

## REVIEW ARTICLE

# Navigating the crossroads: Insights into cardiology's influence on neurointerventional procedures

Mohammed A. Azab<sup>1</sup>, Kevin Pierre<sup>2</sup>, Brandon Lucke-Wold<sup>3,\*</sup>

<sup>1</sup> Department of Neurosurgery, Cairo University, Giza 12613, Egypt

<sup>2</sup> Department of Radiology, University of Florida, Gainesville, FL 32608, United States

<sup>3</sup> Department of Neurosurgery, University of Florida, Gainesville, FL 32608, United States

\* Corresponding author: Brandon Lucke-Wold, [brandon.lucke-wold@neurosurgery.ufl.edu](mailto:brandon.lucke-wold@neurosurgery.ufl.edu)

## ABSTRACT

Since Egaz Moniz introduced angiography, neurovascular interventions have undergone significant advancements. The integration of advanced biomaterials has refined endovascular devices and techniques for complex vascular lesions. The domain of neurointerventions includes neuroendovascular surgery, endovascular neurosurgery, and interventional neurology. Notably, in regions with limited neurointerventional specialists, interventional cardiologists are increasingly treating cerebrovascular strokes. The congruence between coronary and carotid interventions has facilitated the development of adaptable cerebrovascular tools, many inspired by those in cardiac catheter labs. This article provides an overview of key developments in neurointerventions, with a focus on the adaptation of tools between coronary and cerebrovascular procedures.

**Keywords:** interventional neuroradiology; endovascular neurosurgery; angiography; emerging innovation

## 1. Introduction

Neuroendovascular interventions have consistently evolved through the refinement of devices for prevalent neurovascular indications. Enhanced comprehension of the pathophysiology of various neurovascular disorders over the decades has stimulated the advancement of novel endovascular techniques. The inception of neurointervention traces back to the late 1920s with Egaz Moniz's pioneering angiography<sup>[1]</sup>, which ushered in both diagnostic and therapeutic interventions. By 1960, procedures like the endovascular embolization of a brain arteriovenous malformation were described by Luessenhop<sup>[2]</sup>. Innovations like detachable balloons<sup>[3]</sup>, and the Guglielmi detachable coil (GDC) in 1991<sup>[4]</sup> emerged, with endovascular coiling recently superseding surgical clipping for cerebral aneurysms.

Emphasis on evidence-based approaches in neurointervention surged in the early 2000s, marked by pivotal clinical trials like the International Subarachnoid Aneurysm Trial (ISAT) which compared endovascular coiling with surgical clipping<sup>[5]</sup>. Successive developments include balloon-assisted coiling, stent-assisted coiling, and flow diversion<sup>[6,7]</sup>. Additionally, intracranial stents revolutionized carotid stenosis treatment<sup>[6,8]</sup>. There's also been a marked uptrend in mechanical thrombectomy, with multiple randomized

### ARTICLE INFO

Received: 14 July 2023 | Accepted: 25 September 2023 | Available online: 15 December 2023

### CITATION

Azab MA, Pierre K, Lucke-Wold B. Navigating the crossroads: Insights into cardiology's influence on neurointerventional procedures. *Cardiac and Cardiovascular Research* 2023; 4(1): 2243. doi: 10.54517/ccr.v4i1.2243

### COPYRIGHT

Copyright © 2023 by author(s). *Cardiac and Cardiovascular Research* is published by Asia Pacific Academy of Science Pte. Ltd. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0/>), permitting distribution and reproduction in any medium, provided the original work is cited.

trials, including DAWN and DEFUSE, accentuating its expanding role<sup>[9–15]</sup>. In contrast, interventions for AVM have shown a more modest progression.

Beyond novel techniques and devices, the advent of improved antiplatelets, advanced imaging modalities, and contemporary neurocritical monitoring systems has accelerated the evolution of endovascular techniques. This article aims to detail the progression of prominent neuroendovascular tools and discuss the adaptation of certain tools from other interventional disciplines.

### **1.1. Catheters**

Catheters serve both diagnostic and therapeutic functions, encompassing guiding catheters, distal access catheters, and microcatheters. Diagnostic catheters typically range from 90 cm to 100 cm in length and 4F to 6F in size, with variations such as straight or angled tips and Simmon or Headhunter versions<sup>[11]</sup>. When using guide or distal catheters, longer length catheters are preferred.

