Review article

Ukrainian Neurosurgical Journal. 2025;31(2):3-9
doi: 10.25305/unj.326236

Application of endovascular embolization of the middle meningeal artery in the treatment of chronic subdural hematomas: A literature review

Yurii O. Kotlyarevskyi [1], Yuliia G. Serhiienko [2], Volodymyr O. Piatykop [2]

[1] Department of Neurosurgery, Kharkiv Clinical Hospital on Railway Transport No 1, Branch "Healthcare Center," JSC "Ukrzaliznytsia", Kharkiv, Ukraine
[2] Department of Neurosurgery, Kharkiv National Medical University, Kharkiv, Ukraine

Received: 05 April 2025
Accepted: 07 May 2025

Address for correspondence*: Yuliia G. Serhiienko, Department of Neurosurgery, Kharkiv National Medical University, Nauky Avenue, 4, Kharkiv, 61000, Ukraine, e-mail: yh.serhiienko@knmu.edu.ua*

Introduction. Interest in this research topic arises from the fact that chronic subdural hematoma (CSDH) is currently one of the most common neurosurgical diagnoses in adults. Over the past decade, the incidence of CSDH has more than doubled. Recent studies have significantly enhanced our understanding of the mechanisms underlying the formation of CSDH, linking it to recurrent microbleeds in the subdural space from fragile, newly formed vessels within the hematoma capsule. Most of these vessels originate from the distal branches of the middle meningeal artery (MMA). Accordingly, endovascular embolization of the MMA may help eliminate chronic recurrent bleeding into the subdural space and facilitate hematoma resorption.

Objective of the study. To summarize current concepts regarding the pathophysiology of CSDHs and analyze the implementation and use of endovascular embolization of the MMA in contemporary treatment strategies for CSDH based on literature data.

Results. A detailed analysis of the literature indicates that a new understanding of the primary pathological process of CSDH has substantiated approaches to diagnosing and treating this pathology as an angiogenic process. Recent research findings demonstrate that endovascular embolization of the MMA in patients with CSDH is a safe and effective method to prevent recurrence or progression of subdural hematomas. Comparing different classes of embolic materials in the treatment of patients with CSDH represents the next step in ongoing research aimed at standardizing the overall treatment protocol for chronic subdural hematoma.

Keywords*: chronic subdural hematoma, middle meningeal artery, endovascular embolization.*

Relevance

Chronic subdural hematoma (CSDH) is currently one of the most common neurosurgical diagnoses in adults. Its prevalence is significantly higher among the elderly, with the average age at diagnosis being approximately 70–80 years (The data presented are the results of studies conducted in the USA and European countries). The estimated incidence of the condition ranges from 1.7 to 20.6 cases per 100,000 people per year. Over the past few years, the overall incidence of CSDH has more than doubled, and this trend is expected to continue.

In today's world, most countries are experiencing an increase in the elderly population, a wider use of various antiplatelet and anticoagulant medications, and continuous advancements in the accessibility and quality of neuroimaging technologies. These factors collectively explain the current statistical trends in the incidence of CSDH [1, 2].

Unlike acute subdural hematoma, which directly causes acute compression of the adjacent brain areas, CSDH is associated with recurrent microbleeds into the subdural space from fragile newly formed vessels within the hematoma capsule. These vessels predominantly originate from the distal branches of the MMA. Accordingly, endovascular embolization of the MMA can help eliminate chronic recurrent bleeding into the subdural space and facilitate the resorption process of the hematoma [3].

This review aims to summarize current concepts of the pathophysiology of CSDHs and to examine the implementation of MMA endovascular embolization in modern treatment strategies for CSDHs based on data from the literature.

Introduction

Historically, the formation of CSDH was considered a consequence of bleeding primarily from ruptured bridging veins due to traumatic brain injury. However, contemporary understanding of the primary pathological process in CSDH points to the development of neovascularized hematoma capsules [3]. These capsules are a hallmark feature of CSDHs. Recent studies have explored the pathophysiology of CSDH in detail using cerebral angiography and histopathological methods, substantiating the view of CSDH as an angiogenic pathological process. The capsules of CSDHs are characterized by the presence of newly

formed thin-walled capillaries lacking a smooth muscle layer and containing numerous interendothelial gap junctions, which facilitate continuous exudation. Thus, the immature and fragile capillaries within the capsule, prone to rupture, sustain the existence and progression of CSDH [4, 5]. The vascular supply to CSDH capsules predominantly originates from the external carotid artery via the MMA. Due to continuous microbleeds caused by the increased permeability of these capsules, the subdural space becomes filled with fluid [6]. The findings of recent studies have significantly expanded the previous understanding of the mechanism underlying CSDH, which was previously attributed solely to the rupture of bridging veins due to trauma. These advancements have enabled the development of diagnostic and treatment approaches that address CSDH as a complex angiogenic pathology.

