ORIGINAL ARTICLE

Clinical outcomes of middle meningeal artery embolization in trauma-related chronic subdural hematoma

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ABSTRACT

BACKGROUND: Middle meningeal artery (MMA) embolization has emerged as a promising therapeutic option in the management of chronic subdural hematoma (cSDH). However, data specifically focusing on trauma-related cSDH remain limited. This study aimed to evaluate the safety and clinical outcomes of MMA embolization in patients with trauma-related cSDH and to investigate radiological predictors of treatment success.

METHODS: This retrospective study included patients with trauma-related cSDH who underwent MMA embolization at our institution between 2024 and 2025. Demographic, clinical, and radiological data—including midline shift (MLS) and hematoma thickness—were systematically collected. Functional outcomes were assessed using the modified Rankin Scale (mRS). Recurrence, need for surgical intervention, procedural complications, and mortality were recorded. Receiver operating characteristic (ROC) analysis was performed to evaluate the predictive value of midline shift for treatment failure.

RESULTS: A total of 52 patients with a documented history of trauma were included. Embolization alone was performed in 43 patients (82.7%), whereas nine patients (17.3%) underwent combined embolization and surgical treatment. Preprocedural MLS was significantly greater in the embolization-plus-surgery group than in the embolization-only group (7.6±3.9 mm vs. 4.5±3.8 mm, p=0.03). No significant between-group differences were observed in residual hematoma thickness or MLS at 6 weeks (p>0.05). Functional outcomes improved at 90 days compared with baseline. An MLS threshold of 4.5 mm demonstrated the highest predictive accuracy for treatment failure, with a sensitivity of 78% and a specificity of 56%.

CONCLUSION: MMA embolization appears to be a safe and clinically feasible treatment option for trauma-related cSDH. In carefully selected patients, it may serve as both an adjunct and an alternative to surgery. MLS may represent a practical and readily accessible parameter for risk stratification and patient selection. Prospective controlled studies are warranted to further validate these findings.

Keywords: Chronic subdural hematoma; middle meningeal artery embolization; trauma.

INTRODUCTION

Chronic subdural hematoma (cSDH) is one of the most common neurosurgical conditions, particularly among the elderly population.[1] The reported incidence in the general population ranges from 1.7 to 20.6 cases per 100,000 person-years and increases to 58.1 per 100,000 among older individuals.[2] Owing to population aging, surgical treatment of chronic and subacute subdural hematoma is projected to become the most commonly performed neurosurgical procedure by

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2030.[3] Despite advances in surgical management, recurrence rates remain between 8% and 20%, whereas complication rates range from 3% to 28%.[4]

In elderly patients, cSDH is associated with prolonged hospitalization, increased morbidity and mortality, and substantial healthcare costs.[4] These challenges have encouraged the development of minimally invasive alternatives, such as middle meningeal artery (MMA) embolization.[5] The rationale for MMA embolization is to reduce blood flow to the vascularized inflammatory membranes responsible for hematoma persistence and recurrence.[3] Several recent studies have suggested that MMA embolization may reduce recurrence rates and serve as either an adjunct or an alternative to surgery in selected patients.[6]

Trauma is commonly associated with the development of chronic subdural hematoma, particularly in elderly individuals with cerebral atrophy and increased vulnerability of bridging veins.[7] Following one or more traumatic events, an asymptomatic latency period typically occurs.[8] During this interval, biological mediators—including type I and III procollagen, fibrin, angiopoietin-2, vascular endothelial growth factor (VEGF), and various cytokines and chemokines—promote membrane formation and progressive hematoma enlargement.[9-12] These mechanisms are believed to account for the delayed clinical presentation, with symptoms typically developing approximately 4–7 weeks after the initial traumatic event.[7]

Middle meningeal artery embolization can be performed using various embolic agents, including n-butyl cyanoacrylate (nBCA), ethylene-vinyl alcohol copolymer (Onyx), polyvinyl alcohol (PVA) particles, and coils.[13] Although generally considered safe, selection of embolic material may influence procedural risk and complication profiles.[5] Initially introduced as an adjunct to surgical evacuation, MMA embolization has increasingly evolved into a potential primary treatment strategy with advances in endovascular techniques and imaging technology. Despite its growing acceptance, not all patients can be successfully managed with embolization alone. Radiological parameters, particularly the degree of mass effect, may influence the likelihood of requiring subsequent surgical intervention. Identifying these factors is essential for optimizing patient selection and guiding clinical decision-making in trauma-related cSDH.

