CLINICAL RESEARCH

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# Temporal Pattern of Radiological Resolution in Chronic Subdural Hematoma After Middle Meningeal Artery Embolization: A Prospective 2-Center Study

Authors' Contribution:
Study Design A
Data Collection B
Statistical Analysis C
Data Interpretation D
Manuscript Preparation E
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**Background:** Middle meningeal artery embolization (MMAE) treats chronic subdural hematoma (cSDH) by devascularizing the hematoma membrane, but the timing of radiological resolution remains incompletely defined. This prospective 2-center study evaluated computed tomography (CT) outcomes at 1 and 3 months after MMAE in Vietnam.

**Material/Methods:** Consecutive patients treated from November 2021 through December 2024 were enrolled. Maximum hematoma thickness and midline shift were measured on baseline imaging and follow-up non–contrast-enhanced CT. Paired measurements were compared using paired *t* tests. Analyses were performed at the hematoma level using available paired observations.

**Results:** The cohort included 67 patients with 90 cSDHs. Follow-up CT was available for 76 hematomas at 1 month and 40 at 3 months. Mean hematoma thickness decreased from 14.2 ± 5.3 mm at baseline to 8.7 ± 10.2 mm at 1 month and 3.5 ± 5.6 mm at 3 months (both $P < 0.001$). Mean midline shift decreased from 6.1 ± 4.3 mm to 0.81 ± 1.54 mm and 0.69 ± 1.93 mm, respectively (both $P < 0.001$). Complete resolution was observed in 12 of 76 hematomas (15.8%) at 1 month and 23 of 40 (57.5%) at 3 months.

**Conclusions:** MMAE was associated with a gradual reduction in hematoma thickness and midline shift among hematomas with available follow-up imaging. These findings suggest that residual hematoma on early post-treatment imaging may not necessarily indicate treatment failure. However, the delayed radiological trajectory should be interpreted cautiously because 3-month imaging follow-up was incomplete and may be affected by attrition bias.

**Keywords:** Hematoma, Subdural, Chronic • Embolization, Therapeutic • Meningeal Arteries • Tomography Scanners, X-Ray Computed • Treatment Outcome

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## Introduction

Chronic subdural hematoma (cSDH) is a common condition in older adult patients. While surgery is the standard treatment, recurrence and delayed hematoma resolution continue to pose important clinical challenges [1-3].

Middle meningeal artery embolization (MMAE) is now used as an emerging treatment strategy for cSDH by blocking the blood supply to the leaky outer membrane, using polyvinyl alcohol (PVA) particles, liquid embolic agents, or coils [4-6]. Previous studies, including our work, have shown that MMAE is safe and has demonstrated favorable short-term clinical outcomes [7,8].

Recent randomized controlled trials have further strengthened the evidence supporting MMAE for cSDH by demonstrating reductions in recurrence and reintervention rates [9-11]. In addition, recent systematic reviews and meta-analyses have supported its safety and effectiveness, although substantial heterogeneity remains across study populations, treatment strategies, and study designs [12,13]. Consistent with this growing body of evidence, the 2025 Society of Vascular and Interventional Neurology consensus statement recognizes MMAE as an evidence-based treatment option for cSDH [14].

Despite these advances, most previous studies have focused primarily on recurrence, reintervention, or short-term clinical outcomes rather than the temporal evolution of hematoma resolution [6,8,15]. A recent multicenter study by Salem et al involving 636 embolizations evaluated predictors of radiographic failure, underscoring the need for a better understanding of radiological response after MMAE [16]. However, the temporal pattern of radiological resolution following embolization remains incompletely characterized [17-19].

A better understanding of this temporal trajectory may help contextualize residual hematoma on early follow-up imaging and inform follow-up strategies and decisions regarding further intervention. We hypothesized that radiological improvement after MMAE would continue between early and later follow-up and that residual hematoma at 1 month would not necessarily indicate treatment failure. Therefore, we conducted this prospective 2-center study to characterize the temporal CT-based radiological evolution of cSDH at 1 month and 3 months following MMAE.