Recent studies on the **pathophysiological mechanisms** underlying CSDHs have focused on several critical processes implicated in their progression, including angiogenesis, fibrinolysis, and inflammation. The membrane of a CSDH is considered a primary source of both fluid exudation and recurrent microhemorrhages. Angiogenic stimuli contribute to the formation of fragile neovasculature within the hematoma membrane, making it susceptible to repeated bleeding. Concurrently, enhanced fibrinolytic activity prevents stable thrombus formation, thereby facilitating persistent hemorrhagic events. Furthermore, both the hematoma membrane and its fluid content are characterized by a significant presence of inflammatory cells and mediators, which are believed to promote sustained membrane proliferation and hematoma expansion.

A comprehensive understanding of the pathophysiological processes involved in CSDHs formation has been instrumental in guiding the development and rationale of therapeutic strategies for affected patients. Numerous studies have demonstrated that key mediators involved in neovascularization and angiogenesis are present in individuals with CSDHs. Among these, angiopoietins represent a class of growth factors that play a pivotal role in regulating angiogenesis and vascular permeability. The overexpression of angiopoietins may serve as a driving force behind the formation of fragile neovessels within the membranes of chronic subdural hematomas. Moreover, the fluid within CSDHs contains vascular endothelial growth factor (VEGF) at significantly higher concentrations than those observed in peripheral blood and cerebrospinal fluid. VEGF is a potent pro-angiogenic factor known to enhance microvascular permeability.

Recent investigations suggest that multiple interrelated factors contribute to the initiation and progression of CSDHs. Following traumatic brain injury, a complex cascade of events—including hematoma membrane formation, angiogenesis, and fibrinolysis—appears to underlie the gradual enlargement of the hematoma. The vascularized and highly permeable membrane of a chronic subdural hematoma serves as a continuous source of inflammatory mediators and recurrent bleeding. These insights into the underlying pathophysiological mechanisms have paved the way for therapeutic approaches that aim not only to manage the hematoma but also to target its root causes [3, 4, 5].

Clinical diagnosis of CSDH can be challenging, as the disease often progresses without clear or specific symptoms in its early stages. Although the duration of the process is frequently unknown at the time of initial diagnosis, it is believed that CSDH develops over a period of three weeks or more. CSDHs manifest with a wide range of symptoms, from acute plegia to mild cognitive impairment.

The majority of patients with CSDH are elderly, and other age-related conditions, such as strokes, Alzheimer's disease, Parkinson's disease, dementia, and others, can clinically mask this condition. Patients with CSDH often present with complaints of behavioral changes or cognitive decline. In older individuals, these changes are sometimes mistakenly attributed to dementia, particularly if such a diagnosis has been made previously. (CSDH is considered one of the common causes of reversible dementia.)

For this reason, CSDH has earned the nickname "the great imitator," and a significant number of cases are diagnosed at late stages [7, 8].

Various approaches to the treatment of CSDH are actively discussed in the scientific literature. Conservative treatment is generally reserved for patients without neurological deficits when the maximum thickness of the hematoma is less than 10 mm and the midline shift does not exceed 5 mm. For patients with more pronounced symptoms or larger CSDHs, surgical treatment is typically preferred.

Although surgical treatment is considered the mainstay in the management strategy for patients with symptomatic CSDHs, several recent studies have focused on pharmacological treatment in such cases. The use of modern pharmacological approaches is based on a thorough understanding of the pathophysiology of CSDHs. Agents including corticosteroids, tranexamic acid, statins, and angiotensin-converting enzyme inhibitors are employed either as monotherapy or as adjuncts to surgical intervention. According to numerous studies, the rationale for prescribing corticosteroids in the treatment of patients with CSDHs is supported by their well-established anti-inflammatory, antifibrinolytic, and antiangiogenic properties.

The effectiveness of corticosteroid therapy has been evaluated based on the regression of neurological symptoms and the resorption of subdural hematoma as assessed by cranial computed tomography CT (Key radiological indicators included a reduction in hematoma thickness, midline shift, and hematoma density). Thus, corticosteroids may play a significant role as part of the treatment plan for patients with chronic subdural hematomas.

Tranexamic acid is a well-known antifibrinolytic agent that acts by competitively inhibiting plasminogen activation and plasmin activity. Activation of the kallikrein system by plasmin-mediated inflammatory triggers leads to increased vascular permeability and leukocyte migration (processes that have been identified in the capsule of chronic subdural hematomas). Recent studies aim to confirm the hypothesis that tranexamic acid may suppress the hyperfibrinolytic activity and increased vascular permeability of the hematoma capsule, thereby promoting gradual hematoma absorption. Researchers have demonstrated that the use of tranexamic acid

effectively contributes to hematoma volume reduction and lowers the risk of recurrence.