Microcatheters are designed for minimal trauma, hence their soft nature. Assisted by distal or guide catheters, these tools vary in diameter, length, and may be radiopaque. The choice depends on the guide catheter's position and the required microcatheter flexibility<sup>[16]</sup>. Newer steerable microcatheters offer enhanced flexibility over their conventional counterparts<sup>[17–20]</sup>, such as the FDA-approved bendable microcatheter (Bendit Technologies, Petach Tikva, Israel)<sup>[18]</sup>. An example of innovative designs includes the SwiftNINJA steerable microcatheter (Merit Medical Systems, UT, United States) with a 180-degree rotating tip<sup>[21]</sup>, which aims to expedite procedures by eliminating wire manipulation.

Guide catheters, with lengths between 110 cm and 135 cm and sizes from 6F to 8F, facilitate access to major vessels and guide microcatheters to smaller branches<sup>[22]</sup>. Specifically designed balloon guide catheters, when inflated during mechanical thrombectomy, block antegrade blood flow, aiding in clot fragment extraction. They can be integrated with clot retrieval systems for diverse thrombectomy techniques<sup>[19,23]</sup>. Notably, the North American Solitaire Stent Retriever Acute Stroke (NASA) and Trevo Stent-Retriever Acute Stroke (TRACK) registries recorded comparable use of balloon-guided catheters (44% vs. 47%, respectively)<sup>[24,25]</sup>.

Distal access catheters utilize negative pressure to dislodge clots. Made from materials like polytetrafluoroethylene, they navigate vessels smoothly<sup>[13]</sup>. The U.S. Food and Drug Administration (FDA) has approved several designs for these catheters, with Penumbra, Solitaire FR, and REACT catheters as examples.

### **1.2. Wires**

Wires for neurointerventional procedures can be categorized into hydrophilic and stiff types. Hydrophilic wires are preferred for diagnostic procedures, whereas stiff wires are chosen for navigating tortuous vessels and for catheter exchanges. Microwires, specifically, are employed to guide microcatheters, stents, and other intracranial neurointerventional devices<sup>[22]</sup>. The wire selection hinges on the intended application and the specific vessel to be navigated.

### **1.3. Stent retrievers**

Stent retrievers have been developed to promote cerebral reperfusion while minimizing the risk of spontaneous intracerebral hemorrhage, a concern associated with thrombolytics. Initial attempts at stroke management included lasers, micro snares, and rheolytic thrombectomy systems, but these faced challenges in ensuring safety<sup>[26]</sup>. The Concentric Thrombus Retriever, from Concentric Medical, was the first retriever approved for use in the U.S.<sup>[27]</sup> Later, it was dubbed the Mechanical Embolus Removal in Cerebral Ischemia (MERCI) Retriever (Concentric Medical, Mountain View, CA, USA), securing FDA approval in 2004<sup>[27,28]</sup>.

The MERCI trial evaluated its efficacy and safety in clot removal from large intracranial vessels within 8 h of stroke symptom onset<sup>[28]</sup>. Although the recanalization rate with the MERCI device was promising, its overall mortality rate of 44% was deemed high<sup>[23,28]</sup>. A subsequent study, the multi-MERCI trial, demonstrated improved results, boasting a recanalization rate of 68%<sup>[29]</sup>.

Following the MERCI, the next significant advancement was the Penumbra System (Penumbra Inc., Alameda, CA, USA), which employs a thrombus aspiration mechanism. This system continuously aspirates the thrombus until it breaks apart, and also offers a direct mechanical extraction option via a thrombus removal ring<sup>[30]</sup>. The 2009 Penumbra Pivotal Stroke Trial assessed the system's safety and efficacy<sup>[31]</sup>. While it achieved better revascularization than the multi-MERCI trial, only 25% of patients had a favorable 90-day modified Rankin Scale (mRS) score, and mortality remained high<sup>[31]</sup>.

