

Endovascular Evolution in Subarachnoid Hemorrhage Management: A Comprehensive Review of Transitions from Coiling to Contemporary Stent-Assisted Therapies

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ABSTRACT

Aneurysmal subarachnoid hemorrhage (aSAH) remains a critical neurosurgical emergency characterized by high morbidity and mortality, demanding continuous refinement of endovascular techniques. This extensive review synthesizes current evidence on the paradigm shift from simple coil embolization to advanced stent-assisted interventions for intracranial aneurysm management. The discourse navigates through foundational principles of Guglielmi detachable coil occlusion, highlighting its established role in securing ruptured aneurysms while scrutinizing limitations in complex morphologies. Subsequently, the analysis progresses to the integration of intracranial stents—focusing on flow-diverting and intrasaccular devices—which have redefined therapeutic boundaries for wide-necked, fusiform, or previously untreatable lesions. Contemporary literature underscores nuanced considerations in peri-procedural antiplatelet regimens, hemodynamic management, and long-term angiographic outcomes. By examining recent multicenter trials and meta-analyses, this review elucidates evolving indications, safety profiles, and cost-efficacy dynamics, ultimately framing a sophisticated understanding of modern neurointerventional strategy. The synthesis aims to equip clinicians with evidence-based insights for tailored therapeutic decision-making in a rapidly advancing field.

KEYWORDS: subarachnoid hemorrhage; endovascular coiling; flow-diverting stents; intracranial aneurysm; stent-assisted coiling; neurointerventional surgery; aneurysm occlusion; antiplatelet therapy

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INTRODUCTION

Aneurysmal subarachnoid hemorrhage constitutes a dire cerebrovascular event, with global incidence estimates underscoring its persistent threat to functional survival despite decades of surgical and endovascular innovation. The advent of endovascular coil embolization, solidified by landmark studies such as ISAT and BRAT, established a minimal-invasive alternative to microsurgical clipping, fundamentally altering clinical practice. However, anatomical complexities—including wide necks, unfavorable dome-to-neck ratios, or incorporation of branching vessels—often precluded durable coil stabilization, prompting relentless technological advancement. The integration of

intracranial stents, initially as mechanical scaffolds for coil containment, has since evolved into a sophisticated therapeutic arsenal featuring flow-modulating designs that induce progressive intra-aneurysmal thrombosis through hemodynamic redistribution. Recent years have witnessed rapid iteration of stent devices, adjunctive antiplatelet protocols, and imaging surveillance paradigms, generating a complex body of literature that merits systematic consolidation.^{1,2,3}

This review, therefore, endeavors to trace the technical evolution from standalone coiling to contemporary stent-assisted approaches, critically appraising pivotal studies from the past decade. It further contextualizes practical challenges

Endovascular Evolution in Subarachnoid Hemorrhage Management: A Comprehensive Review of Transitions from Coiling to Contemporary Stent-Assisted Therapies

such as peri-procedural thromboembolic risk, hemorrhagic complications in acutely ruptured scenarios, and long-term patency concerns, thereby providing a nuanced framework for neurointerventional specialists navigating an increasingly intricate landscape of therapeutic options

BACKGROUND

The management of aneurysmal subarachnoid hemorrhage (aSAH) represents one of the most dynamic and technically demanding frontiers in neurovascular medicine. Historically, the prognosis for this catastrophic event was overwhelmingly poor, with microsurgical clipping, as refined by pioneers like Yasargil, offering the first definitive means of securing an aneurysm. This open surgical approach, while effective, carried inherent burdens of invasiveness and brain retraction. The landscape underwent a seismic shift with the introduction of the Guglielmi detachable coil (GDC) system in the early 1990s, which catalyzed the rise of endovascular therapy as a less invasive alternative. The subsequent validation provided by the International Subarachnoid Aneurysm Trial (ISAT) and the Barrow Ruptured Aneurysm Trial (BRAT) firmly established endovascular coiling as the first-line intervention for many ruptured aneurysms, primarily due to reduced short-term morbidity. However, this initial triumph revealed its own set of anatomical limitations. Complex aneurysm morphologies—specifically those with wide necks, unfavorable dome-to-neck ratios, or incorporation of essential branch vessels—posed significant challenges for simple coiling, often resulting in incomplete occlusion, coil compaction, or procedural instability leading to higher recanalization rates.^{2,3,4,5}