In most proposed treatment protocols for CSDHs, a statin—most commonly atorvastatin—is used. Atorvastatin acts as a competitive inhibitor of 3-hydroxy-3-methylglutaryl-coenzyme A reductase, thereby enhancing clearance and reducing circulating levels of low-density lipoproteins. Studies show that including atorvastatin in the comprehensive treatment of chronic subdural hematomas significantly improves long-term clinical outcomes.

Although pharmacological treatment is not generally considered an alternative to surgery—which remains the gold standard in the management of CSDH—the use of various pharmacological agents has been associated with improved surgical outcomes. Pharmacological treatment alone is typically deemed appropriate for elderly patients or those with contraindications to surgical intervention [9, 10, 11].

One of the primary challenges of surgical removal of CSDHs is the tendency for hematomas to recur, often accompanied by worsening neurological status and requiring repeat surgical intervention. The recurrence rate reported in different studies varies significantly, ranging from 5% to 37%, with most estimates falling between 10% and 20%. The need for repeat surgeries is reported to be as high as 12%. [9, 10, 11]. Another significant issue with surgical intervention is that most patients with CSDH are elderly individuals with multiple comorbidities, which increase the risk of transcranial surgical procedures. This explains the attractiveness of exploring less invasive treatment options for CSDH. In this context, MMA embolization has been proposed as a promising alternative and/or supplement to transcranial surgical interventions.

A recent meta-analysis by Chen H. et al. demonstrated that the use of endovascular embolization of the MMA in the treatment of CSDH reduces the rate of repeat surgical interventions to 4.6%-6.8% [12].

The results of three randomized, prospective studies on endovascular embolization of the MMA for the treatment of CSDH were presented at the International Stroke Conference 2024 in Phoenix, USA. The study titled "Middle Meningeal Artery Embolization Using Onyx Liquid Embolic System in the Treatment of Subacute and Chronic Subdural Hematoma" (EMBOLISE) NCT04402632 is a multinational, prospective, randomized, controlled, open-label, adaptive clinical trial initiated by researchers to evaluate endovascular embolization for patients with symptomatic CSDH. The study is being conducted at 39 centers across the USA using Onyx (Medtronic Neurovascular, Irvine, CA) with a target enrollment of up to 600 patients, divided into two groups.

The first group consists of patients with mild manifestations of CSDH, specifically with a midline shift <5 mm, hematoma thickness ≤15 mm, and mild neurological symptoms. Patients in this group were randomly assigned into two subgroups (1:1). One group received only conservative treatment for CSDH, while the other subgroup was treated with endovascular embolization of the MMA.

The second group of the study included patients with moderate or severe manifestations of CSDH: those with significant neurological deficits, midline shift ≥5 mm, and/or hematoma thickness >15 mm. This group was also randomly divided into two subgroups (1:1). One subgroup underwent surgical removal of the CSDH, while the other subgroup received surgical removal combined with endovascular embolization of the MMA.

The primary objective of the study was to determine the recurrence rate of CSDH requiring repeat surgical intervention within 90 days. Additionally, the study assessed the completeness of MMA embolization, changes in functional status of patients according to the modified Rankin Scale (mRS), and neuroimaging results after 90 days.

According to the published data from the EMBOLISE study, the recurrence rate of CSDH requiring repeat surgical intervention was significantly lower in the subgroup of patients treated with additional endovascular embolization (4.1% vs. 11.3%) compared to the subgroup receiving only surgical removal (95% CI 0.11–0.80, P=0.0081). Furthermore, in the subgroup receiving surgical removal with MMA embolization, the rate of neurological deterioration (mRS) (11.9% vs. 9.8%; P=0.0022) and the rate of serious complications or death within 90 days did not differ significantly from the control group. (National Institutes of Health. Embolization of the middle meningeal artery with ONYX ™ liquid embolic system for subacute and chronic subdural hematoma(EMBOLISE).2020. https://ClinicalTrials.gov/show/NCT04402632).

A clinical study on MMA embolization for CSDH is also ongoing: Managing Non-Acute Subdural Hematoma Using Liquid Materials: A Chinese Randomized Trial of Middle Meningeal Artery Treatment (MAGIC-MT), a multicenter, prospective, randomized clinical trial involving 722 patients at 31 centers in China. According to the published protocol, the MAGIC-MT study compares the treatment outcomes of two groups of patients with CSDH (randomization 1:1).

