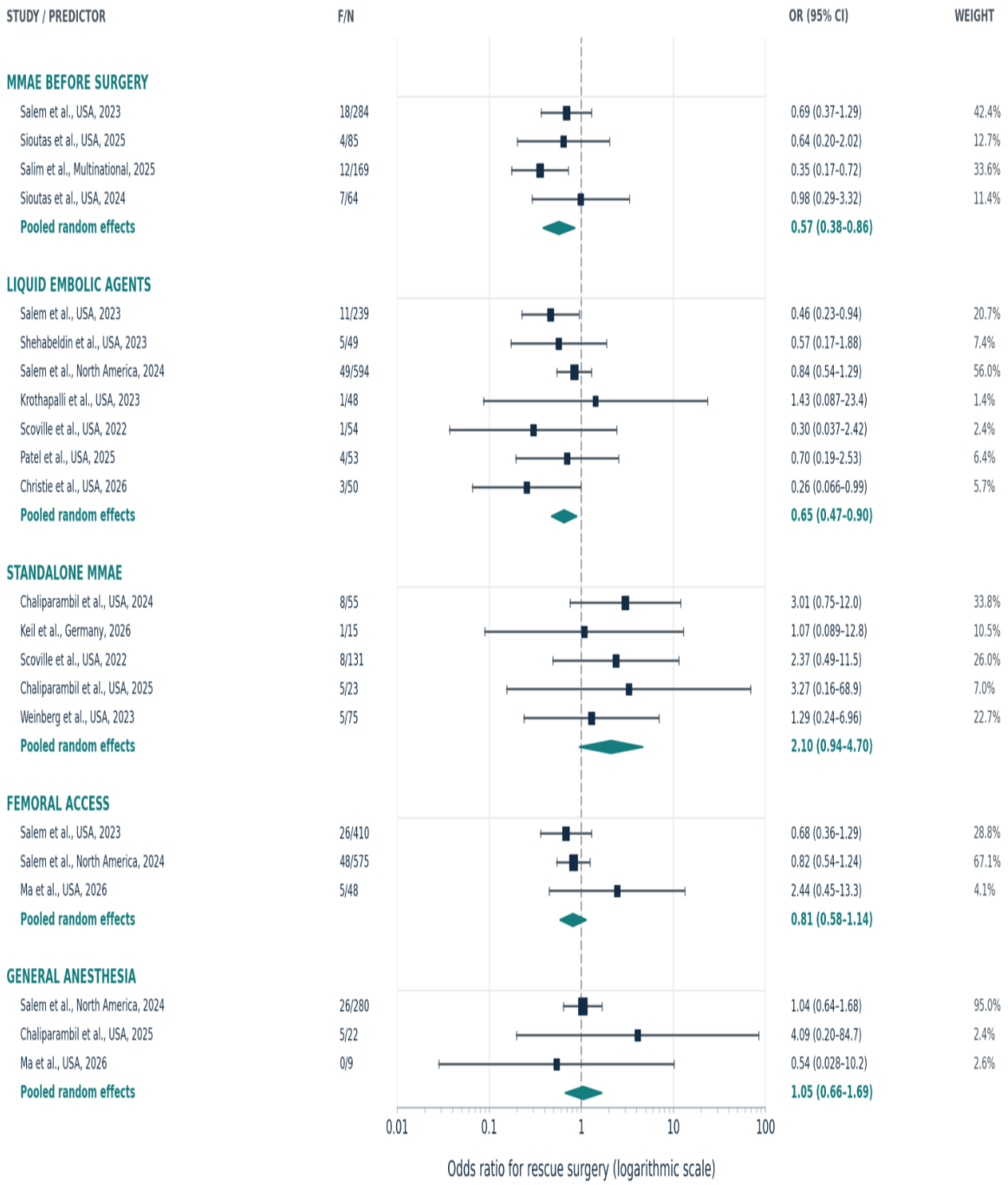


Figure 5

Treatment and procedural characteristics