This therapeutic gap became the crucible for the next phase of innovation: the advent of intracranial stenting. The concept initially materialized with the introduction of self-expanding nitride stents designed to act as a mechanical scaffold across an aneurysm neck, preventing coil prolapse into the parent artery and enabling denser packing of the sac. This stent-assisted coiling (SAC) technique expanded the treatable aneurysm spectrum but introduced new complexities, most notably the imperative for aggressive dual antiplatelet therapy (DAPT) to mitigate in-stent thrombosis, a considerable concern in the context of recent hemorrhage. The evolution did not stop there. A more profound paradigm shift occurred with the development of flow-diverting stents (FDS), such as the Pipeline Embolization Device. These devices, with their high metal coverage and low porosity, function not as scaffolds but as endoluminal reconstructors of the parent vessel. They induce intra-aneurysmal stasis and subsequent thrombosis while preserving flow into perforating and side branches, fundamentally altering the treatment approach for large, giant, and fusiform aneurysms previously deemed untreatable.^{3,4,5,6}

The current therapeutic armamentarium is further diversified by intrasaccular flow disruptors, like the WEB device, which

offer a purely intrasaccular, stent-sparing alternative for bifurcation aneurysms, and by surface-modified coils aimed at enhancing biological healing. This rapid technological proliferation has generated a substantial but sometimes conflicting body of literature. Recent multicenter registries and meta-analyses grapple with nuanced questions: optimizing antiplatelet regimens in the acute rupture setting to balance ischemic and hemorrhagic risks; defining the role of flow diversion in the management of acutely ruptured blister or dissecting aneurysms; and understanding the long-term biological response to permanently implanted devices, including issues of delayed aneurysm occlusion, in-stent stenosis, and neointimal closure. Consequently, the journey from the simple coil to the sophisticated stent embodies not merely a technical progression but a continuous reevaluation of pathophysiological principles, peri-procedural management, and long-term patient outcomes, necessitating a comprehensive synthesis to guide contemporary clinical practice.^{4,5,6,7,8}

Available Therapies and Their Technical Application

The contemporary management of aneurysmal subarachnoid hemorrhage is underpinned by a sophisticated hierarchy of endovascular techniques, each with distinct procedural nuances and anatomical indications. The foundational approach remains simple coil embolization, a minimally invasive procedure conducted under high-resolution digital subtraction angiography. This technique involves the microcatheter navigation into the aneurysm sac, followed by the sequential deployment of platinum coils, typically beginning with a three-dimensional framing coil to create a basket that conforms to the aneurysm's internal geometry. Subsequent filling and finishing coils are deployed to achieve dense, stable packing that promotes intraluminal thrombosis and endothelial overgrowth at the neck. The principal technical objective is to achieve a complete angiographic occlusion, graded by the Raymond-Roy scale, while meticulously avoiding parent vessel compromise or coil protrusion. However, the integrity of this construct is highly contingent on favorable aneurysm geometry, particularly a well-defined neck with a high dome-to-neck ratio, which facilitates stable coil containment.^{8,9,10}

When aneurysm morphology precludes simple coiling, stent-assisted coiling (SAC) emerges as a critical strategy. This technique employs two primary deployment methodologies: the *jailing* technique and the *coil-through* technique. In the *jailing* approach, a self-expanding neurovascular stent—such as those from the Neuroform or Enterprise families—is first deployed across the aneurysm neck, effectively creating a semi-permeable barrier between the parent artery and the aneurysm dome. The microcatheter for coil delivery is then navigated through the stent's interstices into the sac, or more commonly, it is positioned within the aneurysm prior to stent deployment and subsequently "jailed" in place. This method provides robust mechanical support, minimizing the risk of

Endovascular Evolution in Subarachnoid Hemorrhage Management: A Comprehensive Review of Transitions from Coiling to Contemporary Stent-Assisted Therapies

coil herniation. The alternative *coil-through* technique involves deploying the stent first and then navigating a microcatheter through the stent mesh, offering more flexibility in catheter positioning but demanding greater technical finesse to avoid stent displacement. A paramount consideration in SAC is the mandatory peri-procedural administration of dual antiplatelet therapy (DAPT), typically a combination of aspirin and a P2Y₁₂ inhibitor like clopidogrel or prasugrel, with platelet function testing often employed to verify adequate inhibition and mitigate risks of acute in-stent thrombosis or thromboembolic complications, a non-trivial concern in the hypercoagulable state following acute hemorrhage.^{11,12,13}