## Material and Methods

### Study Design and Setting

This prospective cohort study enrolled consecutive patients with chronic cSDH who underwent MMAE at 2 tertiary referral centers in Vietnam (Viet Duc University Hospital and Can Tho Stroke International Services General Hospital) between November 2021 and December 2024. A subset of patients treated at Viet Duc University Hospital was included in our previous publication, which evaluated short-term clinical and imaging outcomes. The present study is a secondary analysis of the prospective cohort with a distinct research objective, specifically to characterize the temporal pattern of radiological resolution after MMAE using serial follow-up imaging.

### Ethics Statement

The Institutional Review Board of Hanoi Medical University approved the study (approval No. 696/GCN-HDDDNCYSH-DHYHN, 2022), and the approved protocol applied to both participating centers. The study was conducted in accordance with the Declaration of Helsinki. Written informed consent for participation and the embolization procedure was obtained from every participant or an authorized representative before treatment.

### Patient Population

#### *Inclusion Criteria*

Patients were eligible when cSDH was confirmed on computed tomography (CT) or magnetic resonance imaging (MRI) and at least 1 of the following applied: recurrent symptomatic cSDH after previous surgical evacuation; cSDH considered at increased risk of recurrence because of patient age of 65 years or older, antiplatelet or anticoagulant treatment, bilateral hematomas, hematoma thickness of at least 20 mm, midline shift of at least 10 mm, septated or layered morphology, or estimated volume greater than 120 mL; or mildly symptomatic cSDH with minimal symptoms, no focal neurological deficit, Markwalder grade 1-2, and preserved consciousness.

#### *Exclusion Criteria*

Patients were excluded for severe neurological impairment, defined as modified Rankin Scale score of 4 or higher, Markwalder grade greater than 3, or Glasgow Coma Scale score below 9; secondary cSDH related to an intracranial tumor, vascular malformation, arachnoid cyst, or spontaneous intracranial hypotension; end-stage systemic disease or expected survival below 6 months; a technical or anatomical contraindication to MMAE, including inaccessible arterial anatomy or dangerous anastomoses that could not be safely avoided; severe iodinated-contrast allergy; renal failure precluding contrast administration; pregnancy; participation in another interventional study; or refusal to participate.

### Treatment Strategy

Treatment approach (stand-alone MMAE, adjunct to surgery, or preoperative embolization) was determined by a multidisciplinary





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team based on clinical presentation and imaging findings. Because the primary objective of this secondary analysis was to characterize the overall temporal radiological trajectory following MMAE, the primary radiological analyses were performed in the pooled cohort irrespective of treatment strategy.

### Diagnosis and Follow-Up

Baseline diagnosis and radiological assessment were established using the diagnostic imaging examination (non–contrast-enhanced CT or MRI) performed before embolization according to routine clinical practice. Baseline radiological measurements were obtained from the corresponding diagnostic examination using predefined anatomical measurement criteria. To ensure consistency in longitudinal assessment, all follow-up imaging at approximately 1 and 3 months consisted of standardized non–contrast-enhanced CT, and all follow-up quantitative radiological measurements were obtained from these CT examinations. The same predefined anatomical measurement criteria were applied to baseline diagnostic imaging and follow-up CT. All radiological measurements were performed using INFINITT PACS software.

### MMAE Procedure

All procedures were performed by experienced interventional radiologists with patients under local or general anesthesia. A vascular access (femoral or radial) was obtained, and a guiding catheter was positioned in the external carotid artery. A microcatheter was then advanced for superselective catheterization of the middle meningeal artery (MMA). When a dangerous collateral was identified, the microcatheter was advanced beyond the anastomosis when feasible, or the hazardous branch was protected with coils before embolization of the remaining target territory. Embolization was performed targeting the branches supplying the hematoma membrane until complete stasis of flow was observed. Embolic materials included PVA particles, n-butyl cyanoacrylate or another liquid embolic agent, coils, or a combination selected according to vascular anatomy and operator judgment.