Therefore, the aim of this study was to evaluate the clinical and radiological outcomes of patients with trauma-related chronic subdural hematoma treated with MMA embolization and to investigate radiological factors associated with the need for subsequent surgical intervention.

MATERIALS AND METHODS

This study was conducted in accordance with the ethical principles of the Declaration of Helsinki (1964) and its subsequent amendments. Ethical approval was obtained from the Ankara Bilkent City Hospital Clinical Research Ethics Committee (Date: 04.02.2026, Decision no: TABED 2-26-1988). Written informed consent was obtained from all patients prior to treatment. The study was reported in accordance with the STROBE (Strengthening the Reporting of Observational Studies in Epidemiology) guidelines.[14]

Patient Population

This retrospective, single-center study included consecutive patients who underwent MMA embolization for cSDH between January 2024 and January 2025. During the study period, 81 patients underwent treatment, of whom 55 had a documented history of cranial trauma. Three patients were excluded because of unavailable follow-up data, resulting in a final study cohort of 52 patients. Inclusion criteria were age ≥18 years, documented head trauma, and treatment with MMA embolization. Patients without documented trauma or with incomplete clinical or radiological data were excluded. Baseline data included demographics, comorbidities, use of antiplatelet or anticoagulant medications, neurological status at admission, and radiological findings. Patients were categorized into two groups: those managed with embolization alone and those requiring subsequent surgical evacuation. Surgical intervention was considered in patients who developed new or progressive neurological deficits or demonstrated no radiological improvement in hematoma thickness or midline shift. The decision to perform burr-hole evacuation or mini-craniotomy was based on membrane characteristics.

Endovascular Technique

All procedures were performed under general anesthesia. Selective MMA angiography was obtained before embolization. Embolization was performed using liquid embolic agents and/or coils. The choice of embolic material was individualized according to anatomical considerations, including MMA caliber, vessel tortuosity, and the presence of hazardous anastomoses, as well as technical availability. In cases involving potentially dangerous anastomoses (e.g., ophthalmic artery connections), the microcatheter was advanced distally beyond the bifurcation of the frontal and parietal branches before embolization. Patients with bilateral cSDH underwent bilateral embolization during the same session. All procedures were performed via transfemoral access using a three-axis distal access system (Fig. 1).

Follow-up and Radiological Assessment

Clinical and radiological data were collected retrospectively from hospital records. All patients underwent non-contrast computed tomography (nCCT) before embolization, and early inpatient computed tomography (CT) scans were obtained within 48 hours after the procedure to assess for complications or procedure-related hemorrhage. Follow-up imaging was performed at approximately 6 weeks, and functional outcomes were evaluated at 90 days using the modified Rankin Scale (mRS) based on available records. A favorable clinical

outcome was defined as an improvement of at least one point in mRS compared with baseline. Radiological analyses were primarily based on six-week follow-up imaging. All images were retrospectively reviewed for hematoma laterality, maximum hematoma thickness, midline shift (MLS), presence of internal membranes, postoperative hemorrhage, newly developed ischemic lesions, and other intracranial findings potentially related to the intervention. Hematoma thickness and MLS were measured on coronal nCCT images. MLS was defined as the perpendicular distance from the anatomical midline—determined by a line connecting the crista frontalis and the posterior falx cerebri—to the septum pellucidum (Fig. 2).

Statistical Analysis

Statistical analyses were performed using SPSS software (version 21.0; IBM Corp., Armonk, NY, USA). Continuous variables were expressed as mean ± standard deviation (SD), whereas categorical variables were presented as frequencies and percentages. Comparisons between the embolization-only and embolization-plus-surgery groups were performed using the independent samples t-test for continuous variables and the chi-square test for categorical variables. Receiver operating characteristic (ROC) curve analysis was performed to evaluate the predictive performance of preprocedural midline shift for the need for subsequent surgical intervention. A p-value <0.05 was considered statistically significant.

