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Middle Meningeal Artery Embolization in Chronic Subdural Hematomas: A Literature Review

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Abstract. Chronic subdural hematoma (CSDH) is one of the most common neurosurgical conditions and is associated with considerable morbidity, mortality, and recurrence despite standard surgical treatment. Although burr-hole evacuation with postoperative drainage remains the main treatment for symptomatic CSDH, recurrence continues to occur even after optimization of surgical technique. Contemporary evidence suggests that CSDH is not merely a passive accumulation of blood, but a dynamic pathological process driven by inflammation, angiogenesis, hyperfibrinolysis, and the formation of vascularized neomembranes. These mechanisms provide the rationale for middle meningeal artery embolization (MMAE), which aims to reduce the arterial supply to the pathological outer membrane and interrupt the self-perpetuating cycle of microbleeding and hematoma persistence.

This review summarizes the pathophysiology of CSDH, current standard surgical treatment, the technical principles of MMAE, and the clinical evidence supporting its use. Early observational studies and retrospective series suggested reduced recurrence and favorable hematoma resolution after MMAE. More recently, randomized controlled trials including EMBOLISE, STEM, and MAGIC-MT have provided higher-level evidence, generally supporting the potential safety and efficacy of MMAE in selected patients, although results vary according to treatment setting and outcome definition. Meta-analytic evidence suggests a possible reduction in symptomatic recurrence or progression, particularly in nonsurgically managed patients, but heterogeneity between trials limits definitive conclusions.

Keywords: chronic subdural hematoma, middle meningeal artery embolization.

Vidurinės meninginės arterijos embolizacija gydant lėtinę subduralinę hematomą: literatūros apžvalga

Santrauka. Lėtinė subduralinė hematoma (LSH) yra dažna neurochirurginė būklė, susijusi su dideliu sergamumu, mirštamumu ir recidyvų dažniu, nepaisant standartinio chirurginio gydymo. Hematomos šalinimas ir drenavimas per trefinacinę angą išlieka pagrindinis simptominės LSH gydymo metodas, tačiau recidyvų pasitaiko net ir optimizavus chirurginę techniką. Šių dienų duomenys rodo, kad LSH yra ne tik pasyvus kraujo kaupimasis, bet ir dinamiškas patologinis procesas, kurį skatina uždegimas, angiogenezė, hiperfibrinolizė ir vaskuliarizuotų neomembranų susidarymas. Šie mechanizmai pagrindžia vidurinės meninginės arterijos embolizaciją (VMAE).

Straipsnyje apibendrinama LSH patofiziologija, dabartinis standartinis chirurginis gydymas, techniniai VMAE principai ir klinikiniai įrodymai, pagrindžiantys jos taikymą. Ankstyvieji stebėjimo tyrimai ir retrospektyvinės serijos rodo mažesnį recidyvų skaičių ir palankų hematomos nykimą atlikus VMAE. Pastaruoju metu atlikti atsitiktinių imčių kontroliuojami tyrimai, įskaitant EMBOLISE, STEM ir MAGIC-MT, pateikė aukštesnio lygio įrodymų, kurie patvirtina VMAE saugumą ir galimą veiksmingumą atrinktiems pacientams, nors rezultatai skiriasi priklausomai nuo gydymo sąlygų ir baigties apibrėžimo. Metaanalizės duomenys rodo galimą simptominio atsinaujinimo ar progresavimo sumažėjimą, ypač pacientams, kuriems nebuvo atlikta chirurginė intervencija. Vis dėlto tyrimų įvairovė riboja galimybę daryti galutines išvadas.

Reikšminiai žodžiai: lėtinė subduralinė hematoma, vidurinės meninginės arterijos embolizacija.

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Introduction

Chronic Subdural Hematoma (CSDH) is among the most common neurosurgical conditions, with an incidence that rises in parallel with the aging population and increased use of anticoagulant and antiplatelet therapies [1]. Despite commonly being considered a benign condition, CSDH is associated with significant morbidity and mortality, as well as a risk of recurrence after standard surgical evacuation [2]. Even with optimized surgical treatment with postoperative drainage, recurrence remains a clinically significant problem with Santarius et al. [2] reporting a recurrence rate of 9%.