Given the high mortality rates associated with the MERCI and Penumbra systems, the late 2000s saw a focus on devising more effective stent retrievers. Some clinicians experimented with self-expanding stents used in aneurysm treatment and intracranial atherosclerotic disease, but these required prolonged antiplatelet therapy<sup>[32]</sup>. The Solitaire FR (Micro Therapeutics Inc. (part of Medtronic), Irvine, CA, USA) emerged as the pioneer in stent retrievers<sup>[33]</sup>, followed by the Trevo Retriever (Concentric Medical, Mountain View, CA, USA)<sup>[33,34]</sup>. The SWIFT trial, comparing Solitaire FR with the Merci Retriever, demonstrated Solitaire's superior efficacy and outcomes<sup>[35]</sup>. Similarly, the TREVO 2 trial pitted the Trevo stent retriever against the Merci Retriever, with the former achieving better 90-day outcomes<sup>[36]</sup>.

#### **1.4. Embolic agents**

In 1904, Dawbarn<sup>[37]</sup> pioneered the technique of embolization, treating lesions in the head and neck by introducing a mixture of paraffin and vaseline into patients via their external carotid arteries. In 1964, Dotter and Judkins<sup>[38]</sup> revolutionized vascular intervention by executing the first percutaneous transluminal angioplasty, targeting atherosclerotic arterial stenosis.

Today, therapeutic embolization addresses a variety of conditions such as intracranial vascular lesions including arteriovenous malformations (AVMs), fistulas, and vascular tumors in the head and neck. Depending on the desired duration of occlusion, clinicians can opt for either temporary or permanent embolic agents. Temporary agents, meant to induce clotting, encompass hemostatics like gelfoam, collagen, and thrombin. In contrast, permanent agents are more diverse and include coils, liquid substances like glue, alcohol, and onyx, as well as other tools like the Amplatzer plug and detachable balloons<sup>[39]</sup>.

Initially, coils posed challenges in retrieval after deployment. However, innovations led to the emergence of the Guglielmi detachable coils (GDC), which introduced the ability to be mechanically detached and repositioned with ease<sup>[40]</sup>. The market now offers a gamut of coil varieties: from bare coils and hydro coils to liquid, fiber, and bioactive coils. A noteworthy advancement in this space is the WEB II (Sequent Medical, Aliso Viejo, CA, USA): a cutting-edge, self-expanding, nitinol mesh device crafted explicitly for aneurysm occlusion<sup>[41]</sup>. A significant concern with traditional coil embolization was the associated risk of prolonged radiation exposure. To address this, the Penumbra occlusion device® (POD) (Penumbra Inc., Alameda, CA, USA) was conceived. Tailored for large vessels, this device curtails both the duration and intensity of radiation exposure<sup>[42]</sup>.

#### **1.5. Carotid stents**

Carotid angioplasty and stenting (CAS) has ascended as a preferred therapeutic modality for severe carotid stenosis, increasingly being recognized for its minimally invasive attributes. This method offers a valuable alternative, especially for patients with high surgical risk profiles and multiple associated

comorbidities<sup>[43,44]</sup>. As technology advances, we witness an array of carotid stents tailored to address diverse carotid lesions<sup>[45]</sup>. Historically, between 1977 and 1979, Mathias et al.<sup>[46,47]</sup> delineated a technique of carotid angioplasty, drawing insights from their animal model experiments. Stent architecture typically comprises multiple rings linked in tandem, and based on the interlinking bridges, stent designs can be classified as either open-cell or closed-cell structures. The introduction of the Palmaz-Schatz balloon-expandable stents (Cordis Corporation (a Johnson & Johnson company), Miami Lakes, FL, USA) marked a significant milestone in the progression of carotid angioplasty<sup>[48]</sup>.

However, balloon-expandable stents are not without limitations. They are notably susceptible to mechanical compressive forces, and concerns regarding inappropriate stent length, along with potential risks such as vessel dissection and injury, underscore some of their inherent challenges<sup>[49]</sup>. Recognizing these shortcomings, there was a paradigm shift towards peripheral self-expandable stents, exemplified by the rolling membrane Wallstent (Boston Scientific, Marlborough, MA, USA). These stents exhibit commendable resilience against external compression and possess the capacity to accommodate extensive vessel segments. Within the domain of self-expandable carotid stents, those fashioned from nickel-titanium alloy—nitinol, stand out. Nitinol stents undergo a unique transformation, conforming to their pre-determined shape upon reaching body temperature. Additionally, covered self-expandable stents have carved a niche as another stent variant. It's imperative to understand that no single stent is universally suitable for all carotid pathologies. Given the variability in carotid anatomy and degree of stenosis amongst patients, stent specifications ought to be meticulously tailored, harmonizing with the nuanced anatomic-pathological variations inherent to each individual, as detailed in **Table 1**.