A paradigm distinct from mechanical scaffolding is embodied by flow-diverting stent (FDS) technology, exemplified by devices such as the Pipeline Embolization Device, the Flow Redirection Endoluminal Device (FRED), and the Surpass Streamline. The technical execution of flow diversion involves the precise deployment of a single high-density mesh stent, or occasionally telescoping multiple devices, across the aneurysm neck with the goal of achieving complete parent vessel reconstruction. The mechanism is not immediate occlusion but a profound alteration in intra-aneurysmal hemodynamics, inducing stasis, progressive thrombosis, and ultimately, neointimal growth across the neck over weeks to months. The procedure demands meticulous sizing to ensure wall apposition and coverage of the diseased segment, and it often requires adjunctive coiling in large or giant aneurysms to accelerate thrombosis and reduce the risk of post-procedural rupture from intra-aneurysmal pressure shifts. The peri-procedural antithrombotic regimen remains intensive, and its management in the acute rupture setting is a subject of ongoing refinement, often involving a balance of intraprocedural intravenous antiplatelet agents and post-procedural oral DAPT.^{14,15,16}

Further expanding the arsenal are intrasaccular flow disruptors, most notably the Woven EndoBridge (WEB) device. This technique represents a fundamentally different philosophy, as it forsakes both the parent vessel and the need for permanent stenting. The procedure involves deploying a self-expanding, braided, spherical or cylindrical mesh implant directly within the aneurysm fundus via a dedicated microcatheter. The device expands to conform to the aneurysm walls, acting as an intraseccular flow disruptor that induces immediate flow stagnation and subsequent occlusion. Its primary application lies in the treatment of wide-neck bifurcation aneurysms of the middle cerebral, basilar tip, or anterior communicating arteries, where it offers a compelling stent-sparing alternative that eliminates the necessity for long-term antiplatelet therapy. The technical success hinges on precise device sizing relative to the aneurysm dimensions to ensure stable positioning and wall opposition, thereby preventing device migration or compaction. This modality

has been substantiated by recent large-scale clinical series and post-market studies, establishing its role within the modern neurointerventional algorithm for select aneurysm subtypes. Each of these techniques, from foundational coiling to advanced reconstruction and disruption, constitutes a vital instrument, with the selection algorithm being guided by a complex calculus of aneurysm morphology, location, rupture status, and patient-specific cerebrovascular physiology.¹⁷

Surgical Techniques in Aneurysmal Subarachnoid Hemorrhage Management

While the advent and refinement of endovascular therapies have profoundly reshaped the therapeutic landscape for aneurysmal subarachnoid hemorrhage, microsurgical clipping retains an indispensable and nuanced role within the contemporary management paradigm. The surgical approach remains the definitive comparator against which novel endovascular techniques are measured, offering the unique advantage of direct anatomical visualization and immediate, durable aneurysm exclusion from the cerebral circulation. The cornerstone of open surgical management is the pterional (frontotemporal) craniotomy, a meticulously planned approach that provides a versatile corridor to the anterior circulation and upper basilar artery. This exposure is fundamental, allowing for proximal vascular control, meticulous arachnoid dissection within the Sylvian fissure and basal cisterns to achieve adequate brain relaxation through cerebrospinal fluid egress, and the ultimate isolation of the aneurysm neck.^{17,18}

The technical execution of microsurgical clipping demands an orchestration of precise maneuvers under high-magnification operative microscopy. Following dural opening and brain relaxation, the surgical trajectory proceeds with a microsurgical dissection of the arachnoid membranes to sequentially identify and expose the parent artery, its relevant branches, and finally, the aneurysm dome and neck. This dissection is performed with scrupulous care to avoid premature aneurysm rupture, a catastrophic intraoperative event. The philosophy of proximal control—achieved by preparing a temporary clip placement site on the parent vessel—is paramount for safety. The selection and application of the permanent titanium clip constitute the critical act of definitive treatment. The clip, chosen from a vast array of shapes (straight, curved, fenestrated) and lengths, must be positioned to fully encompass the aneurysm neck without compromising the lumen of the parent artery or incorporating perforating or branch vessels. The fenestrated clip is of particular utility for complex configurations, allowing the parent vessel or a branch to pass through the fenestration while the clip blades close across the neck. The surgeon must often employ multiple clips in tandem, stacking, or tandem-clipping techniques to reconstruct a broad or irregular neck, a strategy known as clip reconstruction.^{18,19,20}