Contemporary evidence suggests CSDH to be a dynamic pathological process driven by persistent inflammation, angiogenesis and hyperfibrinolysis, rather than a simple accumulation of blood [3]. The evolving understanding has highlighted limitations of standard surgical treatment, which focuses on the hematoma evacuation but does not target the underlying causes for recurrence.

Middle Meningeal Artery Embolization (MMAE) is emerging as a new therapeutic strategy to devascularize the pathological neomembranes by occluding their main arterial supply from the middle meningeal artery. Early clinical studies such as Ban et al. [4] demonstrated favorable outcomes with recurrence observed in 1 out of 72 patients treated with MMAE either as standalone or adjunct therapy to surgery. In recent years, multiple randomized controlled trials have been published providing high-quality evidence demonstrating favorable outcomes after MMAE. The aim of this review is to provide a comprehensive overview of the pathophysiology of CSDH, the rationale and technique of MMAE, and the current clinical evidence supporting its use.

Pathophysiology

Chronic subdural hematoma is now understood as a dynamic and self-sustaining pathological process rather than a passive liquefaction of blood. CSDH usually follows minor head trauma, during which rupture of the bridging veins results in bleeding into the subdural space [3]. This initial hemorrhage triggers an inflammatory cascade characterized by activation and recruitment of immune cells, as well as stimulation of the dural border cells. These processes lead to the formation of inflammatory neomembranes surrounding the hematoma cavity [5].

The neomembrane is composed of distinct inner and outer layers [6]. Histopathological studies have demonstrated that this outer membrane consists of proliferating fibroblasts, inflammatory cells and an extensive network of newly formed capillaries [5, 6]. These vessels were shown to be structurally immature and highly permeable, lacking normal endothelial integrity, which predisposes them to continuous leakage and recurrent microhemorrhage [7].

Chronic inflammation plays a central role in maintaining this pathological environment. Elevated levels of inflammatory mediators and cytokines promote ongoing cellular proliferation and tissue remodelling within the membrane. In parallel, angiogenesis is a result of the increased expression of pro-angiogenic factors, particularly vascular endothelial growth factor (VEGF), leading to the formation of fragile neovessels perpetuating the bleeding into the subdural space [3, 8].

In addition, a state of enhanced fibrinolysis has been demonstrated within the hematoma fluid. Increased fibrinolytic activity prevents stable clot formation, resulting in hematoma liquefaction and persistence. This creates the self-sustaining cycle of microbleeding, inflammation and impaired coagulation which continuously reinforces itself [6].

Importantly, the vascular supply to the outer membrane is predominantly derived from the middle meningeal artery, which serves as a key driver of the ongoing pathological process. Understanding the

pathophysiological processes underlying the CSDH helps explain why the standard surgical evacuation is insufficient in many cases and recurrence remains common. MMAE is designed to target the key mechanisms of CSDH and aims to interrupt the self-perpetuating pathological cycle [9].

Standard surgical treatment

Surgical evacuation remains the standard treatment for symptomatic CSDH, particularly in patients presenting with neurological deficits, significant mass effect, or clinical deterioration. The most commonly used approach is a burr-hole craniostomy to achieve evacuation of hematoma. Studies have shown that placing of postoperative drainage further improved outcomes and reduced recurrence [2, 10]. However the literature describes a variety of surgical strategies, including twist-drill craniostomy with catheter drainage, larger craniotomy with hematoma evacuation and membranectomy, and small craniotomy with endoscopic evacuation [10].

Regarding burr-hole craniostomy, several studies have compared outcomes with and without postoperative drainage in an effort to further optimize surgical treatment. In a meta-analysis including 10 studies with 1,961 patients, postoperative drainage was associated with a lower mortality rate compared with non-drainage (OR = 0.65, 95% CI 0.43 to 0.97; $P = 0.04$). Additionally, the drainage group showed a lower rate of recurrence (OR = 0.39, 95% CI 0.28 to 0.55; $P < 0.00001$) [11].