**Table 1.** Different stents characteristics.

Type of stent	Advantages	Disadvantages
Nitinol open-cell stents	Flexible Comfortable Highly adaptable No shortening	Tent strut malalignment in extensive carotid lesions.
Nitinol closed-cell stents (either cylindrical or tapered)	No change in length during deployment.	Stiffness and poor flexibility.
Hybrid nitinol stent	Flexible Comfortable Highly adaptable No shortening	Closed cell portion has a fixed length.
Cobalto alloy braided mesh stents	Ability to accommodate carotid bifurcation.	Loss of structural flexibility when inserted into vessels. Unpredictable length.

## 1.6. Flow diversion (FD)

Historically, the endovascular approach to aneurysm management primarily centered around coiling embolization, which could be augmented with balloon or stent assistance. However, this strategy frequently fell short in effectively addressing large and giant aneurysms<sup>[50]</sup>. It's noteworthy that coil embolization carries an association with a 20% recurrence rate in aneurysms, often necessitating subsequent interventions<sup>[51]</sup>. Early attempts at excluding large aneurysms from circulation were marked by pioneering in-vivo experimental methodologies<sup>[52,53]</sup>. Building on these insights, Wakhloo et al.<sup>[54]</sup> theorized that concurrent exclusion of the aneurysm from circulation and stent graft placement across the aneurysm neck would culminate in efficacious aneurysm occlusion. This occlusion process typically spans a duration of 6–12 months<sup>[55]</sup>.

Innovation in this domain was spearheaded by the advent of flow diverters, which marked a notable

departure from conventional arterial stents<sup>[56]</sup>. Uniquely designed, flow diverters bolster flow continuity along the parent vessel while concurrently diminishing the inflow into the aneurysm. Their distinct architecture boasts a substantial metal surface area, yet they retain impressive permeability, ensuring the preservation of flow within branch vessels<sup>[57]</sup>. One such eminent device is the Pipeline embolization device (Medtronic, Irvine, CA, USA), which is an amalgamation of 25% platinum and 75% nickel-cobalt chromium alloy, exhibiting a porosity spectrum between 65% to 70%<sup>[55]</sup>.

In 2011, the medical landscape was enriched with the FDA's approval of the Pipeline Embolization Device (PED) (Medtronic, Irvine, CA, USA)<sup>[55]</sup>. The subsequent Pipeline of Uncoilable or Failed Aneurysms (PUFS) study shed light on its superior efficacy compared to conventional stents<sup>[58,59]</sup>. On the European front, the pipeline embolization device for the intracranial treatment of aneurysms trial (PITA) specifically targeted aneurysms with necks exceeding 4 mm and a dome/neck ratio less than 1.5, achieving a remarkable 93.3% occlusion rate<sup>[60,61]</sup>. Further augmenting the portfolio of flow diverters are the Silk flow diverter and the SURPASS flow diverter. In 2008, the Silk flow diverter (Balt Extrusion, Montmorency, France) garnered approval from the European Commission<sup>[62]</sup>. At the one-year mark, the Silk flow diverter exhibited an occlusion rate of 81.8%. In contrast, the SURPASS flow diverter (Stryker Corporation, Kalamazoo, MI, USA) documented a 94% occlusion rate for non-bifurcation aneurysms and 50% for bifurcation aneurysms within a 6-month window<sup>[63,64]</sup>.

## **2. Cross-disciplinary contributions to the neurointerventional arena: The influence of cardiology interventions**

Mechanical thrombectomy has recently emerged as a cornerstone therapeutic approach for stroke management. The initial thrust in addressing acute arterial occlusions, especially in ST-Elevation Myocardial Infarction (STEMI), was predicated on understanding the pathophysiological nuances of acute thrombotic blockages in primary coronary arteries. Intriguingly, the pathophysiological underpinnings of atherosclerotic plaques manifest congruently in both coronary and carotid vessels. Such parallels have paved the way for leveraging techniques and instruments traditionally reserved for coronary angioplasty in the realm of carotid angioplasty, albeit with necessary calibrations in tool dimensions.