### Outcome Definitions and Assessment

Technical success was defined as successful catheterization and embolization of the intended MMA territory supplying the hematoma membrane, confirmed by post-embolization angiography. Technical failure was defined as inability to catheterize the MMA or inability to perform embolization safely because of unfavorable anatomy, vessel injury, or an unavoidable dangerous anastomosis.

Clinical status was assessed at baseline and during follow-up using the modified Rankin Scale and presenting symptoms. Clinical improvement was defined as improvement in presenting symptoms and/or a decrease of at least 1 point in the modified Rankin Scale score. Clinical success was defined as clinical improvement without unplanned surgical evacuation for hematoma progression during follow-up.

Procedure-related complications included arterial dissection, vessel rupture, non-target embolization, ischemic or hemorrhagic events, new neurological deficits, visual complications, and access-site complications.

The primary radiological outcome was the change in maximum hematoma thickness from baseline to 1 month and from baseline to 3 months. The change in hematoma thickness between 1 and 3 months was also evaluated among hematomas with imaging available at both follow-up time points.

Secondary radiological outcomes included changes in midline shift and categorical hematoma response. Categorical response was classified as complete resolution, defined as no visible residual hematoma on follow-up CT; at least 50% reduction in maximum hematoma thickness compared with baseline; or less than 50% reduction compared with baseline.

Maximum hematoma thickness was measured on axial images as the greatest perpendicular distance from the inner table of the skull to the inner margin of the hematoma. Midline shift was measured at the level of the septum pellucidum. Baseline measurements were obtained from the diagnostic CT or MRI examination performed before embolization, whereas all 1-month and 3-month follow-up measurements were obtained from standardized non–contrast-enhanced CT examinations.

Radiological outcomes were analyzed at the hematoma level because bilateral hematomas could demonstrate different radiological trajectories. Follow-up measurements were performed by experienced neuroradiologists blinded to clinical outcomes and treatment strategy. Disagreements were resolved by consensus. Interobserver reliability was not prospectively assessed, and the consensus measurement was used for analysis.

The MMA diameter was measured on preprocedural digital subtraction angiography in the coronal projection at the proximal arterial segment near the foramen spinosum using calibrated INFINITT PACS measurement tools. The lesion side was defined as the side ipsilateral to the cSDH, and the normal side as the contralateral side without a hematoma. Two neuroradiologists independently measured the arterial diameter while blinded to clinical outcomes, and the mean of their measurements was recorded in millimeters.

### Statistical Analysis

Continuous variables are reported as mean ± standard deviation (SD), and categorical variables as number and percentage.







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**Table 1.** Baseline clinical characteristics (n = 67 patients).

| Variable | Value |
|---|---|
| Age, mean ± SD (years) | 67.3 ± 10.1 |
| History of trauma, n (%) | 41 (61.2%) |
| Antithrombotic therapy, n (%) | 6 (9.0%) |
| Headache, n (%) | 55 (82.1%) |
| Dizziness, n (%) | 21 (31.3%) |
| Focal neurological deficit, n (%) | 16 (23.9%) |
| Impaired consciousness, n (%) | 14 (20.9%) |
| Baseline modified Rankin Scale = 1, n (%) | 47 (70.1%) |