In the first group, patients underwent embolization using Onyx for the MMA before CSDH drainage, while the second group received conservative treatment. Treatment outcomes were compared by the recurrence or progression of CSDH requiring surgical intervention within 90 days.

Patients who received endovascular MMA embolization for the treatment of CSDH had a significantly lower risk of repeat surgical interventions compared to the control group—7.2% vs. 12.2% (95% CI 0.37 - 0.63, P=0.02). Additionally, this group of patients experienced significantly fewer complications within 90 days—6.7% vs. 11.6% (95% CI 0.32 - 0.92, P=0.02) [13].

Another study, Squid Trial for the Embolization of the MMA for the Treatment of CSDH (STEM), is a prospective, randomized clinical trial conducted at 33 centers in the USA, France, and Spain, involving 310 patients with CSDH. In the STEM study, patients with CSDH were randomized into two groups (1:1): a standard treatment group and a group treated with MMA embolization using Squid (Balt, Montmorency, France).

The treatment outcomes were compared based on the recurrence rate of CSDH that required repeat surgical removal of the hematomas within 180 days. (National Institutes of Health. The SQUID trial for the embolization of the MMA for the treatment of CSDH (STEM). 2020. https: // ClinicalTrials.gov /show / NCT04410146).

The STEM study, like EMBOLISE and MAGIC-MT, showed that treatment of CSDH with endovascular embolization was more effective than treatment without this technique in preventing recurrence or progression of CSDH (15.2% vs. 39.2%; 95% CI 1.91–6.78, P=0.0001).

The results of all three studies suggest that MMA embolization in the treatment of CSDH is a safe and effective method for preventing recurrence/progression of CSDH, especially as an adjunct to surgical treatment. MMA embolization has been proposed as a potential option for the standard treatment protocol for CSDH. This represents a significant positive breakthrough in the treatment of CSDH in recent years [14].

Currently, additional studies are planned, specifically focusing on the role of endovascular embolization of the MMA as a standalone treatment method for CSDH, as well as its effectiveness in patients with bilateral subdural hematomas. Ongoing randomized, multi-center studies investigate these aspects, along with the effectiveness of different embolization agents. These studies aim to further clarify the potential of MMA embolization in various clinical scenarios and contribute to optimizing treatment protocols for CSDH [15, 16].

Ebolic Agents: As endovascular embolization of the MMA is actively being studied as a treatment option for CSDH, significant attention in recent research has been given to studying embolic materials. In modern clinical practice, the aforementioned embolic agents are used in the treatment of cerebral arteriovenous malformations, dural arteriovenous fistulas, and other cerebrovascular pathologies requiring vascular occlusion.

The extensive experience gained over recent decades with various classes of embolic agents enables the selection of the optimal approach to the procedure based on the clinical context.

Polyvinyl Alcohol (PVA) (Boston Scientific, Natick, MA, USA) and **Embosphere** (Merit Medical, USA) Embosphere Microspheres are biocompatible, hydrophilic, nonresorbable, microspheres produced from an acrylic polymer and impregnated with porcine gelatin. The mechanism of action of these agents involves adhesion to the vessel walls, which induces a chronic inflammatory response leading to vessel occlusion. However, the occlusion may be temporary due to the possibility of recanalization. Currently, PVA particles are the most commonly used embolic agents in studies examining endovascular embolization of the MMA in patients with CSDH. Both non-calibrated (non-spherical) PVA particles and calibrated (spherical) PVA microspheres are used.

PVA microspheres represent an innovative approach to embolization, offering increased accuracy and reducing the risk of complications associated with unpredictable reflux or particle aggregation. This advancement allows for more controlled and effective treatment outcomes in patients undergoing MMA embolization for CSDH. [17, 18]. In the study by Schwarz et al., PVA particles sized 250–350 micrometers were used for MMA embolization in patients with CSDH. This particle size range is often selected to balance effective occlusion of the targeted vessels while minimizing the risk of non-target embolization and other potential complications [19]. Kim et al. performed MMA embolization in patients with unsatisfactory evacuation of, particularly those who were on antithrombotic medications. This group of patients presents a unique challenge, as antithrombotic drugs can increase the risk of recurrence or complications due to ongoing bleeding or incomplete resolution of the hematoma after surgery. By using embolization, Kim et al. aimed to address these challenges by reducing the recurrence rate of CSDH and improving clinical outcomes in patients who might be at higher risk due to anticoagulant or antiplatelet therapy [20]. Ban et al. were the first to evaluate PVA particle embolization (150–250 μm) of the MMA as a primary treatment for CSDH in a cohort of 72 patients. In their study, all asymptomatic patients with subdural hematomas thicker than 10 mm demonstrated spontaneous resorption of the hematoma following the embolization procedure. This finding suggests that embolization of the MMA using PVA particles could be an effective approach for treating certain cases of CSDH, especially in asymptomatic patients, leading to a reduction in the need for surgical evacuation [21]. In the study by Onyinzo et al., all patients who underwent endovascular embolization of the MMA showed complete hematoma resorption, including those receiving antithrombotic medications. This result is particularly significant, as antithrombotic therapy is often associated with an increased risk of hematoma recurrence or complications. The success of embolization in these patients suggests that endovascular treatment can effectively manage CSDH, even in high-risk groups, by preventing further bleeding and promoting the complete resolution of the hematoma [22].