Another meta-analysis compared subdural drainage (SDD) against subperiosteal (SPD) drainage, including 10 articles where 1,553 patients were being treated with SPD against 1782 who were being treated with SDD. The study reported a slightly lower recurrence rate in SPD in comparison to SDD (11.9 and 12.3%). The mortality rate was reported to be lower in SDD without showing statistical significance (5.0% for SPD and 4.6% for SDD). Overall, the authors concluded that the insertion of a SPD may be more favorable than SDD [12].

The optimal duration of postoperative drainage has also been investigated as a factor in surgical optimization. In a meta-analysis including seven studies with a total of 1,842 patients, six-day drainage showed the highest probability of reducing recurrence with a probability of 86.2%, compared with 13.8% for three-day drainage. Shorter drainage durations, particularly less than 24 hours, were associated with a higher risk of recurrence [13].

In a major meta-analysis, recurrence was reported across 174 studies including 34,393 patients treated with burr-hole surgery and postoperative drainage. The pooled recurrence incidence was 11.2% (95% CI: 10.3–12.1; $I^2 = 87.7\%$). In a subgroup analysis of 48 higher quality studies including 15,298 patients the pooled recurrence incidence was higher at 12.8% (95% CI 11.4–14.2; $I^2 = 86.1\%$). The authors suggested that recurrence may be underestimated in some studies and recommend using 12.8% as an outcome measure for power calculations in future research [14].

Taken together, these findings suggest that even with optimization of surgical technique, patients remain at risk of substantial recurrence, which may lead to clinically unfavorable outcomes.

MMAE technique

MMAE is a minimally invasive endovascular procedure aimed at occluding the arterial supply to the vascularized outer membrane in CSDH. Unlike surgical evacuation, which primarily removes the hematoma and relieves mass effect, MMAE targets the underlying vascularity thought to maintain hematoma persistence and recurrence. By reducing perfusion to the pathological neomembrane, embolization aims to

interrupt the inflammatory and angiogenic cycle responsible for repeated microhemorrhage and continued hematoma expansion [9].

The procedure can be performed through different endovascular approaches: transradial and transfemoral [1, 15]. After vascular access is established, a guide catheter is advanced into the proximal external carotid or distal common carotid artery, followed by selective microcatheterization into the middle meningeal artery. Selective angiography is performed to confirm the anatomy of the MMA, identify the frontal and parietal branches, and evaluate for potentially dangerous anastomoses [4, 16]. Particular attention must be paid to connections with the ophthalmic artery, internal carotid artery, or branches supplying the cranial nerves, as non-target embolization may result in serious complications [4, 17].

Once the safe catheter position has been confirmed, embolization is performed. The prior through angiography selected target vessels are embolized while dangerous collaterals and the petrosal branches are avoided [4, 15]. The technical endpoint of the procedure is achieved when flow stasis is observed within the middle meningeal artery and its targeted branches [4]. The procedure can be performed under general anesthesia, moderate/light sedation, or no sedation in selected cases, potentially reducing the physiological burden on medically fragile patients [1, 16].

Although MMAE is considered to be a generally safe procedure, several potential complications must be considered, many of which are related to non-target embolization. These include ischemic events, cranial nerve injury, visual complications, skin or scalp necrosis, and access-site complications [17, 18]. In early clinical series Link et al. [1] reported no procedure-related complications in 50 embolizations, while Ban et al. [4] similarly reported no procedure-related complications in 72 embolizations.

The procedure can be done using different embolic agents. The most commonly used ones are particulate agents such as polyvinyl alcohol particles (PVA) or liquid embolic agents including Onyx or n-butyl cyanoacrylate (nBCA). Liquid agents are described to allow more continuous penetration into the distal vascular network of the pathological membranes [15]. In a study including 94 embolizations, the effectiveness of Onyx and PVA was compared. The authors reported no clinically relevant difference between the two groups and concluded that treatment can be safely performed using either embolic agent. However, they also emphasized that both agents have distinct technical characteristics that may influence procedural planning and operator preference [16].