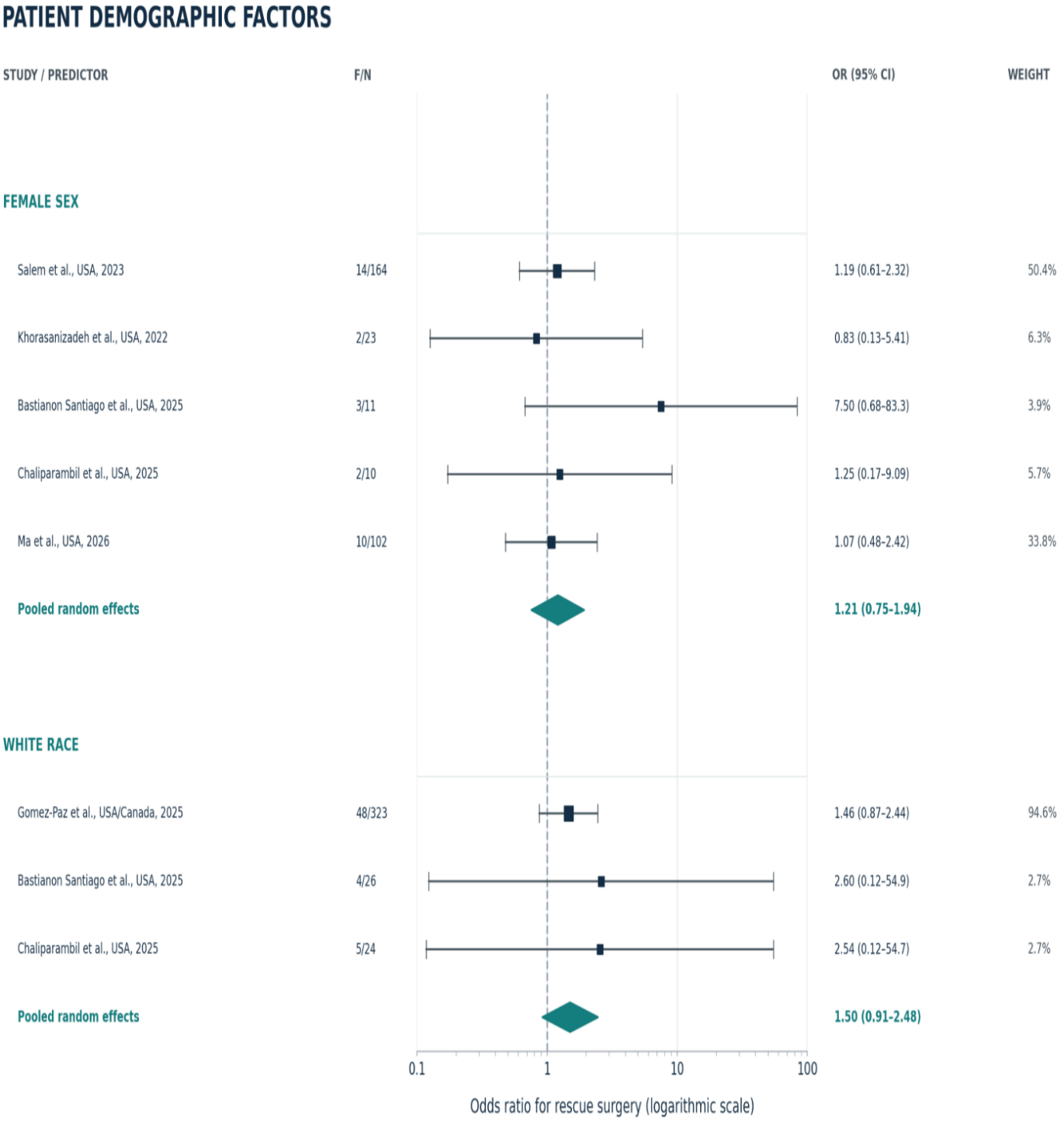


Figure 6

Patient demographic factors