RESULTS

A total of 52 patients with a documented history of cranial trauma who underwent middle meningeal artery embolization for chronic subdural hematoma were included in the final analysis. The mean patient age was 66.5±15.7 years (range, 25–89 years), and 43 patients (82.7%) were male. Comorbidi-

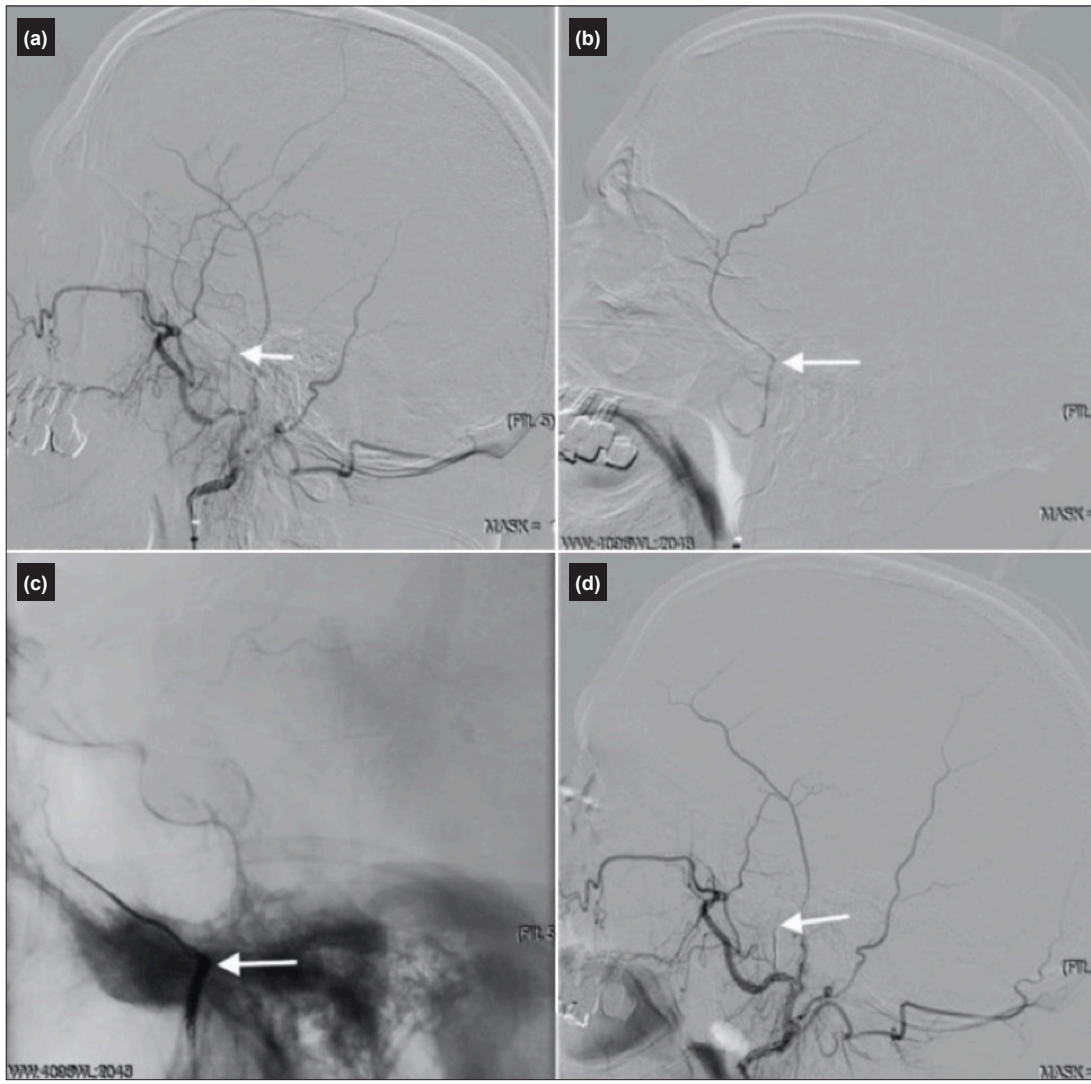

Figure 1. (a) Preoperative digital subtraction angiography (DSA) demonstrating the middle meningeal artery (MMA). **(b)** Selective angiography of the MMA. (**c**) Deployment of coil embolization material within the MMA. **(d)** Post-embolization control angiography demonstrating successful occlusion.