The results of studies demonstrate that endovascular embolization of the MMA using PVA particles is an effective method both for preventing recurrences and as a primary treatment for CSDH, particularly in patients with high surgical risk. This approach offers a less invasive alternative to traditional surgical methods, reducing the likelihood of reoperation and improving outcomes, especially for elderly patients or those with comorbidities that increase the risks associated with surgery.

Several recent studies have described the use of Embosphere 300–500 μm (Merit Medical) in the treatment of patients with CSDH. Tiwari et al. used Embosphere as the sole method for treating primary and recurrent CSDH, without surgical removal of the hematoma. The authors noted that the volume of the hematoma significantly reduced after embolization, regardless of the initial size. Follow-up examination at 6 months showed no recurrences. This suggests that Embosphere can be an effective and reliable option for managing CSDH, particularly in cases where surgery is not preferred or feasible [23]. Gomez-Paz et al. studied the resorption time of hematomas after embolization using Embosphere and EmboGold microspheres, which are impregnated with 2% elemental gold for visibility (Merit Medical, USA). Their findings suggest that Embosphere is a promising material for endovascular embolization of the MMA in the treatment of CSDH. It demonstrates high effectiveness and safety, particularly in patients at risk of recurrence or in cases of primary treatment. This highlights Embosphere as a valuable option in managing CSDH, offering a potential alternative to more invasive treatments [24].

Liquid embolic materials represent a broad class of agents that differ in chemical composition and mechanisms of action. They are unified by a physical property that aids in preventing unintended embolization and enhances imaging visibility. Owing to their ease of handling and the ability to achieve controlled delivery, liquid embolic agents have proven to be highly effective for MMA embolization. This category encompasses polymeric blends and sclerosing agents. Polymeric adhesive compounds undergo rapid polymerization upon contact with ionic components of blood, resulting in the formation of intravascular emboli. NBCA (n-Butyl Cyanoacrylate) (TruFill, USA) is a monomeric cyanoacrylate compound that promptly polymerizes into a solid matrix when exposed to blood plasma ions. Copolymers such as Onyx (Medtronic, USA) and Squid (Balt, France) precipitate within the vasculature, forming a cohesive, sponge-like embolic mass. Sclerosing agents induce endothelial injury and protein denaturation, leading to vascular sclerosis. Compared to particulate embolic agents, liquid embolics offer superior radiographic visualization and a reduced risk of non-target embolization. [25, 26].

NBCA (n-Butyl Cyanoacrylate) (TruFill, USA) is a monomeric cyanoacrylate adhesive that polymerizes into a solid mass upon contact with blood plasma ions. It also reacts with endothelial cells, catalyzing the formation of emboli. Lipiodol acts as a solvent for NBCA, allowing for adjustment of the concentration to regulate the polymerization speed of the mixture. This enables control over the flow rate and depth of penetration during embolization. It is precisely these properties of NBCA that enable controlled endovascular embolization, which, according to most researchers, is considered an advantage of this agent over other embolic materials. Additionally, Lipiodol improves the visualization of the embolizing material during and after the procedure. Ishihara H. et al. were among the first to use NBCA as the primary embolic agent for endovascular embolization of the MMA in the treatment of CSDH in patients with at least two recurrences. For embolizing the frontal and parietal branches of the MMA, the researchers used a solution of NBCA and Lipiodol in a 1:6 ratio. After 21 days, neuroimaging showed a reduction in the volume of the subdural hematoma by more than 75% in all patients. During the 15-month follow-up after the procedure, no recurrences were observed, and all patients showed a decrease in the size of the CSDH. [27, 28].