Comparisons of hematoma thickness and midline shift from baseline to follow-up used paired *t* tests restricted to hematomas with both measurements available. The analysis from baseline to 1-month follow-up included 76 hematomas, and the analysis from baseline to 3-month follow-up included 40 hematomas. The comparison of 1-month to 3-month follow-up used the 40 hematomas with CT at both follow-up visits. A paired *t* test compared MMA diameter on the lesion and contralateral normal sides. Exploratory subgroup analyses according to treatment strategy (stand-alone MMAE vs MMAE combined with surgery) were also performed using the same analytical approach to assess the consistency of radiological trends across treatment groups. Categorical radiological outcomes were summarized descriptively because the denominators differed between follow-up visits and 3-month imaging was incomplete. Exploratory treatment-strategy analyses used the same available-case approach. No imputation was performed. Because 23 patients contributed bilateral hematomas, observations were not fully independent; clustering by patient was not modeled because of the small number of bilateral cases, and this was considered in interpretation. All tests were 2-sided, and $P < 0.05$ indicated statistical significance. Analyses were performed using IBM SPSS Statistics, version 26.0 (IBM Corp, Armonk, NY, USA).

## Results

### Patient Characteristics

The study included 67 patients with a mean age of 67.3 ± 10.1 years. A history of head trauma was present in 41 patients (61.2%). Headache was the most frequent presenting symptom, occurring in 55 patients (82.1%), followed by dizziness in 21 (31.3%), focal neurological deficit in 16 (23.9%), and impaired consciousness in 14 (20.9%). At baseline, 47 patients (70.1%) had a modified Rankin Scale score of 1 (**Table 1**).

**Table 2.** Baseline patient- and hematoma-level radiological characteristics.

| Variable | Value |
|---|---|
| Bilateral hematomas, n (%) | 23 (34.4%) |
| Hematoma thickness (mm), mean ± SD | 14.2 ± 5.3 |
| Midline shift (mm), mean ± SD | 6.1 ± 4.3 |
| Brain atrophy, n (%) | 35 (52.2%) |
| Middle meningeal artery diameter (lesion side, mm) | 1.49 ± 0.48 |
| Middle meningeal artery diameter (normal side, mm) | 1.25 ± 0.53 |
| *P* value | 0.014 |

**Table 3.** Procedural characteristics and outcomes.

| Variable | Value |
|---|---|
| Technical success, n (%) | 66 (98.5%) |
| Clinical success, n (%) | 64 (95.5%) |
| Procedure time (minutes), mean ± SD | 36.0 ± 18.3 |
| Complications, n (%) | 4 (6.0%) |

### Treatment Strategy and Baseline Imaging

Stand-alone MMAE was performed in 30 patients (44.8%), and 37 patients (55.2%) underwent MMAE combined with surgical management, including 4 who underwent preoperative embolization. Bilateral hematomas were present in 23 patients (34.4%), resulting in 90 hematomas for radiological analysis. Mean baseline hematoma thickness was 14.2 ± 5.3 mm, and mean midline shift was 6.1 ± 4.3 mm. The MMA diameter was larger on the lesion side than on the contralateral normal side (1.49 ± 0.48 mm vs 1.25 ± 0.53 mm; $P = 0.014$) (**Table 2**).

### Procedural Outcomes

MMA embolization was successfully performed in most cases, with technical success achieved in 66 of 67 patients (98.5%) and a clinical success rate of 95.5%. Recurrence requiring surgical evacuation occurred in 1 patient. Procedure-related complications occurred in 4 patients. One patient developed severe visual impairment due to reflux into an ophthalmic collateral branch, resulting in permanent vision loss. Two patients experienced MMA rupture, including 1 patient who underwent surgical evacuation because of worsening headache; neither patient developed permanent neurological sequelae. One patient developed MMA ostial dissection that prevented embolization, but remained asymptomatic (**Table 3**).