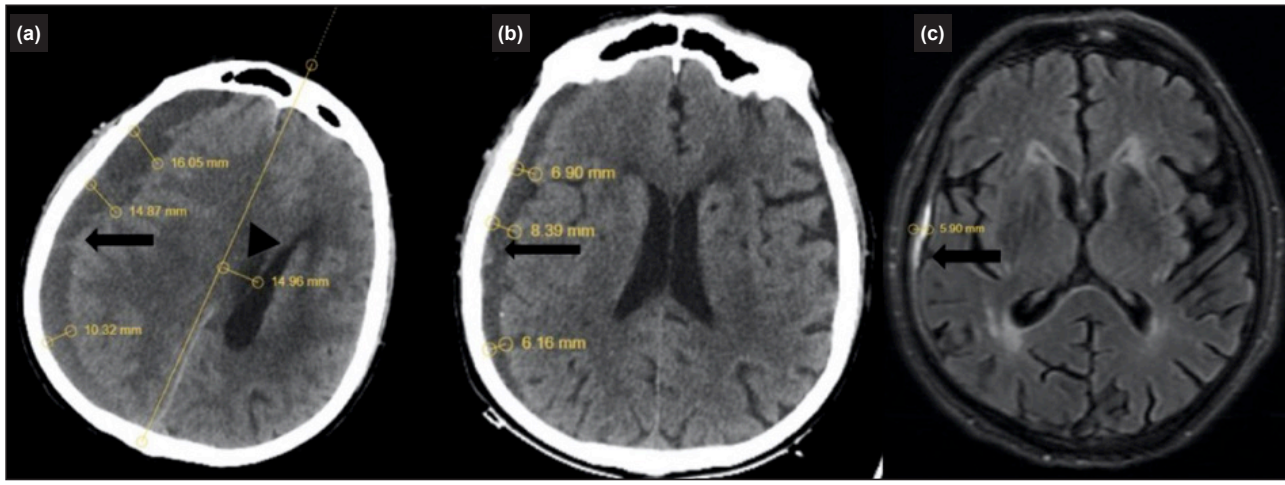

Figure 2. (a) Preoperative computed tomography (CT) image demonstrating measurements of hematoma thickness and midline shift (MLS). **(b)** Sixth-week follow-up CT image after embolization alone. **(c)** Third-month follow-up magnetic resonance imaging (MRI) demonstrating radiological resolution. ↑: hematoma thickness; ▲: midline shift (MLS).

ties were present in 28 patients (53.8%), including hypertension, diabetes mellitus, coronary artery disease, and atrial fibrillation. Regarding antithrombotic therapy, 19.2% of patients were receiving acetylsalicylic acid, 7.7% were receiving prasugrel, 7.7% were receiving warfarin, and one patient was receiving multiple antiplatelet agents. Among the study population, 43 patients (82.7%) were treated with embolization alone, whereas nine patients (17.3%) required subsequent surgical evacuation following embolization. No statistically significant differences were observed between the embolization-only and embolization-plus-surgery groups regarding demographic characteristics or comorbidities (p>0.05) (Table 1).

Hematomas were located on the right side in 20 patients (38.5%), on the left side in 23 patients (44.2%), and bilaterally in nine patients (17.3%). The mean preprocedural hematoma thickness was 20.7±7.9 mm, and the mean MLS was 5.1±4.0 mm. Among patients who required surgical intervention, mini-craniotomy was performed in eight patients (88.9%), whereas burr-hole evacuation was performed in one patient (11.1%). Procedure-related complications following embolization occurred in two patients, including one case of transient facial paralysis and one case of palpebral edema. When treatment groups were compared, the mean preprocedural MLS was 4.5±3.8 mm in the embolization-only group and 7.6±3.9 mm in the embolization-plus-surgery group. This difference was statistically significant (p=0.03). However, no statistically significant between-group differences were observed in baseline hematoma thickness or other baseline radiological parameters (p>0.05). At the six-week follow-up, no significant differences were observed between groups regarding residual hematoma thickness or midline shift (p>0.05) (Table 1).

Table 1. Comparison of demographic characteristics, comorbidities, and radiological outcomes between treatment groups

Variable	Embolization only (n=43)	Embolization + surgery (n=9)	p
Age (years)	67.4±15.9	62.2±14.9	0.36*
Sex (Male/Female)	35 (67.3%)/8 (15.4%)	8 (15.4%)/1 (1.9%)	0.59≠
Comorbidities (Yes/No)	25 (48.1%)/18 (34.6%)	2 (3.8%)/7 (13.5%)	0.06≠
Preprocedural MLS (mm)	4.5±3.8	7.6±3.9	0.03*
Postprocedural MLS (mm, 6 weeks)	0.6±1.6	1.8±2.7	0.08*
Preprocedural SDHT (mm)	20.9±7.9	20.0±8.2	0.77*
Postprocedural SDHT (mm, 6 weeks)	8.1±6.7	9.2±10.6	0.06*

*Continuous variables are presented as mean ± standard deviation (min-max) and were compared using the independent samples t-test. ≠Categorical variables are presented as number (%) and were compared using the chi-square test. A p-value <0.05 was considered statistically significant. MLS: Midline shift; SDHT: Subdural hematoma thickness.