There has been a surge in interventional cardiologists transitioning to stroke treatments via mechanical thrombectomy<sup>[48]</sup>. This interdisciplinary shift can be attributed to a notable dearth of neurointerventional specialists and training hubs on a global scale, creating a role for cardiologists to bridge this deficit<sup>[65,66]</sup>. Contemporary cardiology catheter labs have been repurposed to facilitate stroke intervention protocols. Putman et al.<sup>[67]</sup> extolled the virtues of specific large-caliber (ranging from 7F to 9F) coronary guiding catheters for select neuroendovascular procedures. Their exploration revealed that these coronary catheters can navigate the brachiocephalic vessels, while their design features harmonize seamlessly with neuroendovascular modalities. Instruments like the Judkins coronary catheters closely mirror the design of Hincks headhunter catheters, making them potential assets in carotid navigation<sup>[68]</sup>. Furthermore, catheters like the Brite Tip (Cordis Endovascular systems, Miami Lakes, Fla, USA) and Sherpa Peak Flow (Medtronic, Inc, Minneapolis, Minn, USA) can catheterize the proximal brachiocephalic arteries<sup>[67]</sup>.

Nardai et al.<sup>[69]</sup> delved into evaluating the outcomes of using coronary stents in endovascular interventions for acute atherosclerotic basilar artery occlusion. Their findings underscored that timely management of occlusive stenosis in the basilar artery, in tandem with coronary stents and a dual antiplatelet regimen, corresponded to more favorable patient outcomes. By harnessing coronary stents and executing nuanced technical adjustments, neurovascular lesions can be adeptly managed. The adaptability of cardiological instruments, especially given the scarcity of specialized neurointerventional facilities and expertise,

particularly in resource-constrained regions, becomes invaluable. It's worth noting that interventional cardiologists have showcased comparable efficacy in stroke management to their neurosurgical counterparts<sup>[70]</sup>.

The symbiosis between cardiac and neurointerventional procedures isn't just limited to tools but extends to procedural methodologies. The transfemoral route, a mainstay in interventional neuroradiology, remains the preferred vascular conduit for cerebral vessel catheterization. Campeau, in 1989, pioneered the radial approach for coronary interventions<sup>[71]</sup>. A decade later, Matsumoto et al.<sup>[72,73]</sup> echoed this innovation, elucidating the transradial methodology for neurointerventional applications. This cross-pollination of techniques between the cardiac and neurointerventional labs is a testament to the adaptability and confluence of medical innovations across disciplines.

### **3. Biodegradable materials in neurointervention: A new horizon**

Cardiovascular stents have evolved from non-degradable bare-metal stents to drug-eluting stents, and now, to biodegradable stents. Biodegradable materials have seen extensive use in cardiovascular interventions; however, their application in cerebrovascular procedures remains largely limited to animal models.

Biodegradable materials offer an alternative to permanent medical devices, with potentially reduced side effects. They degrade or corrode over time and exhibit higher mechanical strength compared to non-degradable materials<sup>[74,75]</sup>. Despite the established use of biodegradable materials in other medical domains, their integration into neurointerventional procedures is still emerging<sup>[76,77]</sup>. Recent developments include biodegradable devices for the brain, such as electrodes for electrophysiological recordings and optical sensors for pressure monitoring<sup>[78,79]</sup>. Among these, Mg alloys are frequently used due to their mechanical properties and coating potential<sup>[80]</sup>.

In cardiology, biodegradable coronary stents have demonstrated efficacy in lumen patency and have been implicated in vessel remodeling and arterial healing processes<sup>[81]</sup>. Lactic acid-based stents are currently approved for coronary interventions<sup>[82]</sup>.

Conventional cerebrovascular stents are non-degradable and can lead to long-term complications such as thrombosis and stenosis. Biodegradable stents aim to mitigate these issues by degrading after serving their purpose<sup>[83]</sup>. These stents should have a controlled degradation rate, especially during the initial 6–12 months<sup>[83]</sup>.

Studies on biodegradable materials in neurointervention include the use of an Mg alloy stent for treating a saccular aneurysm in rats<sup>[84]</sup>, assessing biodegradable polymers in porcine carotid arteries<sup>[85]</sup>, and trialing polytetrafluoroethylene membrane-coated Mg-Nd-Zn-Zr alloy stents in rabbits<sup>[86]</sup>. Additionally, Grüter et al.<sup>[84]</sup> reported no complications six months post Mg alloy stent implantation in a cerebral aneurysm model, and Zhang et al.<sup>[87]</sup> observed the successful integration of a Mg-Nd-Zn-Zr (JDBM) stent in a rabbit model.