Onyx (Medtronic, USA) is a liquid embolic agent composed of an ethylene-vinyl alcohol copolymer solution and dimethyl sulfoxide. In contrast to cyanoacrylate-based adhesive compositions (NBCA), Onyx is a non-adhesive material, which reduces the risk of microcatheter occlusion. Waqas et al. conducted one of the first studies on MMA embolization for the treatment of CSDH using Onyx. In their study, all patients showed positive outcomes: complete resorption of the hematoma or a reduction in its size by more than 50% (according to neuroimaging methods) at the 2-month follow-up. Additionally, all patients experienced a full regression of neurological symptoms [29]. Another study involving 46 patients with CSDH treated with MMA embolization using Onyx-18 provided further evidence of the efficacy of this embolic agent. After 2 months, 86.4% of patients showed partial or complete resorption of the hematoma. Most of these patients underwent endovascular embolization of the MMA as the primary treatment method without the need for additional surgical hematoma removal. This reinforces Onyx-18's effectiveness as a stand-alone treatment option for CSDH, particularly in patients who are not candidates for or prefer to avoid surgery [30].

Squid (Balt, Montmorency, France) is a liquid embolic agent that contains a copolymer of ethylene-vinyl alcohol, micronized tantalum powder, and dimethyl sulfoxide. Similar to Onyx, Squid is used for endovascular embolization, but it features smaller particles of tantalum powder, which may enhance visualization compared to Onyx. A pilot study conducted by an international group of researchers involved patients who underwent MMA embolization with Squid 12 or Squid 18 after unsuccessful surgical removal of CSDH. The study found no thromboembolic or hemorrhagic complications, and all patients showed partial reduction of the CSDH (more than 50%) within 3 months following the embolization. This suggests Squid as a promising alternative for patients who do not respond well to surgery [31]. Currently, randomized controlled trials are ongoing to assess the efficacy and safety of new embolic agents, such as Squid and PHIL (MicroVention, USA), for the treatment of CSDH. Although these agents have not yet received FDA approval for the treatment of CSDH, they have already shown promising results in treating cerebral arteriovenous malformations (AVMs).

Squid and PHIL are copolymers that have different mechanisms of action compared to traditional agents like PVA or NBCA. They offer advantages in terms of controlled delivery and visualization, which is important for precise placement of the embolic material. However, since both materials have not been officially approved for CSDH treatment, further research is needed to compare their efficacy and safety with other embolization methods. Studies that involve comparing different embolic agents with varying mechanisms of action are likely to help determine the optimal treatment regimen for CSDH.

Conclusions

It is predicted that the incidence of CSDHs will continue to rise in the coming years. Therefore, the results of studies on treatment strategies for CSDH are becoming increasingly important.

According to current scientific sources, a new understanding of the pathogenesis of CSDH has emerged, linking the development of CSDH with angiogenic processes in the hematoma capsule, which explain the mechanisms underlying the transition and transformation of an acute subdural hematoma into a chronic subdural hematoma.These processes contribute to the persistence of recurrent microbleeds from fragile newly-formed blood vessels in the capsule into the subdural space, with most of these vessels originating from the distal branches of the MMA. This justifies the use of endovascular embolization of the MMA in the treatment of patients with CSDH.

The published results of randomized studies to date provide, for the first time, a sufficient level of evidence (level II) for clinical practice regarding the use of liquid

embolic agents in the endovascular embolization of the MMA for the treatment of CSDH in patients.

These studies demonstrate that endovascular embolization of the MMA should be considered a safe and effective treatment option and represents a significant breakthrough in the management of CSDH.

Currently, studies are planned and ongoing that compare different classes of embolizing materials to evaluate their relative efficacy and safety in the treatment of CSDH, as well as to determine their role in the overall treatment strategy for CSDH.

Disclosure

Conflict of Interest

The authors declare no conflicts of interest.

Funding

This study received no financial support or sponsorship.