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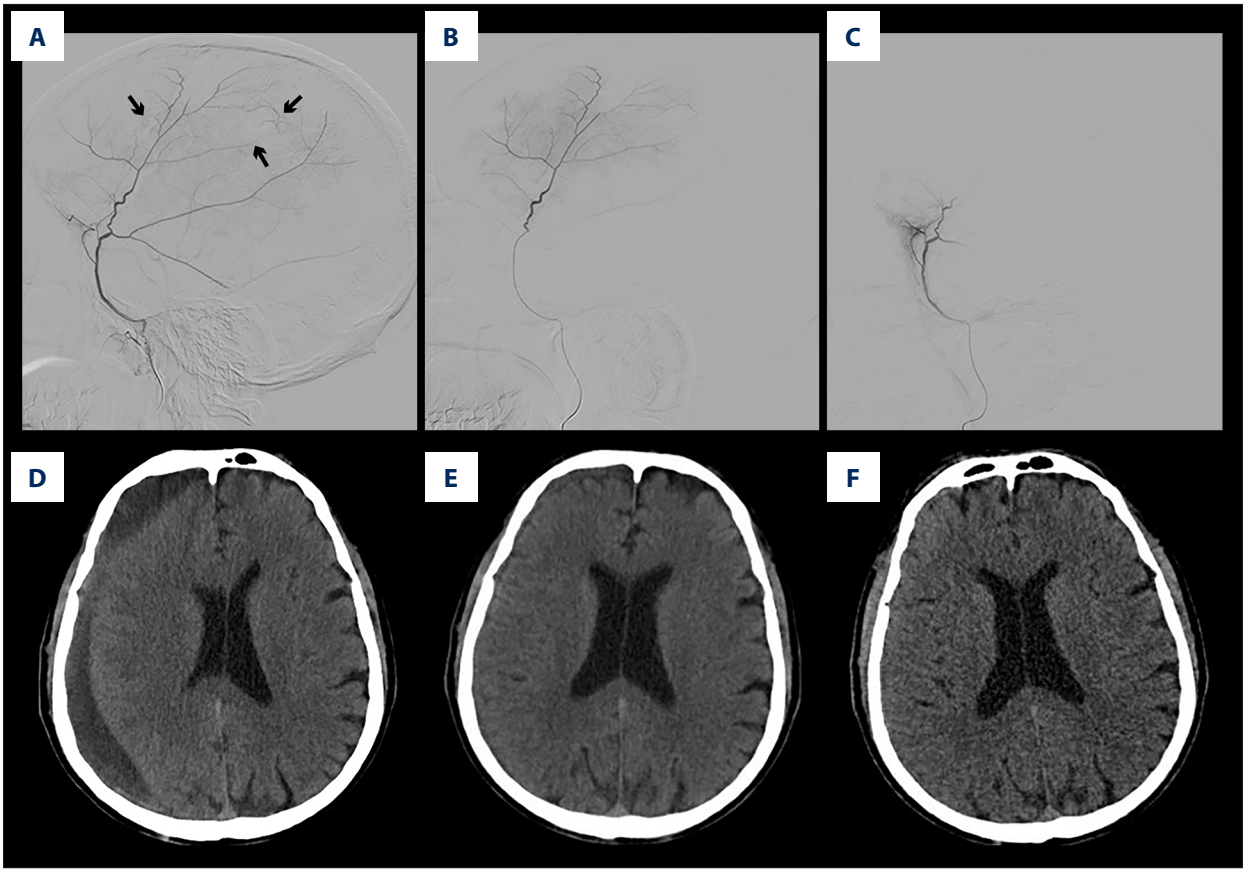


**Figure 1. Representative case demonstrating progressive radiological resolution after middle meningeal artery embolization.** (**A**) Pre-embolization angiography shows hypertrophied branches (arrows) of the middle meningeal artery supplying the hematoma membrane. (**B**) Superselective catheterization of the anterior branch of the middle meningeal artery is demonstrated. (**C**) Post-embolization angiography demonstrates occlusion of the pathological vascular supply. (**D**) Baseline computed tomography (CT) reveals a chronic subdural hematoma with mass effect. (**E**) Follow-up CT at 1 month shows a significant reduction in hematoma thickness. (**F**) At 3 months, complete resolution of the hematoma is observed.

### Follow-Up Availability

Clinical follow-up was available in all patients (100%). Radiological follow-up was available in 76 hematomas (84.4%) at 1 month and 40 hematomas (44.4%) at 3 months. Three-month CT was obtained according to routine clinical practice rather than a protocol-mandated imaging schedule. Therefore, the 3-month findings should be interpreted among hematomas with available follow-up imaging, as informative missingness cannot be excluded.