The next step involves clinical trials to evaluate the potential of these biodegradable materials in human neurovascular interventions.

### **4. Discussion**

The advancements in carotid angioplasty and stenting (CAS) highlight the rapid evolution of endovascular technologies in addressing carotid stenosis. As we dive into the historical context, we observe a trajectory from traditional techniques to those that are now minimally invasive, presenting a versatile alternative for high-risk patients. This is emblematic of a larger trend within medicine: as technology evolves, treatments become less invasive and more patient-centered.

The spectrum of stent designs, including balloon-expandable stents, self-expandable stents, and those

fabricated from nickel-titanium alloy (nitinol), caters to the heterogeneity of carotid pathologies. As highlighted in **Table 1**, each stent type bears its set of advantages and challenges. It is crucial to understand that no single stent design can fit all clinical scenarios. Tailored intervention, considering an individual's unique anatomy and the extent of stenosis, is important.

Flow diversion (FD) offers a paradigm shift in the management of aneurysms. Where coil embolization has its limitations, particularly with large and giant aneurysms, flow diverters emerge as an innovative tool. The Pipeline Embolization Device, the silk flow diverter, and the SURPASS flow diverter have all showcased commendable results in their respective studies. Their primary utility lies in their ability to divert flow from the aneurysm, which can potentially result in aneurysm occlusion, all the while maintaining patency in parent and branch vessels.

The interplay between cardiology and neurointerventional procedures is a testament to the further potential cross-disciplinary growth within the medical field. Leveraging tools and techniques from coronary angioplasty for carotid interventions highlights the universality of certain foundational principles across specialties. This is particularly important in addressing the shortage of neurointerventional specialists globally. However, it is essential to emphasize the need for specialized training and calibrations when transitioning tools and methodologies between the heart and brain. Observed outcomes indicate potential, but they also suggest the importance of careful evaluation and caution.

Lastly, the realm of biodegradable materials in neurointervention is on the horizon. While cardiovascular interventions have capitalized on the advantages of biodegradable stents, their adaptation for cerebrovascular procedures remains in its infancy. Current research with animal models is promising. The rationale for biodegradable materials, notably their potential to reduce long-term complications like thrombosis and stenosis, is compelling. However, it is important to tread with caution. We anticipate clinical trials to play an important role in shaping the future of biodegradable materials in neurovascular interventions.

Several randomized controlled trials are expanding the scope of mechanical thrombectomy for acute stroke. The pursuit for advanced treatment technologies, pre-hospital imaging tools, and machine learning's integration into stroke imaging signify this ongoing transformation. Innovations are not limited to procedural techniques. The development of antithrombogenic coatings for stents and flow diverters is in progress, aiming to replace dual antiplatelet regimens. There is also a role for remote mentoring, which can be effective even in emergency cases. While these developments hold a promising future, challenges persist. Simulators still need substantial enhancements, and the introduction of robotics into the neurointerventional routine remains in its infancy, marked by small case series and preliminary frameworks. Multifactorial decision-making tools for endovascular stroke treatment are in the conceptual phase, with their integration into clinical routine still a topic of debate. As we look further ahead, hopes of future breakthroughs in the field remain, tethered more to changes in human behavior than technological innovation. The field stands to benefit from a systematic approach to adopting new technologies, which requires a concerted effort from all stakeholders involved<sup>[88]</sup>.

In conclusion, the advancements in carotid and cerebrovascular interventions, from stent designs to flow diverters and the promise of biodegradable materials, paint a hopeful future. Yet, as always in medicine, we are urged to balance enthusiasm with prudence, continually grounding our innovations in scientific evaluation and patient-centered care.

## **Conflicts of interest**

The authors declare no conflict of interest.

