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RADIOGRAPHIC AND ANGIOGRAPHIC PREDICTORS OF RESPONSE AFTER MIDDLE MENINGEAL ARTERY EMBOLIZATION FOR CHRONIC SUBDURAL HEMATOMA

Kadek Virginia Mas Cahya Dewi[1]*, Pande Putu Bagus Premana[2]
[1]General Practitioner, Windu Husada Hospital, Jl. Raya Mambal No. 17, Mekar Bhuwana, Abiansemal, Badung, Bali 80352, Indonesia
[2]Radiologist, Department of Radiology, Mangusada General Hospital, Jl. Raya Kapal, Mengwi, Badung, Bali 80351, Indonesia
*virginiamas99@gmail.com

ABSTRACT
Middle meningeal artery embolization (MMAE) is a minimally invasive treatment for chronic subdural hematoma (cSDH), yet predictors of treatment response remain incompletely defined. To evaluate radiographic, angiographic, and procedural predictors of treatment response after MMAE in adults with cSDH. The literature search, covering January 2000 to June 2026, identified 582 records from PubMed, the Cochrane Library, and ScienceDirect. After screening and eligibility assessment, 11 studies were included in the narrative synthesis. Septated, laminar, and trabecular hematomas were associated with better or faster response, whereas homogeneous or separated architecture, residual thickness, mixed density, and greater midline shift were associated with delayed resolution or failure. Small MMA diameter and limited distal embolic penetration were linked to poorer outcomes, while greater embolic volume favored radiographic resolution. Embolizing additional branches or selectively targeting the dominant branch did not consistently improve outcomes. MMAE response depends on hematoma biology, vascular anatomy, and embolic distribution rather than a single imaging variable, offering a framework that may help guide risk stratification, patient selection, and follow-up planning in research on MMAE.

Keywords: angiographic predictors; chronic subdural hematoma; middle meningeal artery embolization; radiographic predictors; treatment response

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INTRODUCTION

Chronic subdural hematoma (cSDH) is a common neurosurgical condition in older adults, with an incidence of 14–20 per 100,000 people per year, driven by repeated microhemorrhage, inflammation, neomembrane formation, and impaired resorption (Iorio-Morin et al., 2018). Although invasive procedures such as burr-hole drainage and craniotomy are the standard therapy for this condition, recurrence and reoperation remain important concerns (Nouri et al., 2021; Rauhala et al., 2020). Middle meningeal artery embolization (MMAE) has emerged as a minimally invasive treatment that may promote resolution and reduce recurrence as standalone or adjunctive therapy (Enriquez-Marulanda et al., 2021; Kan et al., 2021). However, unlike surgical evacuation, the radiographic response after MMAE is usually gradual, making early interpretation of treatment success or failure less straightforward (Tiwari et al., 2021).

Determining which patients benefit most from MMAE, and which imaging or angiographic features predict poor response, are important clinical questions. Residual hematoma thickness, postoperative midline shift, mixed-density appearance, and separated morphology may be associated with delayed resolution, whereas septated, laminar, or trabecular hematomas may respond more favorably, possibly reflecting different biological stages of cSDH organization (Chida & Akamatsu, 2026; Z. Liu et al., 2023). Angiographic and technical variables, MMA diameter, completeness of embolization, embolic distribution, distal penetration, embolic volume, and number of embolized

branches, have also been proposed as factors affecting response (Omura & Ishiguro, 2023). However, existing studies vary widely in design, technique, follow-up, and outcome definitions, making it difficult to translate individual findings into a coherent decision framework. This systematic review therefore aimed to evaluate radiographic and angiographic predictors of treatment response after MMAE in adult patients with cSDH.

METHOD

Study Design

This systematic review synthesized evidence on radiographic, angiographic, and procedural predictors of treatment response after MMAE in adult cSDH patients, prepared per the PRISMA framework. The review question followed the PICO framework: population, adults with cSDH undergoing MMAE; exposure, presence of radiographic/angiographic predictors; comparator, their absence or lower-risk features; outcome, treatment response or failure.

Literature Search Strategy

A systematic search of PubMed, the Cochrane Library, and ScienceDirect was conducted from 2000 through June 2026 to identify studies evaluating radiographic, angiographic, or procedural predictors of response following middle meningeal artery embolization for chronic subdural hematoma. Search terms combined synonyms for “chronic subdural hematoma”, “middle meningeal artery embolization,” “imaging or procedural predictors,” and “treatment outcomes.” Reference lists of eligible studies and relevant reviews were also screened manually.