In another study including 41 embolizing procedures, different embolic agents were used according to the preference of the treating physician. No clinically relevant differences between Onyx, nBCA and particles, or particles with coils were observed. The authors emphasized that successful embolization of both the anterior and posterior divisions of the middle meningeal artery was more important for complete CSDH resolution than the specific embolic agent used. They further suggested that the choice of embolic agent may therefore be guided by operator preference [15]. Less commonly, coils have also been described as an embolic option during MMAE [15, 17].

Clinical outcomes and current evidence for MMAE

Early observational studies first suggested that MMAE may be effective in reducing recurrence and promoting hematoma resolution. In a study including 72 embolization procedures and a historical control group of 469 patients treated with observation or surgical evacuation, MMAE was associated with improved outcomes compared with the control group. Treatment failure was significantly lower in the MMAE group than in the control group (one of 72 patients [1.4%] vs. 129 of 469 patients [27.5%]). Similarly the need for surgical rescue was lower after MMAE compared with conventional treatment (one of 72 patients

[1.4%] vs. 88 of 469 patients [18.8%]). Based on these findings, the authors suggested that MMAE may be considered as an alternative treatment strategy in selected patients [4].

Following such initial promising reports, several retrospective studies further supported the potential role of MMAE, reporting lower recurrence rates and favorable clinical outcomes in selected patients [19, 20]. More recently, three major randomized controlled trials have been published, providing higher-level evidence regarding the efficacy and safety of MMAE as an adjunctive or alternative treatment strategy for CSDH [21–23].

A major area of evidence for MMAE has emerged from studies evaluating its use as an adjunct treatment to surgical evacuation. The EMBOLISE randomized controlled trial included a total of 400 patients with 197 being randomly assigned to the treatment group (MMAE plus surgery) and 203 to the control group (surgery alone). Recurrence or progression requiring repeat surgery occurred less frequently in the MMAE plus surgery group than in the surgery alone group (8 patients [4.1%] vs. 23 patients [11.3%]).

The risk of functional deterioration was noted to be similar in both groups, 11.9% in the treatment group and 9.8% in the control group. Mortality at 90 days was noted to be numerically higher in the treatment group (5.1%) compared to the control group (3.0%). The trial was able to show significantly lower risk of recurrence which would lead to further surgical interventions, but did not show better functional outcomes or mortality rates. The authors suggest that further studies with more participants are needed for proper evaluation for safety and efficacy of the procedure [21].

The STEM randomized controlled trial further explored the role of adjunctive MMAE in symptomatic CSDH treatment. Patients were randomized into standard treatment with adjunctive MMAE or to standard treatment alone. Standard treatment, which could be surgical or nonsurgical, was determined before randomization. A total of 310 patients were enrolled with 149 assigned to the adjunctive MMAE group and 161 to the control group. Treatment failure occurred less frequently in the MMAE group than in the control group (16% vs. 36%). Interestingly, the authors noted that the observed benefit of MMAE appeared more pronounced in patients managed nonsurgically than in those undergoing surgical treatment, suggesting that future research should further clarify which patient subgroups benefit most from adjunctive embolization. Through 180 days, all-cause mortality was 8% in the embolization group and 5% in the control group, while neurologic-cause mortality was 1% and 2%, respectively. The authors concluded that adjunctive MMAE reduced the risk of recurrence or treatment failure without increasing the short-term incidence of disabling stroke or death. However, further research is still needed to better define the long-term safety profile of the treatment [22].