### Progressive Radiological Response

A representative case demonstrating progressive radiological resolution after MMAE is shown in **Figure 1**. At 1 month, hematoma thickness decreased significantly from 14.2 ± 5.3 mm at baseline to 8.7 ± 10.2 mm ($P < 0.001$). At 3 months, further reduction was observed, with hematoma thickness decreasing to 3.5 ± 5.6 mm ($P < 0.001$) (**Table 4, Figure 2**).

Midline shift showed a similar pattern of gradual improvement, decreasing from 6.1 ± 4.3 mm at baseline to 0.81 ± 1.54 mm at 1 month and 0.69 ± 1.93 mm at 3 months ($P < 0.001$).

Subgroup analysis according to treatment strategy showed significant radiological improvement in both treatment groups. In the stand-alone MMAE group, mean hematoma thickness decreased from 14.0 ± 3.67 mm to 7.86 ± 5.43 mm at 1 month ($P < 0.001$), whereas in the MMAE plus surgery group it decreased from 13.59 ± 4.39 mm to 7.46 ± 3.82 mm ($P < 0.001$). Similarly, midline shift decreased from 3.0 ± 2.85 mm to 0.73 ± 1.56 mm in the stand-alone MMAE group and from 4.15 ± 2.87 mm to 0.85 ± 1.66 mm in the MMAE plus surgery group (both $P < 0.001$).

Among the 40 hematomas with imaging available at both follow-up time points, hematoma thickness and midline shift continued to improve significantly between 1 and 3 months (all $P < 0.001$).







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**Table 4.** Continuous radiological outcomes (time-dependent change).

| Variable | Baseline | 1 Month (n=76) | 3 Months (n=40) | P value |
|---|---|---|---|---|
| Hematoma thickness (mm) | 14.2 ± 5.3 | 8.7 ± 10.2 | 3.5 ± 5.6 | <0.001 |
| Midline shift (mm) | 6.1 ± 4.3 | 0.81 ± 1.54 | 0.69 ± 1.93 | <0.001 |

* *P* values represent paired comparisons between baseline and the corresponding follow-up time point (baseline vs 1 month and baseline vs 3 months). Baseline values were restricted to hematomas with available imaging at each follow-up.