References

1. Feghali J, Yang W, Huang J. Updates in Chronic Subdural Hematoma: Epidemiology, Etiology, Pathogenesis, Treatment, and Outcome. World Neurosurg. 2020 Sep; 141:339-345. doi: 10.1016/j.wneu.2020.06.140
2. Neifert SN, Chaman EK, Hardigan T, Ladner TR, Feng R, Caridi JM, Kellner CP, Oermann EK. Increases in Subdural Hematoma with an Aging Population-the Future of American Cerebrovascular Disease. World Neurosurg. 2020 Sep;141:e166-e174. doi: 10.1016/j.wneu.2020.05.060
3. Edlmann E, Giorgi-Coll S, Whitfield PC, Carpenter KLH, Hutchinson PJ. Pathophysiology of chronic subdural haematoma: inflammation, angiogenesis and implications for pharmacotherapy. J Neuroinflammation. 2017 May 30;14(1):108. doi: 10.1186/s12974-017-0881-y
4. Yamashima T, Yamamoto S, Friede RL. The role of endothelial gap junctions in the enlargement of chronic subdural hematomas. J Neurosurg. 1983 Aug;59(2):298-303. doi: 10.3171/jns.1983.59.2.0298
5. Weigel R, Schilling L, Krauss JK. The pathophysiology of chronic subdural hematoma revisited: emphasis on aging processes as key factor. Geroscience. 2022 Jun;44(3):1353-1371. doi: 10.1007/s11357-022-00570-y
6. Takizawa K, Sorimachi T, Ishizaka H, Osada T, Srivatanakul K, Momose H, Matsumae M. Enlargement of the middle meningeal artery on MR angiography in chronic subdural hematoma. J Neurosurg. 2016 Jun;124(6):1679-83. doi: 10.3171/2015.5.JNS1567
7. Sahyouni R, Goshtasbi K, Mahmoodi A, Tran DK, Chen JW. Chronic Subdural Hematoma: A Perspective on Subdural Membranes and Dementia. World Neurosurg. 2017 Dec;108:954-958. doi: 10.1016/j.wneu.2017.09.063
8. Sahyouni R, Goshtasbi K, Mahmoodi A, Tran DK, Chen JW. Chronic Subdural Hematoma: A Historical and Clinical Perspective. World Neurosurg. 2017 Dec;108:948-953. doi: 10.1016/j.wneu.2017.09.064
9. Wang X, Song J, He Q, You C. Pharmacological Treatment in the Management of Chronic Subdural Hematoma. Front Aging Neurosci. 2021 Jul 1;13:684501. doi: 10.3389/fnagi.2021.684501
10. Kim KH, Lee Y. Medical Management of Chronic Subdural Hematoma. Korean J Neurotrauma. 2023 Sep 19;19(3):288-297. doi: 10.13004/kjnt.2023.19.e47
11. Wang D, Gao C, Xu X, Chen T, Tian Y, et al. Treatment of chronic subdural hematoma with atorvastatin combined with low-dose dexamethasone: phase II randomized proof-of-concept clinical trial. J Neurosurg. 2020 Jan 31;134(1):235-243. doi: 10.3171/2019.11.JNS192020
12. Apostolakis S, Vlachos K. Complications From Subdural Drains in Burr Hole Drainage of Chronic and Subacute Subdural Haematomas: A Single-Centre Experience. Cureus. 2023 May 16;15(5):e39068. doi: 10.7759/cureus.39068
13. Matsumoto H, Hanayama H, Okada T, Sakurai Y, Minami H, Masuda A, Tominaga S, Miyaji K, Yamaura I, Yoshida Y. Which surgical procedure is effective for refractory chronic subdural hematoma? Analysis of our surgical procedures and literature review. J Clin Neurosci. 2018 Mar;49:40-47. doi: 10.1016/j.jocn.2017.11.009
14. Maroufi SF, Farahbakhsh F, Macdonald RL, Khoshnevisan A. Risk factors for recurrence of chronic subdural hematoma after surgical evacuation: a systematic review and meta-analysis. Neurosurg Rev. 2023 Oct 16;46(1):270. doi: 10.1007/s10143-023-02175-1
15. Chen H, Colasurdo M, Kan PT. Middle meningeal artery embolization as standalone treatment versus combined with surgical evacuation for chronic subdural hematomas: systematic review and meta-analysis. J Neurosurg. 2023 Sep 29;140(3):819-825. doi: 10.3171/2023.7.JNS231262
16. Zuo Q, Ni W, Yang P, Gu Y, Yu Y, Yang H, Majoie CBLM, Goyal M, Liu J, Mao Y; MAGIC-MT investigators. Managing non-acute subdural hematoma using liquid materials: a Chinese randomized trial of middle meningeal artery treatment (MAGIC-MT)-protocol. Trials. 2023 Sep 14;24(1):586. doi: 10.1186/s13063-023-07608-2
17. Levitt MR, Hirsch JA, Chen M. Middle meningeal artery embolization for chronic subdural hematoma: an effective treatment with a bright future. J Neurointerv Surg. 2024 Mar 14;16(4):329-330. doi: 10.1136/jnis-2024-021602
18. Shotar E, Mathon B, Rouchaud A, et al; EMPROTECT collaboration. Embolization of the middle meningeal artery for the prevention of chronic subdural hematoma recurrence in high-risk patients: a randomized controlled trial-the EMPROTECT study protocol. J Neurointerv Surg. 2024 Feb 2:jnis-2023-021249. doi: 10.1136/jnis-2023-021249
19. Tudor T, Capone S, Vivanco-Suarez J, et al. Middle meningeal artery embolization for chronic subdural hematoma: a review of established and emerging embolic agents. SVIN 2024;4. doi.org/10.1161/SVIN.123.000906
20. Vaidya S, Tozer KR, Chen J. An overview of embolic agents. Semin Intervent Radiol. 2008 Sep;25(3):204-15. doi: 10.1055/s-0028-1085930
21. Rana MM, Melancon MP. Emerging Polymer Materials in Trackable Endovascular Embolization and Cell Delivery: From Hype to Hope. Biomimetics (Basel). 2022 Jun 10;7(2):77. doi: 10.3390/biomimetics7020077
22. Schwarz J, Carnevale JA, Goldberg JL, Ramos AD, Link TW, Knopman J. Perioperative prophylactic middle meningeal artery embolization for chronic subdural hematoma: a series of 44 cases. J Neurosurg. 2021 May 21;135(6):1627-1635. doi: 10.3171/2020.10.JNS202856
23. Kim E. Embolization Therapy for Refractory Hemorrhage in Patients with Chronic Subdural Hematomas. World Neurosurg. 2017 May;101:520-527. doi: 10.1016/j.wneu.2017.02.070
24. Ban SP, Hwang G, Byoun HS, Kim T, Lee SU, Bang JS, Han JH, Kim CY, Kwon OK, Oh CW. Middle Meningeal Artery Embolization for Chronic Subdural Hematoma. Radiology. 2018 Mar;286(3):992-999. doi: 10.1148/radiol.2017170053
25. Onyinzo C, Berlis A, Abel M, et al. Efficacy and mid-term outcome of middle meningeal artery embolization with or without burr hole evacuation for chronic subdural hematoma compared with burr hole evacuation alone. J Neurointerv Surg. 2022 Mar;14(3):297-300. doi: 10.1136/neurintsurg-2021-017450
26. Tiwari A, Dmytriw AA, Bo R, Farkas N, et al. Recurrence and Coniglobus Volumetric Resolution of Subacute and Chronic Subdural Hematoma Post-Middle Meningeal Artery Embolization. Diagnostics (Basel). 2021 Feb 7;11(2):257. doi: 10.3390/diagnostics11020257
27. Gomez-Paz S, Akamatsu Y, Salem MM, et al. Upfront middle meningeal artery embolization for treatment of chronic subdural hematomas in patients with or without midline shift. Interv Neuroradiol. 2021 Aug;27(4):571-576. doi: 10.1177/1591019920982816
28. Lord J, Britton H, Spain SG, Lewis AL. Advancements in the development on new liquid embolic agents for use in therapeutic embolisation. J Mater Chem B. 2020 Sep 23;8(36):8207-8218. doi: 10.1039/d0tb01576h
29. Vollherbst DF, Chapot R, Bendszus M, Möhlenbruch MA. Glue, Onyx, Squid or PHIL? Liquid Embolic Agents for the