MAGIC-MT was another randomized controlled trial including 722 patients with symptomatic nonacute subdural hematomas with mass effect. Patients were assigned to nonsurgical treatment or burr-hole drainage at the surgeon's discretion before randomization. They were then randomized to adjunctive MMAE or usual care alone. The MMAE group showed a numerically lower rate of symptomatic recurrence or progression, 6.7% vs. 9.9%, but this difference was not statistically significant. Furthermore, the incidence of serious adverse events was reported to be lower in the MMAE group compared to the usual care group (6.7% vs. 11.6%). Among the major randomized trials, MAGIC-MT was the only study that did not demonstrate a significant reduction in symptomatic recurrence or progression, although it reported a lower incidence of serious adverse events in the MMAE group compared with usual care [23].

Overall, the randomized evidence suggests that MMAE can reduce recurrence, progression, or treatment failure in selected patients with CSDH. However, the magnitude of benefit appears to vary according to treatment strategy, with stronger signals in adjunctive or nonsurgically managed cohorts than in

uniformly surgically treated populations. These differences highlight the importance of patient selection and outcome definition when interpreting the current evidence.

A meta-analysis of the three published randomized controlled trials, MAGIC-MT, STEM, and EMBOLISE, included 1,432 patients and found that MMAE was associated with a numerically lower risk of symptomatic recurrence or progression, although the overall effect did not reach statistical significance (RR 0.50, 95% CI 0.23–1.06; $P = 0.058$). This suggests a possible treatment effect, but the available pooled RCT data remain underpowered or heterogeneous for a definitive conclusion on symptomatic recurrence/progression. No significant improvement in functional outcome was observed. However, subgroup analysis suggested that MMA embolization significantly reduced hematoma progression in nonsurgically managed patients, whereas no significant reduction in recurrence was demonstrated among surgically treated patients [24].

Interpretation of this meta-analysis is limited by heterogeneity between the included trials, including differences in patient selection, surgical versus nonsurgical management, embolic agents, follow-up duration, and primary outcome definitions. Furthermore, the absence of individual patient data limited adjustment for baseline differences and prevented more detailed subgroup analyses. The open-label design of the included trials and the lack of standardized surgical rescue or reoperation endpoints further complicate direct comparison between studies [24].

Discussion

The current evidence supports MMAE as a promising addition to the management of CSDH, particularly because it addresses a mechanism not directly targeted by conventional surgical evacuation. While burr-hole evacuation remains effective for rapid decompression, recurrence persists despite technical optimization, suggesting that hematoma removal alone may be insufficient in selected patients [9, 14]. MMAE offers a biologically rational approach by targeting the vascular supply of the outer neomembrane, which is involved in the inflammatory and angiogenic cycle underlying hematoma persistence [3, 5].

The clinical evidence has evolved from early observational studies to randomized controlled trials. Overall, these studies suggest that MMAE can reduce recurrence, progression, or treatment failure in selected patients [1, 4, 21, 22]. However, the benefit is not uniform across all trials. EMBOLISE and STEM showed favorable results, whereas MAGIC-MT demonstrated only a numerical, non-significant reduction in symptomatic recurrence or progression [21–23]. These differences likely reflect variation in patient selection, surgical versus nonsurgical management, timing of embolization, and outcome definitions [24].

Therefore, MMAE should not yet be considered a universal replacement for surgery. Its most appropriate role may be as an adjunctive treatment in patients at increased risk of recurrence, as an option in recurrent CSDH, or as a less invasive strategy in selected patients managed nonsurgically [21, 22, 24]. At the same time, the procedure requires careful angiographic assessment because complications related to non-target embolization, although uncommon, may be serious [17, 18].

Future studies should focus less on whether MMAE "works" in general and more on defining which patients benefit most, the optimal timing of embolization, and whether technical factors such as embolic agent, extent of distal penetration, or embolization of specific MMA branches influence outcomes [15, 16, 24]. Standardized endpoints and longer follow-up will be essential to determine the long-term durability and safety of the procedure [24]. Current evidence supports its use in selected patients with CSDH, but further data are needed before its role can be fully standardized within treatment algorithms.

Author contributions

Nikolai Stolz – conducted literature search, data extraction, drafting of the initial manuscript.
Gytis Šustickas – conceptualization, supervision, validation, writing (review and editing).

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