Endovascular Evolution in Subarachnoid Hemorrhage Management: A Comprehensive Review of Transitions from Coiling to Contemporary Stent-Assisted Therapies

For aneurysms with particularly challenging morphology—such as those with calcified or atherosclerotic necks, giant size incorporating the parent vessel, or fusiform anatomy—bypass surgery may be integrated into the operative plan. This represents the most complex tier of cerebrovascular microsurgery, involving the creation of an extracranial-to-intracranial (EC-IC) bypass. The most common conduit is the superficial temporal artery (STA), which is anastomosed to a cortical branch of the middle cerebral artery (STA-MCA bypass) to augment or replace flow prior to planned parent vessel occlusion or trapping of the aneurysm. In scenarios requiring high-flow replacement, such as for internal carotid artery sacrifice, an interposition graft using a saphenous vein or radial artery may be anastomosed between the external carotid and an M2 segment. These bypass procedures extend the realm of operability to lesions otherwise considered untreatable, albeit with associated morbidity.²⁰

The technical considerations extend beyond the act of clipping itself. Adjuncts such as intraoperative neurophysiological monitoring (somatosensory and motor evoked potentials), intraoperative indocyanine green (ICG) videoangiography, and Doppler ultrasonography are now standard to verify patency of adjacent vessels and completeness of aneurysm occlusion immediately after clip placement. Furthermore, the management of intraoperative rupture, a formidable complication, requires a disciplined, sequential response involving temporary clipping, suction, and controlled repair, underscoring the high-stakes nature of the procedure. The persistence of surgical expertise is vital, as it provides the sole therapeutic option for aneurysms that have failed endovascular treatment, present with large intraparenchymal hematomas requiring evacuation, or possess morphological features—like a very small, dysplastic neck or a major branch artery emanating directly from the dome—that currently render them suboptimal for safe endovascular intervention. Thus, surgical clipping exists not in opposition to but in sophisticated synergy with endovascular progress, its continued evolution in technique and technology ensuring its place as a pillar of comprehensive cerebrovascular care.^{20,21}

Indications and Therapeutic Selection in Aneurysmal Subarachnoid Hemorrhage

The determination of the optimal therapeutic intervention for a ruptured intracranial aneurysm is a complex clinical decision-making process, predicated on a meticulous synthesis of patient-specific variables, aneurysm morphology, and institutional expertise. This decision framework has evolved substantially from the initial binary choice between clipping and coiling into a sophisticated algorithm that integrates advanced endovascular constructs. The foundational indications for endovascular coiling, firmly established by pivotal trials, continue to prioritize aneurysms of the posterior circulation, notably those of the basilar apex, where surgical morbidity is historically elevated. Similarly,

advanced patient age, significant medical comorbidities that heighten anesthetic risk, and an unfavorable clinical grade at presentation, such as a poor World Federation of Neurosurgical Societies (WFNS) score, traditionally favor a minimally invasive endovascular approach to secure the aneurysm and mitigate the risks associated with open cranial surgery and brain retraction.^{20,21}

The morphological characteristics of the aneurysm itself constitute perhaps the most critical determinant in selecting between simple coiling and stent-assisted modalities. Aneurysms exhibiting a well-defined, narrow neck with a dome-to-neck ratio greater than 2:1 are generally amenable to primary coil embolization, as the geometry allows for stable coil framing and containment within the sac. However, the landscape shifts decisively with wide-necked aneurysms, conventionally defined by a neck diameter exceeding 4 mm or a dome-to-neck ratio less than 2:1. This anatomical configuration presents a prohibitive risk of coil prolapse into the parent artery, rendering simple coiling inadequate or hazardous. It is in this domain that stent-assisted coiling (SAC) finds its primary indication, providing the necessary endoluminal scaffold to bridge the neck and permit dense, secure coil packing. This approach is particularly germane to aneurysms located at arterial bifurcations, such as the middle cerebral artery (MCA) bifurcation or the basilar apex, where branch incorporation is common.²¹

The advent of flow-diverting stents (FDS) has created a distinct and expanding set of indications, largely focused on aneurysms with pathological vessel wall segments rather than simple saccular outpouchings. The quintessential candidates for flow diversion include large or giant saccular aneurysms of the internal carotid artery proximal to the posterior communicating segment, where the device can achieve parent vessel reconstruction. Furthermore, fusiform, dolichoectatic, and blister-like aneurysms, which are inherently lacking a discrete neck and are often surgically unclippable and challenging for conventional coiling, now fall within the purview of flow diversion. The rationale hinges on the device's ability to induce endothelialization across a diseased arterial segment. Recent clinical series have also explored, with cautious protocolization, the use of FDS in the acute rupture setting for select cases of dissecting or recurrent aneurysms after previous coiling, though this remains an area of intense investigation due to the imperative for dual antiplatelet therapy.²²