Embolization of Cerebral Arteriovenous Malformations and Dural Arteriovenous Fistulas. Clin Neuroradiol. 2022 Mar;32(1):25-38. doi: 10.1007/s00062-021-01066-6
30. Ishihara H, Ishihara S, Kohyama S, Yamane F, et al. Experience in endovascular treatment of recurrent chronic subdural hematoma. Interv Neuroradiol. 2007 Mar 15;13 Suppl 1(Suppl 1):141-4. doi: 10.1177/15910199070130S121
31. Al-Mufti F, Kaur G, Amuluru K, Cooper JB, et al. Middle Meningeal Artery Embolization Using Combined Particle Embolization and n-BCA with the Dextrose 5% in Water Push Technique for Chronic Subdural Hematomas: A Prospective Safety and Feasibility Study. AJNR Am J Neuroradiol. 2021 May;42(5):916-920. doi: 10.3174/ajnr.A7077
32. Waqas M, Vakhari K, Weimer PV, Hashmi E, Davies JM, Siddiqui AH. Safety and Effectiveness of Embolization for Chronic Subdural Hematoma: Systematic Review and Case Series. World Neurosurg. 2019 Jun;126:228-236. doi: 10.1016/j.wneu.2019.02.208
33. Rajah GB, Waqas M, Dossani RH, Vakharia K, et al. Transradial middle meningeal artery embolization for chronic subdural hematoma using Onyx: case series. J Neurointerv Surg. 2020 Dec;12(12):1214-1218. doi: 10.1136/neurintsurg-2020-016185
34. Petrov A, Bhogal P, Cimpoca A, Henkes H. Endovascular Treatment of Chronic Subdural Hematomas through Embolization: A Pilot Study with a Non-Adhesive Liquid Embolic Agent of Minimal Viscosity (Squid). J Clin Med. 2021 Sep 27;10(19):4436. doi: 10.3390/jcm10194436