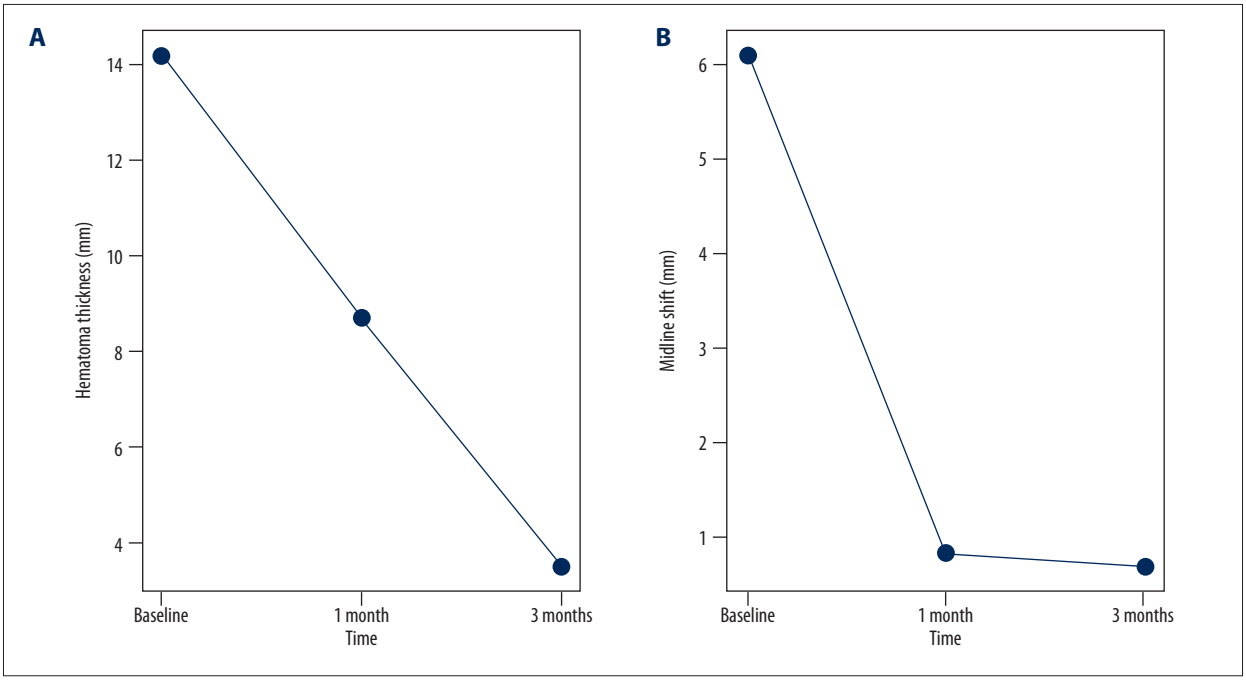


**Figure 2. Time-dependent changes in hematoma thickness (A) and midline shift (B) following middle meningeal artery embolization.** Both parameters demonstrate a progressive reduction from baseline to 1 month and 3 months, consistent with a delayed but sustained radiological response.

### Categorical Radiological Outcomes

Categorical analysis confirmed this progressive trend. At 1 month, complete hematoma resolution was observed in 15.8% of cases, while 55.3% of hematomas showed less than 50% reduction. At 3 months, the proportion of complete resolution increased to 57.5%, and the proportion of hematomas with less than 50% reduction decreased to 17.5% (**Table 5**). These proportions should not be interpreted as definitive estimates for the entire cohort, because of incomplete follow-up imaging.

**Table 5.** Categorical radiological outcomes.

| Outcome | 1 Month (n=76) | 3 Months (n=40) |
|---|---|---|
| Complete resolution | 12 (15.8%) | 23 (57.5%) |
| ≥ 50% reduction | 22 (28.9%) | 10 (25.0%) |
| < 50% reduction | 42 (55.3%) | 7 (17.5%) |

## Discussion

This prospective 2-center cohort showed that radiological improvement after MMAE continued over the first 3 months of follow-up. Among hematomas with available paired imaging, thickness and midline shift were already reduced at 1 month and decreased further by 3 months. The proportion with complete resolution also increased from 15.8% at 1 month to 57.5% at 3 months, although the latter estimate is limited by incomplete follow-up data.

This pattern differs from the immediate mechanical decompression achieved by surgical evacuation and is consistent with the biological mechanism of MMAE. The EMBOLISE, MAGIC-MT, and STEM trials primarily evaluated recurrence, progression, rescue surgery, or composite treatment failure rather







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than serial radiological resolution [9-11]. The present study therefore complements those trials by focusing on the early CT trajectory after treatment, while recognizing that the cohort combined stand-alone and surgically adjunctive MMAE.

Our findings are consistent with the multicenter analysis by Salem et al, in which radiographic success, defined as at least 50% reduction in maximal hematoma thickness, became more frequent with longer follow-up [16]. Using a comparable threshold, 44.7% of hematomas in our cohort had either complete resolution or at least 50% reduction at 1 month, increasing to 82.5% among those imaged at 3 months. These data support interpreting radiological response as time dependent rather than as a single early binary endpoint. Direct comparison of percentages should nevertheless be cautious because follow-up completeness, treatment strategy, imaging schedules, and case mix differed between studies.