Table 2. Distribution of modified Rankin Scale scores at admission, post-intervention, and 90-day follow-up

mRS score	Admission n (%)	Post-intervention n (%)	90-day follow-up n (%)
0	-	-	20 (38.5%)
1	-	2 (3.8%)	14 (26.9%)
2	7 (13.5%)	4 (7.7%)	8 (15.4%)
3	37 (71.2%)	38 (73.1%)	5 (9.6%)
4	6 (11.5%)	6 (11.5%)	3 (5.8%)
5	2 (3.8%)	0	0
6 (death)	0	0	2 (3.8%)

mRS: Modified Rankin Scale.

ROC curve analysis demonstrated that preprocedural MLS was significantly associated with the need for subsequent surgical intervention following embolization, with an area under the curve (AUC) of 0.73, indicating acceptable discriminatory performance. An MLS threshold of 4.5 mm provided the optimal balance between sensitivity and specificity, yielding a sensitivity of 78% and specificity of 56% (Fig. 3).

Clinical outcomes were assessed using the mRS. The distribution of mRS scores at admission and at the 90-day follow-up is presented in Table 2. Overall, functional status improved at 90 days compared with baseline. Two patients (3.8%) died during follow-up due to pulmonary complications unrelated to the embolization procedure.

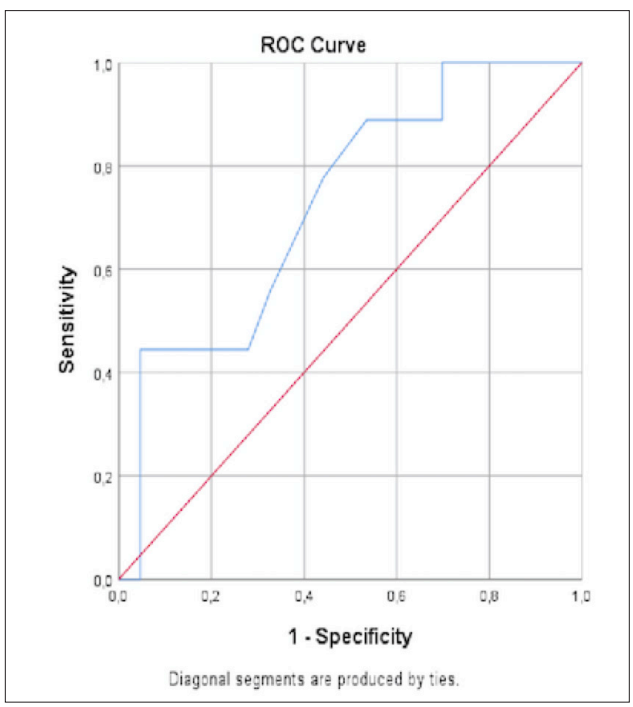

Figure 3. Receiver operating characteristic (ROC) curve analysis of preprocedural midline shift (MLS) for predicting the need for subsequent surgical intervention. Area under the curve (AUC)=0.73; optimal cut-off value 4.5 mm (sensitivity 78%, specificity 56%).

DISCUSSION

In this retrospective study, we evaluated the clinical and radiological outcomes of different treatment strategies in patients with cSDH and a documented history of cranial trauma. Our findings suggest that MMA embolization is associated with favorable radiological evolution and acceptable clinical outcomes, particularly in carefully selected patients.

Over the past decade, MMA embolization has emerged as a promising minimally invasive endovascular treatment strategy for cSDH.[5,6] The rationale for this approach is based on the pathophysiology of cSDH, in which fragile neomembranes supplied predominantly by distal branches of the MMA contribute to persistent inflammation, recurrent microhemorrhage, and progressive hematoma expansion.[3,7] By targeting this vascular supply, embolization aims to interrupt the cycle of rebleeding and membrane-driven exudation, thereby promoting hematoma stabilization and gradual resorption.[3,6]

Despite growing evidence supporting its efficacy, integration of MMA embolization into routine clinical practice remains cautious. Concerns regarding its relatively recent adoption, procedural cost, variability in embolic materials and techniques, and the absence of universally accepted selection criteria continue to influence treatment decisions. Additionally, heterogeneity among published studies contributes to ongoing debate regarding optimal indications and patient selection.