Eligibility Criteria

Studies were included if they met the following criteria: adult patients with chronic or non-acute subdural hematoma; treatment with MMAE either as standalone therapy, adjunctive therapy, or after previous surgical evacuation; evaluation of at least one radiographic, angiographic, procedural, or clinically relevant predictor of treatment response; and reporting of treatment response or failure outcomes such as hematoma resolution, hematoma reduction, recurrence, need for rescue surgery, reintervention, complications, or poor clinical outcome.

Studies were excluded if they involved predominantly pediatric patients, acute traumatic subdural hematoma without chronic or subacute components, non-MMAE interventions without extractable MMAE-specific data, case reports with insufficient predictor-outcome information, conference abstracts without full-text data, reviews, editorials, letters, technical notes without patient-level outcomes, or studies in which the outcome of interest could not be linked to radiographic, angiographic, or procedural predictors.

Study Selection

All records retrieved from the database search were screened through title and abstract review. Potentially relevant studies were then assessed in full text according to the predefined eligibility criteria. Duplicate records were removed before final inclusion. Studies were included in the qualitative synthesis when they provided extractable data on predictors of MMAE response or failure in patients with cSDH. Disagreements during study selection were resolved through re-evaluation of the full text and discussion until consensus was reached.

Data Extraction

Data were extracted using a standardized form covering study characteristics, patient and cSDH features, MMAE technique, predictors assessed, outcome definitions, follow-up duration, main findings, and risk of bias. Radiographic outcomes included complete or near-complete resolution, changes or prespecified reductions in hematoma thickness or volume, time to resolution, radiographic nonresolution or failure, and recurrence or progression. Clinical outcomes included treatment failure requiring rescue surgery or reintervention and functional status. Procedural

complications and mortality were extracted as safety outcomes.

Risk of Bias Assessment

Risk of bias was assessed according to study design. Non-randomized interventional studies were assessed using ROBINS-I principles when appropriate. Randomized controlled trials, if identified, would be assessed using RoB 2. The final judgment was categorized as low or moderate risk of bias based on patient selection, comparability of groups, clarity of outcome definition, adequacy of follow-up, and control for confounding. Because the included evidence was expected to be predominantly retrospective and observational, special attention was given to selection bias, heterogeneous treatment indications, inconsistent follow-up intervals, and variability in outcome definitions.

Data Synthesis

A narrative synthesis was performed because of heterogeneity in study design, MMAE technique, predictor definitions, follow-up, and outcomes. Findings were grouped into radiographic, angiographic/procedural, and patient-level factors. Meta-analysis was not performed because comparable predictor–outcome estimates were insufficient.

RESULT

Study Selection

The database search identified 582 records, consisting of 404 records from PubMed, 49 from the Cochrane Library, and 129 from ScienceDirect. After title and abstract screening, 569 records were excluded because lack of relevancy to the review question, did not evaluate middle meningeal artery embolization (MMAE), or did not outcome desired. This left 13 records for duplicate assessment, of which 1 duplicate was removed. Subsequently, 12 full-text articles were assessed for eligibility. One article was excluded because of inappropriate participant characteristics and study design. Finally, 11 studies were included in the qualitative synthesis (Figure 1).

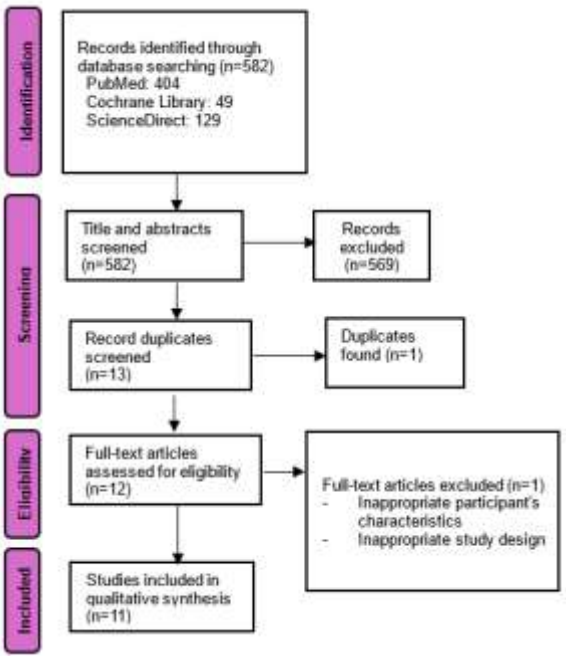

Figure 1. PRISMA Flowchart

Risk of Bias Assessment

Overall, the methodological quality of the included studies was acceptable for a systematic review of observational evidence. Ten studies were assessed as having low risk of bias, while one study, Tiwari et al. (2021), was assessed as having moderate risk of bias, mainly because of its small sample size and retrospective case-series design. The most common limitations across studies were retrospective design,

single-center sampling, heterogeneous procedural techniques, variable follow-up duration, inconsistent definitions of radiographic resolution or failure, and limited adjustment for confounding. Despite these limitations, the included studies consistently provided clinically relevant data. (Figure 2).