Intrasaccular flow disruptors, such as the Woven EndoBridge (WEB) device, have carved out a specific niche, offering a stent-sparing solution for wide-neck bifurcation aneurysms. Their use is particularly indicated for true bifurcation aneurysms arising from the MCA, anterior communicating complex, and basilar tip where the preservation of efferent branch vessels is paramount. The WEB provides an attractive alternative when the anatomy is unfavorable for simple coiling yet the clinician wishes to avoid the long-term

Endovascular Evolution in Subarachnoid Hemorrhage Management: A Comprehensive Review of Transitions from Coiling to Contemporary Stent-Assisted Therapies

antiplatelet commitment mandated by intracranial stents, a consideration of elevated importance in younger patients or those with compliance concerns.²²

Conversely, the indications for microsurgical clipping endure and are often defined by the limitations of endovascular therapy. Aneurysms with a morphology featuring a very small, dysplastic neck or a major branch artery originating directly from the fundus may be deemed unsuitable for endovascular protection. The presence of a substantial intraparenchymal hematoma with mass effect requiring concurrent surgical evacuation frequently dictates an open approach, allowing for clot removal and aneurysm securement in a single procedure. Furthermore, logistical constraints, such as the lack of immediate endovascular capability or the failure of a prior endovascular attempt with recanalization, reassert the primacy of surgical intervention. Ultimately, the modern management of aSAH is guided by a multidisciplinary neurovascular team discussion, where the integration of clinical status, detailed angiographic architecture, and a nuanced understanding of each technique's strengths and limitations converges to formulate a patient-centric therapeutic strategy.²²

Contraindications and Procedural Limitations in Endovascular and Surgical Management of Subarachnoid Hemorrhage

The selection of an intervention for aneurysmal subarachnoid hemorrhage, while guided by clear indications, is equally governed by a matrix of absolute and relative contraindications. These constraints stem from patient-specific physiological factors, intricate aneurysm morphology, and the inherent pharmacological demands of the devices employed, creating a risk calculus that must be carefully navigated to avoid catastrophic complications. For the foundational technique of simple coil embolization, the primary contraindication is morphological. Aneurysms with extremely wide necks or those that are fusiform or dissecting in nature lack the anatomical substrate to securely retain coils, presenting a high probability of coil migration or parent vessel occlusion. Similarly, aneurysms with a critical branch artery emanating directly from the fundus, rather than the neck, risk branch occlusion with coil placement, potentially precipitating a territorial infarct. Patient factors, though less common, include severe iodinated contrast allergy that cannot be adequately pre-medicated and, in rare instances, an inability to achieve vascular access due to extreme tortuosity or occlusive aortic-iliac disease.²³

The paradigm shifts significantly with the introduction of stent-assisted techniques, where pharmacological considerations ascend to paramount importance. The most salient contraindication to stent-assisted coiling or flow diversion in the context of acute rupture is the mandatory requirement for dual antiplatelet therapy (DAPT). This presents a profound conflict in patients presenting with large intracerebral hematomas, where the risk of hemorrhagic

expansion under the influence of potent platelet inhibition is unacceptably high. This same principle extends to patients requiring urgent external ventricular drain placement or other invasive procedures shortly after aneurysm securement, where the iatrogenic bleeding risk is substantially elevated. Furthermore, a known hyper-sensitivity or resistance to clopidogrel or other P2Y₁₂ inhibitors, particularly when rapid and reliable platelet inhibition is non-negotiable, may preclude elective stenting. From a morphological standpoint, the deployment of a flow-diverting stent is generally contraindicated across an aneurysm neck that gives rise to critical, unfenestrated side branches or perforator vessels, such as those originating from the mid-basilar artery or the A1 segment, due to the unacceptable risk of occluding these essential vessels with the device's high-density mesh.²³