Early observational studies reported encouraging technical and clinical outcomes, demonstrating high procedural success rates and meaningful radiological resolution.[15-18] Campos et al.[15] reported a technical success rate of 100% in a cohort of 132 patients, with complete radiological resolution observed in nearly half of cases. More recently, higher-level evidence has emerged. In a large multicenter randomized trial includ-

ing 310 patients, Fiorella et al.,[16] demonstrated that MMA embolization significantly reduced recurrence and treatment failure rates compared with standard management alone. These findings are further supported by contemporary meta-analyses. A systematic review by Chen et al.[17] concluded that both standalone embolization and combined embolization with surgical evacuation are effective approaches, with treatment selection largely influenced by baseline hematoma characteristics. Similarly, the meta-analysis of randomized controlled trials by Papageorgiou et al.[18] demonstrated a significant reduction in recurrence rates with MMA embolization. Collectively, accumulating evidence—from observational studies to randomized trials and meta-analyses—supports MMA embolization as a safe and effective therapeutic option, particularly in carefully selected patients. Importantly, most large randomized trials have included heterogeneous cSDH populations, whereas the present study specifically focused on trauma-related cases, providing a more etiologically homogeneous cohort.

While several recent meta-analyses have consistently shown reduced recurrence and progression rates after MMA embolization, improvements in functional outcomes have not been uniformly demonstrated. For example, the systematic review by Kabir et al.[19] reported lower recurrence rates without significant improvement in functional outcomes. Similarly, pooled analyses of randomized trials, including MAGIC-MT (Managing Non-acute Subdural Hematoma Using Liquid Materials: A Chinese Randomized Trial of Middle Meningeal Artery Treatment), STEM (SQUID Trial for the Embolization of the Middle Meningeal Artery for the Treatment of Chronic Subdural Hematoma), and EMBOLISE (Embolization of the Middle Meningeal Artery to Prevent Recurrence of Chronic Subdural Hematoma), demonstrated reduced hematoma progression but no clear superiority in functional recovery.[3,16,20,21] In contrast, we observed significant improvement in mRS scores at 90 days compared with baseline. Two patients died during follow-up; however, neither death was attributable to the embolization procedure. Nevertheless, this finding should be interpreted cautiously because the present study did not include a non-embolization control group, and observed functional improvement may partially reflect the natural clinical course of cSDH rather than the isolated effect of embolization.

In our cohort, embolization was performed either as a primary treatment or in combination with surgical evacuation during the same session. Importantly, patients treated with embolization alone demonstrated significantly lower baseline midline shift values than those who subsequently required surgery, suggesting that treatment allocation was influenced by initial disease severity. These findings further emphasize the importance of individualized treatment selection in patients with trauma-related cSDH. Although radiological improvement was observed in both treatment groups, baseline midline shift differed significantly between patients managed with embolization alone and those requiring additional surgical evacuation, indicating that initial disease severity played a central role in therapeutic decision-making. Rather than reflecting differences in intrinsic treatment efficacy, the observed outcomes appear to be closely associated with appropriate patient stratification. Therefore, careful assessment of radiological findings and clinical status remains essential when determining the optimal treatment strategy.

ROC curve analysis demonstrated that preprocedural MLS was associated with the need for subsequent surgical intervention, with an AUC of 0.73, indicating acceptable discriminatory performance. An MLS threshold of 4.5 mm provided the optimal balance between sensitivity (78%) and specificity (56%). Although specificity was moderate, this threshold may serve as a practical reference value for treatment planning and patient counseling. Given its simplicity and broad availability, MLS represents a pragmatic radiological parameter for risk stratification.

This study has several limitations. First, its retrospective, non-randomized design limits causal inference and introduces the potential for selection bias. Second, the relatively small sample size reduced statistical power and precluded multivariable adjustment. Furthermore, treatment decisions were based on institutional practice patterns rather than predefined standardized criteria. These limitations should be considered when interpreting the present findings.