Figure 2. Risk of bias light plot.

Study Characteristics

The 11 included studies were published between 2021 and 2026 and evaluated radiographic, angiographic, procedural, and clinical predictors of treatment response after MMAE for chronic subdural hematoma (cSDH). Most studies were retrospective cohort studies, while one was a retrospective case series. The studies were predominantly conducted in the United States, with additional studies from China and Canada. Sample sizes varied considerably, ranging from 10 patients with 13 hematomas in Tiwari et al. (2021) to 530 patients with 636 embolization procedures in Salem et al. (2023). Several studies focused specifically on standalone MMAE, while others included adjunctive or comparative treatment strategies involving surgical evacuation, burr-hole irrigation, or prior failed surgery (Table 1).

Table 1.
Characteristics and results of the included studies

Study	Country; design	Study period	Sample and unit of analysis	MMAE context	Outcome assessment/follow-up
Z. Liu et al. (2023)	China; retrospective cohort	Dec 2018–Dec 2022 in Methods; abstract states Dec 2021	53 patients/53 unilateral cSDHs	MMAE alone, n=31; burr-hole irrigation followed by MMAE, n=22	Resolution assessed primarily at 4 and 6 months; median time to resolution 19 weeks
Housley et al. (2023)	United States; retrospective propensity-score matched cohort	Jan 2016–Apr 2022	92 patients/96 cSDHs; 48 matched hematoma pairs	Standalone MMAE versus surgical evacuation alone	24 hours, 3–12 weeks, and >12–60 weeks
Martinez-Gutierrez et al. (2025)	United States; retrospective cohort from a prospective registry	Jan 2018–Jul 2022	80 patients; 96 embolizations in the analytic cohort; abstract reports 99 cSDHs	Standalone or adjunctive MMAE	Recurrence and radiographic change within 90 days; median follow-up CT approximately 24 days
Abdelghafar et al. (2024)	Canada; retrospective single-center cohort	Jan 2020–Dec 2023	52 consecutive cSDH cases	MMAE using particles, coils, liquid agents, or combinations	CT assessment at 1–3, 3–6, and 6–12 months
Tiwari et al. (2021)	United States; retrospective case series	Not reported	10 patients/13 subacute or chronic SDHs	Primary or recurrent/post-surgical MMAE	Serial short- and long-term volumetric assessment

Study	Country; design	Study period	Sample and unit of analysis	MMAE context	Outcome assessment/follow-up
Gomez-Paz et al. (2021)	United States; retrospective single-center cohort	2018–2020	23 patients/27 cSDHs	Upfront standalone MMAE	Serial imaging at approximately 2 weeks, 6 weeks, 90 days, and final follow-up
Salem et al. (2023)	United States; multicenter retrospective cohort	Feb 2018–Apr 2022	530 patients/636 MMAE procedures	Standalone, concurrent with surgery, or after previous surgical treatment	Minimum 2-week CT follow-up; median clinical follow-up 4.1 months
Chaliparambil et al. (2024)	United States; retrospective single-center cohort	Jan 2018–Dec 2022	85 MMAE procedures reported in the abstract;	Primary or recurrent cSDH treated with MMAE	At least 20 days of follow-up and at least one radiographic study
Khorasanizadeh et al. (2023)	United States; retrospective single-center cohort	Jul 2018–Sep 2021	78 patients/94 cSDHs	Upfront, adjunctive to burr-hole drainage, or after failed burr-hole drainage	Mean radiographic follow-up approximately 114 days
Hung et al. (2026)	United States; retrospective single-center cohort	Jan 2019–Jul 2024	104 patients/131 embolized cSDHs	MMAE using liquid embolic agents; standalone and peri-surgical contexts included	Complete resolution assessed at 90 days and last radiographic follow-up
Golub et al. (2024)	United States; retrospective single-center cohort	2020–2023	134 patients/164 non-acute SDHs	Standalone MMAE as first-line treatment for new or recurrent SDH	Imaging at day 1, 2 weeks, 6 weeks, 3 months, and final follow-up

The included studies assessed a broad range of imaging and procedural variables. Radiographic predictors included hematoma thickness, hematoma volume, midline shift, septation, internal architecture, density pattern, laterality, residual hematoma thickness, postoperative midline shift, and serial changes in hematoma size. Angiographic and procedural predictors included MMA diameter, embolic material type, embolic volume, extent of distal penetration, number of embolized branches, selective versus nonselective catheterization, proximal versus distal branch embolization, and technical success. Several studies also incorporated patient-level predictors such as age, anticoagulant or antiplatelet use, comorbidity burden, frailty index, chronic kidney disease, and baseline functional status.