The delayed response is biologically plausible. Occlusion of the MMA reduces arterial inflow to the vascularized outer membrane, thereby limiting repeated microhemorrhage and exudation while allowing gradual resorption of the existing collection [20,21]. The larger MMA diameter on the lesion side in this cohort is also consistent with vascular remodeling associated with cSDH. However, the observational design cannot establish that MMA enlargement caused hematoma persistence or that embolization alone produced the entire radiological change.

The cohort included PVA particles, liquid embolic agents, coils, and combinations. Systematic evidence has not established a single superior embolic material across all settings, and technical penetration, radiopacity, reflux control, cost, and operator experience can influence selection [22]. Because agent choice was not randomized and material-specific sample sizes were small, this study cannot compare efficacy between agents. Standardized prospective comparisons should report agent type, particle size, liquid concentration, coil use, target territory, and angiographic endpoint.

Clinically, the observed trajectory suggests that residual hematoma on an early CT scan should be interpreted together with symptoms, neurological examination, mass effect, and interval change. In a stable or improving patient, incomplete radiological resolution at 1 month may represent an expected phase of recovery rather than definitive failure. This interpretation is compatible with current consensus guidance, but the present data do not justify delaying surgery when neurological deterioration, increasing mass effect, or hematoma progression is present [14].

Technical and clinical success rates were high, but clinically important complications occurred, including permanent visual impairment, MMA rupture, and arterial dissection. These events emphasize the need for careful angiographic evaluation of ophthalmic and intracranial anastomoses, distal microcatheter positioning when safe, controlled embolic delivery, and immediate cessation or protective coiling when hazardous reflux or vessel injury is suspected.

This study has several limitations. First, only 40 of 90 hematomas (44.4%) had 3-month CT, creating substantial attrition bias and possible informative missingness; the magnitude of late resolution may therefore differ from that in the full cohort. Second, the cohort combined stand-alone, adjunctive, and preoperative MMAE; therefore, the separate contributions of embolization, surgical evacuation, and natural hematoma evolution cannot be determined. Third, radiological analyses were performed at the hematoma level, and bilateral hematomas from the same patient were treated as independent observations without a mixed-effects or cluster-robust model. Fourth, baseline imaging could be CT or MRI, CT acquisition was not fully protocolized across centers, and volumetric analysis was not performed. Fifth, interobserver agreement for thickness and midline-shift measurements was not prospectively assessed. Sixth, embolic materials and procedural techniques were heterogeneous, and material-specific effectiveness could not be evaluated. Finally, the absence of a concurrent control group limits causal inference and comparison with surgery or observation alone.

## Conclusions

In this prospective 2-center cohort, MMAE was associated with progressive reductions in hematoma thickness and midline shift among hematomas with available follow-up imaging. Residual hematoma on early follow-up CT may represent ongoing radiological resolution and should not, in isolation, be considered evidence of treatment failure. Given the observational design, heterogeneous treatment strategies, hematoma-level clustering, and incomplete 3-month imaging, these findings should be considered hypothesis-generating.

### Institution Where Work Was Done

Viet Duc University Hospital, Hanoi, Vietnam and the Can Tho Stroke International Services General Hospital, Can Tho, Vietnam.

### Ethics Statement

The Institutional Review Board of Hanoi Medical University approved the study (approval No. 696/GCN-HDDDNCYSH-DHYHN, 2022), and the approved protocol applied to both participating centers. The study was conducted in accordance with the Declaration of Helsinki. Written informed consent for







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participation and the embolization procedure was obtained from every participant or an authorized representative before treatment.

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During preparation of this manuscript, the authors used ChatGPT (OpenAI, San Francisco, CA, USA) solely to improve English-language clarity, grammar, and readability. The tool was not used to formulate the study hypothesis, collect data, perform statistical analyses, interpret clinical findings, create figures, or alter study results. All AI-assisted text was critically reviewed and revised by the authors, who take full responsibility for the accuracy and integrity of the final manuscript.

**Declaration of Figures' Authenticity**

All figures submitted have been created by the authors who confirm that the images are original with no duplication and have not been previously published in whole or in part.

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