Microsurgical clipping, while free from the pharmacological constraints of antiplatelet agents, carries its own distinct set of contraindications largely rooted in patient physiology and anatomy. Severe medical comorbidities, particularly uncompensated cardiac or pulmonary disease, may render the patient an unsuitable candidate for prolonged general anesthesia and the physiological stresses of craniotomy. The patient's neurological condition itself can be a limiting factor; those in profound cerebral edema or with signs of irreversible brainstem failure may derive no benefit from intervention. Anatomical contraindications are also prevalent and include aneurysms located in deep, surgically inaccessible regions, such as those on the posterior inferior cerebellar artery or within the cavernous segment of the internal carotid artery, where surgical exposure carries disproportionate morbidity. Additionally, the presence of a calcified, atherosclerotic aneurysm neck that is non-pliable and cannot be safely closed with a clip without risking fragmentation or parent vessel injury may force a reconsideration towards an endovascular strategy, despite the theoretical advantages of surgery.²³

A critical and often underappreciated layer of contraindication pertains to the timing and logistics of care. The lack of immediately available neurointerventional expertise or appropriate device inventories can functionally contraindicate an advanced endovascular procedure, just as the absence of a dedicated neuro-critical care unit can compromise postoperative management. Finally, a critical review of the literature underscores that patient or surrogate preference, when informed by a comprehensive understanding of the risk-benefit profile including long-term durability and need for surveillance, constitutes a legitimate and powerful factor in therapeutic decision-making. Thus, the identification of contraindications is not merely an exercise in exclusion, but a dynamic and essential component of personalized neurovascular care, ensuring that the formidable armamentarium of coils, stents, and clips is deployed with judicious precision and respect for individual patient vulnerabilities.²³

Endovascular Evolution in Subarachnoid Hemorrhage Management: A Comprehensive Review of Transitions from Coiling to Contemporary Stent-Assisted Therapies

CONCLUSION

The management of aneurysmal subarachnoid hemorrhage has undergone a transformative journey, propelled by technological innovation and rigorous clinical inquiry. From the initial disruption introduced by the Guglielmi detachable coil to the sophisticated paradigm of endoluminal reconstruction with flow-diverting stents and intrasaccular disruption, the evolution has fundamentally expanded the therapeutic horizon for lesions once deemed inoperable. This progression, however, is not a linear narrative of obsolescence but rather a complex stratification of complementary techniques, each with a defined and nuanced role within the contemporary neurointerventional armamentarium. The enduring legacy of microsurgical clipping remains firmly established, providing definitive anatomical reconstruction for morphologies unfavorable to endovascular approaches and addressing the critical need for hematoma evacuation. Concurrently, the expansion of endovascular options has facilitated a more patient-centric approach, allowing therapeutic strategies to be tailored to specific aneurysm architectures and individual clinical vulnerabilities.

The synthesis of current evidence underscores that the choice between coil, stent, or clip is governed by a sophisticated calculus integrating aneurysm location, neck morphology, rupture status, and the patient's physiological reserve. The advent of stent-assisted modalities has successfully addressed the anatomical limitations of simple coiling, yet introduced the intricate challenge of peri-procedural antiplatelet management in the acute hemorrhage setting. Flow diversion, while revolutionizing the treatment of fusiform and giant aneurysms, demands a sustained commitment to pharmacological therapy and long-term radiographic surveillance, with ongoing research refining its application in the acutely ruptured context. The development of devices like the Woven EndoBridge offers a compelling stent-sparing alternative for complex bifurcation aneurysms, highlighting the field's trajectory towards minimizing implant burden and simplifying post-procedural care.

Future directions will undoubtedly focus on the refinement of bioactive and surface-modified implants designed to accelerate healing and reduce recanalization, the optimization of antiplatelet regimens through pharmacogenomics and point-of-care testing, and the continued evaluation of long-term durability and neointimal response to permanent implants. The imperative for a multidisciplinary neurovascular team, engaging in nuanced deliberation of each case, has never been more critical. It is within this collaborative framework that the historical lessons from the coil, the strategic advancements of the stent, and the enduring principles of microsurgery converge. The ultimate objective remains unchanged: the secure and durable exclusion of the aneurysm from the cerebral circulation with the preservation of neurological function. As the technological landscape

continues its rapid advance, this goal will be increasingly realized through personalized, anatomy-specific interventions, ensuring that the formidable challenge of subarachnoid hemorrhage is met with an ever-more sophisticated and effective array of solutions.

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Endovascular Evolution in Subarachnoid Hemorrhage Management: A Comprehensive Review of Transitions from Coiling to Contemporary Stent-Assisted Therapies

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