Radiographic Predictors of Treatment Response

Radiographic features were the most frequently investigated predictors across the included studies. Hematoma thickness, volume, midline shift, internal architecture, and septation were repeatedly examined as markers of treatment response or failure.

Table 2.
Radiographic predictors of treatment response

Study	Predictor outcome	Key result	Interpretation
Z. Liu et al. (2023)	Mixed density and separated architecture at baseline; residual thickness and post-treatment MLS → nonresolution at 4 months	Reported adjusted ORs: residual thickness 2.08; post-treatment MLS 3.12; mixed density 1.45; separated architecture 1.31	Reported as multivariable associations with delayed resolution, but the 95% CIs crossed 1 despite $P<0.05$; estimates should be interpreted cautiously.
Martinez-Gutierrez et al. (2025)	Baseline septation → recurrence and thickness reduction within 90 days	Recurrence: 3.1% vs 23.4%; adjusted OR 0.06 (95% CI 0.006–0.536), $P=0.012$. Thickness reduction: −8.2 vs −4.8	Septation was independently associated with lower recurrence. Greater thickness reduction was an unadjusted secondary finding.

Study	Predictor outcome	Key result	Interpretation
		mm, *P*=0.031	
Abdelghafar et al. (2024)	Spontaneous vs traumatic cause and non-mature vs mature architecture → thickness and volume reduction at 1–12 months	No significant adjusted between-group differences at any follow-up interval	Cause and architecture were not demonstrated to independently predict superior radiographic reduction.
Salem et al. (2023)	MMA diameter, baseline MLS, catheter position, and concurrent surgery → radiographic failure at last CT, ≥2 weeks	MMA diameter <1.5 mm: OR 1.70, *P*=0.044; MLS per 1 mm: OR 1.10, *P*=0.020; branch-only catheterization: OR 2.00 (95% CI 1.07–3.72); concurrent surgery: OR 0.43 (95% CI 0.22–0.81)	Small MMA diameter, greater MLS, and branch-only catheterization were independently associated with failure; concurrent surgery was associated with lower failure odds.
Khorasanizadeh et al. (2023)	Embolization location, number of branches, and dominant-branch targeting → rescue surgery and ≥50% volume reduction	≥50% reduction: 74.1%, 80.0%, and 77.5% for proximal, distal, and combined approaches, *P*=0.88; one vs >1 branch: 75.6% vs 78.3%, *P*=0.76	No significant association was detected between branch-selection strategy and radiographic response; the findings do not establish equivalence.

Evidence directly evaluating radiographic predictors of treatment response was limited and heterogeneous (Table 2). Z. Liu et al. (2023) reported that mixed-density appearance and separated architecture were associated with nonresolution at four months, while residual thickness and post-treatment midline shift were linked to delayed resolution but are better classified as early response markers than baseline predictors; these estimates should be interpreted cautiously as reported confidence intervals crossed unity despite P values <0.05. Martinez-Gutierrez et al. (2025) found septated cSDHs had lower 90-day recurrence than nonseptated lesions (3.1% vs 23.4%; adjusted OR 0.06, 95% CI 0.006-0.536). In contrast, Abdelghafar et al. (2024) found no significant adjusted differences in thickness/volume reduction between spontaneous vs traumatic or non-mature vs mature architecture groups.

Angiographic and Procedural Predictors

Salem et al. (2023) found MMA diameter <1.5 mm independently associated with clinical (OR 2.52, P=0.027) and radiographic failure (OR 1.70, P=0.044); greater midline shift and distal-only selective catheterization were also linked to radiographic failure, while liquid embolic agents and concurrent surgery were associated with lower failure odds. Khorasanizadeh et al. (2023), however, found no significant differences in rescue surgery or >=50% volume reduction by proximal/distal/combined embolization or number of branches treated, suggesting vessel caliber and catheterization strategy may matter more than branch count, though evidence remains retrospective.

Clinical Predictors and Patient-Level Factors

Chaliparambil et al. (2024) found higher comorbidity burden, older age, and antithrombotic resumption associated with nonresolution (CCI: OR 0.66, 95% CI 0.48-0.91; ACCI AUROC 0.75; mFI-5 AUROC 0.64). Salem et al. (2023) found pretreatment anticoagulation independently predicted clinical failure (OR 3.23, P=0.007), while antiplatelet therapy was not significant after adjustment. Hung et al. (2026) found unadjusted associations of older age, chronic kidney disease, larger baseline hematoma, and worse mRS with nonresolution; Golub et al. (2024) found no association with antithrombotic use/restart timing. Overall, patient-level findings were inconsistent across studies.