CONCLUSION

In this cohort of patients with trauma-related cSDH, MMA embolization was associated with hematoma regression and functional stabilization or improvement in functional outcomes in appropriately selected cases. Patients managed with embolization alone demonstrated lower baseline midline shift values, reflecting real-world selection of patients with less severe disease.

Preprocedural midline shift showed moderate predictive value for subsequent surgical intervention, and a threshold of 4.5 mm may aid treatment stratification. MMA embolization appears to be a safe and clinically feasible therapeutic option, serving not only as an adjunct to surgery but also as a viable alternative in carefully selected patients. Prospective randomized studies with larger cohorts are warranted to better define treatment indications and optimize patient selection.

Ethics Committee Approval: This study was approved by the Ankara Bilkent City Hospital Clinical Research Ethics Committee (Date: 04.02.2026, Decision No: TABED 2-26-1988).

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Authorship Contributions: Concept: A.E.S., H.E.Ç.; Design: A.E.S., H.E.Ç.; Supervision: E.D., B.S.; Resource: E.D., A.E.S., B.S.; Materials: H.E.Ç., A.E.S., M.O.Ö., A.E.A.; Data collection and/or processing: A.E.S., M.O.Ö., H.E.Ç.; Analysis and/or interpretation: A.E.S., H.E.Ç., A.E.A.; Literature re-

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ORİJİNAL ÇALIŞMA - *ÖZ*

Travmaya bağlı kronik subdural hematomda middle meningeal arter embolizasyonunun klinik sonuçları

AMAÇ: Middle meningeal arter (MMA) embolizasyonu, kronik subdural hematom (kSDH) tedavisinde umut verici bir terapötik seçenek olarak öne çıkmıştır. Ancak özellikle travmaya bağlı kSDH olgularına odaklanan veriler sınırlıdır. Bu çalışmada, travmaya bağlı kSDH hastalarında MMA embolizasyonunun güvenliğinin ve klinik sonuçlarının değerlendirilmesi ve tedavi başarısının radyolojik belirleyicilerinin araştırılması amaçlanmıştır.
GEREÇ VE YÖNTEM: Bu retrospektif çalışmaya, 2024–2025 yılları arasında kurumumuzda travmaya bağlı kSDH nedeniyle MMA embolizasyonu uygulanan hastalar dahil edilmiştir. Demografik, klinik ve radyolojik veriler - orta hat kayması (MLS) ve hematom kalınlığı - sistematik olarak toplanmıştır. Fonksiyonel sonuçlar, modifiye Rankin Skalası (mRS) kullanılarak değerlendirilmiştir. Nüks, cerrahi gereksinimi, işleme bağlı komplikasyonlar ve mortalite kaydedilmiştir. MLS'nin tedavi başarısızlığını öngörmedeki değerini değerlendirmek amacıyla ROC analizi yapılmıştır.
BULGULAR: Travma öyküsü bilinen toplam 52 hasta çalışmaya dahil edilmiştir. Kırk üç hastada (%82.7) yalnızca embolizasyon uygulanırken 9 hastada (%17.3) embolizasyon ve cerrahi kombine edilmiştir. İşlem öncesi MLS değeri, yalnızca embolizasyon uygulanan gruba kıyasla embolizasyon + cerrahi grubunda anlamlı olarak daha yüksek bulunmuştur (7.6±3.9 mm'ye karşı 4.5±3.8 mm; p=0.03). Altıncı haftada rezidüel hematom kalınlığı veya MLS açısından gruplar arasında anlamlı fark saptanmamıştır (p>0.05). Doksanıncı günde fonksiyonel durumun başlangıca göre iyileştiği gözlenmiştir. 4.5 mm'lik MLS eşik değeri, tedavi başarısızlığını öngörmede en yüksek prediktif doğruluğu göstermiş olup %78 duyarlılık ve %56 özgüllük sağlamıştır.
SONUÇ: MMA embolizasyonu, travmaya bağlı kSDH tedavisinde güvenli ve klinik olarak uygulanabilir bir seçenek gibi görünmektedir. Uygun hasta seçimi yapıldığında cerrahiye hem tamamlayıcı hem de alternatif bir yaklaşım olarak değerlendirilebilir. MLS, risk sınıflandırması ve hasta seçimi açısından pratik ve erişilebilir bir parametre olabilir. Bu bulguların doğrulanması için prospektif kontrollü çalışmalara ihtiyaç vardır.

Anahtar sözcükler: Kronik subdural hematom; middle meningeal arter embolizasyonu; travma.

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