Treatment Response, Failure, and Safety Outcomes

Response rates varied by definition and follow-up: complete/near-complete resolution ranged 42.6%-50.0%, while >=50% reduction thresholds yielded 73%-80%. Z. Liu et al. (2023) reported resolution in 50.9% at four months and 90.6% at six months. Clinical failure/rescue surgery occurred in 6.8%-15% of cases, with procedural complications generally below 5% in larger cohorts (ischemic/hemorrhagic events, visual loss, facial nerve palsy, seizures, access-site complications), uncommon but clinically important.

DISCUSSION

This review identified several candidate radiographic predictors, though the findings were inconsistent and largely derived from retrospective cohorts. Hematoma morphology appeared potentially relevant. Martinez-Gutierrez et al. (2025) reported lower recurrence among septated lesions, whereas Golub et al. (2024) found homogeneous/separated architecture associated with failure. In contrast, Abdelghafar et al. (2024) found no significant adjusted difference by maturity. Z. Liu et al. (2023) reported associations of mixed density and separated architecture with four-month nonresolution, but weakened by weakened by CI-P value inconsistencies. Residual thickness and post-treatment midline shift were additionally associated with delayed resolution; however, these findings are more appropriately considered early response markers than pretreatment predictors. Internal architecture may reflect differences in hematoma organization and vascularity, but no single feature is yet validated for routine patient selection.

Angiographic findings suggest embolization quality/distribution may matter more than branch count. Salem et al. (2023) found that an MMA diameter below 1.5 mm was independently associated with both clinical and radiographic failure, while greater midline shift and branch-only selective catheterization were associated with radiographic failure. Hung et al. (2026) linked greater liquid embolic volume and complete resolution, although this was based primarily on unadjusted comparisons, whereas Khorasanizadeh et al. (2023) found no benefit from proximal versus distal embolization, one versus multiple branches, or dominant-branch targeting. Supporting technical literature associates distal penetration and the "bright falx" sign with faster clearance, favoring adequate, safe penetration over maximal branch coverage while avoiding reflux and dangerous anastomoses (Catapano et al., 2022). The available evidence therefore favors adequate and safe embolic penetration over maximal branch coverage, while avoiding reflux and dangerous ophthalmic or petrosal anastomoses. Patient-level factors (comorbidity, age, frailty, CKD, antithrombotic exposure) were inconsistent and should be seen as modifiers rather than contraindications (Hung et al., 2026).

These favorable responses and low failure rates align broadly with recent randomized evidence. EMBOLISE showed adjunctive MMAE reduced recurrence/progression requiring repeat surgery; STEM showed reduced 180-day treatment failure (Davies et al., 2024; Fiorella et al., 2025). By contrast, MAGIC-MT did not find a significant reduction in 90-day recurrence, though serious adverse events were less frequent with embolization (J. Liu et al., 2024). These trials support MMAE's broader efficacy but do not validate the specific predictors reviewed here. Interpretation is limited by retrospective design, heterogeneous indications, variable outcomes/follow-up, and inconsistent confounder adjustment. Until validated prospectively, hematoma architecture, midline shift, MMA diameter, and embolic penetration should be viewed as hypothesis-generating markers rather than definitive selection criteria.

Future Directions and Limitations

This review is limited by predominantly retrospective, single-center, U.S.-based studies, heterogeneity precluding meta-analysis, variable confounder adjustment, and inconsistent follow-up. Future prospective, multicenter studies should standardize predictor and outcome definitions and follow-up intervals to validate whether hematoma architecture, midline shift, MMA diameter, and embolic penetration/volume reliably predict response, potentially integrated with frailty and antithrombotic status into a selection model.

CONCLUSION

MMAE is a promising treatment for cSDH, but radiographic response varies and should not be judged by hematoma size alone. Current evidence suggests septated, laminar, and trabecular architecture may predict favorable response, whereas homogeneous/separated morphology, residual thickness, and greater midline shift may indicate delayed resolution or failure. Small MMA

diameter and limited embolic penetration are also relevant, whereas treating more branches does not consistently improve outcomes. MMAE response is best understood through an integrated framework combining hematoma morphology, vascular anatomy, embolic distribution, and patient-level factors such as frailty and antithrombotic status, a framework that may guide future prospective studies toward more precise patient selection and procedural planning.

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