## References

1. Artico M, Spoletini M, Fumagalli L, et al. Egas Moniz: 90 years (1927–2017) from Cerebral Angiography. *Frontiers in Neuroanatomy* 2017; 11: 81. doi: 10.3389/fnana.2017.00081
2. Luessenhop AJ. Artificial embolization of cerebral arteries. *Journal of the American Medical Association* 1960; 172(11): 1153–1155. doi: 10.1001/jama.1960.63020110001009
3. Serbinenko FA. Balloon catheterization and occlusion of major cerebral vessels. *Journal of Neurosurgery* 1974; 41(2): 125–145. doi: 10.3171/jns.1974.41.2.0125
4. Guglielmi G, Viñuela F, Sepetka I, Macellari V. Electrothrombosis of saccular aneurysms via endovascular approach. *Journal of Neurosurgery* 1991; 75(1): 1–7. doi: 10.3171/jns.1991.75.1.0001
5. Molyneux AJ, Kerr RS, Yu LM, et al. International subarachnoid aneurysm trial (ISAT) of neurosurgical clipping versus endovascular coiling in 2143 patients with ruptured intracranial aneurysms: A randomised comparison of effects on survival, dependency, seizures, rebleeding, subgroups, and aneurysm occlusion. *Lancet* 2005; 366(9488): 809–817. doi: 10.1016/S0140-6736(05)67214-5
6. Andre C, Schan L, Scott M, et al. Neurointerventional radiology: History, present and future. *Journal of Radiology and Oncology* 2023; 7(2): 26–32. doi: 10.29328/journal.jro.1001049
7. Fiorella D, Woo HH, Albuquerque FC, Nelson PK. Definitive reconstruction of circumferential, fusiform intracranial aneurysms with the pipeline embolization device. *Neurosurgery* 2008; 62(5): 1115–1121. doi: 10.1227/01.neu.0000325873.44881.6e
8. Jahan R, Murayama Y, Pierre Gobin Y, et al. Embolization of arteriovenous malformations with onyx: Clinicopathological experience in 23 patients. *Neurosurgery* 2001; 48(5): 984–997. doi: 10.1227/00006123-200105000-00003
9. Nogueira RG, Jadhav AP, Haussen DC, et al. Thrombectomy 6 to 24 hours after stroke with a mismatch between deficit and infarct. *The New England Journal of Medicine* 2018; 378(1): 11–21. doi: 10.1056/nejmoa1706442
10. Albers GW, Marks MP, Kemp S, et al. Thrombectomy for stroke at 6 to 16 hours with selection by perfusion imaging. *The New England Journal of Medicine* 2018; 378(8): 708–718. doi: 10.1056/nejmoa1713973
11. Jia ZY, Lee SH, Kim YE, et al. Optimal guiding catheter length for endovascular coiling of intracranial aneurysms in anterior circulation in era of flourishing distal access system. *Neurointervention* 2017; 12(2): 91–99. doi: 10.5469/neuroint.2017.12.2.91
12. Campbell BCV, Mitchell PJ, Kleinig TJ, et al. Endovascular therapy for ischemic stroke with perfusion-imaging selection. *The New England Journal of Medicine* 2015; 372(11): 1009–1018. doi: 10.1056/nejmoa1414792
13. Li J, Castaño O, Tomasello A, et al. EP50\* Catheter tip distensibility substantially influences the aspiration force of thrombectomy devices. ESMINT 2021—Abstract book. *Journal of NeuroInterventional Surgery* 2021; 13(Suppl 2). doi: 10.1136/neurintsurg-2021-esmint.49
14. Goyal M, Menon BK, van Zwam WH, et al. Endovascular thrombectomy after large-vessel ischaemic stroke: A meta-analysis of individual patient data from five randomised trials. *Lancet* 2016; 387(10029): 1723–1731. doi: 10.1016/S0140-6736(16)00163-X
15. Berkhemer OA, Fransen PSS, Beumer D, et al. A randomized trial of intraarterial treatment for acute ischemic stroke. *The New England Journal of Medicine* 2015; 372(1): 11–20. doi: 10.1056/nejmoa1411587
16. Madigan J. Vascular access: Guide catheter selection, usage, and compatibility. In: Murphy K, Robertson F (editors). *Interventional Neuroradiology*. Springer London; 2014.
17. Inaba Y, Arai Y, Sone M, et al. Clinical trial for development of a steerable microcatheter. *Minimally Invasive Therapy & Allied Technologies* 2018; 28(1): 1–5. doi: 10.1080/13645706.2018.1467458
18. Berenstein A, Cabiri O, Broussalis E, et al. New concept in neurovascular navigation: Technical description and preclinical experience with the Bendit 17 and Bendit 21 microcatheters in a rabbit aneurysm model. *Journal of Neurointerventional Surgery* 2022; 15(2): 172–175. doi: 10.1136/neurintsurg-2022-018644
19. Oh JS, Yoon SM, Shim JJ, et al. Efficacy of balloon-guiding catheter for mechanical thrombectomy in patients with anterior circulation ischemic stroke. *Journal of Korean Neurosurgical Society* 2017; 60(2): 155–164. doi: 10.3340/jkns.2016.0809.003
20. Hoffmann JC, Minkin J, Primiano N, et al. Use of a steerable microcatheter during superselective angiography: Impact on radiation exposure and procedural efficiency. *CVIR Endovascular* 2019; 2(1): 35. doi: 10.1186/s42155-019-0078-9
21. MeritMedical. SwiftNINJA steerable microcatheter MeritMedical 2023. Available online: <https://www.merit.com/peripheral-intervention/delivery-systems/microcatheters/swiftninja-steerable-microcatheter> (accessed on 16 November 2023).
22. Chewning R, Wyse G, Murphy K. Neurointervention for the peripheral radiologist: Tips and tricks. *Seminars in Interventional Radiology* 2008; 25(1): 42–47. doi: 10.1055/s-2008-1052305
23. Kammerer S, du Mesnil de Rochemont R, Wagner M, et al. Efficacy of mechanical thrombectomy using stent retriever and balloon-guiding catheter. *Cardiovascular and Interventional Radiology* 2018; 41(5): 699–705. doi:

- 10.1007/s00270-018-1901-8
24. Nguyen TN, Malisch T, Castonguay AC, et al. Balloon guide catheter improves revascularization and clinical outcomes with the solitaire device. *Stroke* 2014; 45(1): 141–145. doi: 10.1161/strokeaha.113.002407
25. Zaidat OO, Castonguay AC, Nogueira RG, et al. TREVO stent-retriever mechanical thrombectomy for acute ischemic stroke secondary to large vessel occlusion registry. *Journal of Neurointerventional Surgery* 2017; 10(6): 516–524. doi: 10.1136/neurintsurg-2017-013328
26. Leary MC, Saver JL, Gobin YP, et al. Beyond tissue plasminogen activator: Mechanical intervention in acute stroke. *Annals of Emergency Medicine* 2003; 41(6): 838–846. doi: 10.1067/mem.2003.194
27. Hameed A, Zafar H, Mylotte D, Sharif F. Recent trends in clot retrieval devices: A review. *Cardiology and Therapy* 2017; 6(2): 193–202. doi: 10.1007/s40119-017-0098-2
28. Smith WS, Sung G, Starkman S, et al. Safety and efficacy of mechanical embolectomy in acute ischemic stroke. *Stroke* 2005; 36(7): 1432–1438. doi: 10.1161/01.str.0000171066.25248.1d
29. Smith WS, Sung G, Saver J, et al. Mechanical thrombectomy for acute ischemic stroke. *Stroke* 2008; 39(4): 1205–1212. doi: 10.1161/strokeaha.107.497115
30. Bose A, Henkes H, Alfke K, et al. The penumbra system: A mechanical device for the treatment of acute stroke due to thromboembolism. *AJNR. American Journal of Neuroradiology* 2008; 29(7): 1409–1413. doi: 10.3174/ajnr.a1110
31. The Penumbra Pivotal Stroke Trial. Safety and effectiveness of a new generation of mechanical devices for clot removal in intracranial large vessel occlusive disease. *Stroke* 2009; 40(8): 2761–2768. doi: 10.1161/strokeaha.108.544957
32. Levy EI, Siddiqui AH, Crumlish A, et al. First food and drug administration-approved prospective trial of primary intracranial stenting for acute stroke. *Stroke* 2009; 40(11): 3552–3556. doi: 10.1161/strokeaha.109.561274
33. Castaño C, Dorado L, Guerrero C, et al. Mechanical thrombectomy with the solitaire AB device in large artery occlusions of the anterior circulation. *Stroke* 2010; 41(8): 1836–1840. doi: 10.1161/strokeaha.110.584904
34. San Román L, Obach V, Blasco J, et al. Single-center experience of cerebral artery thrombectomy using the TREVO device in 60 patients with acute ischemic stroke. *Stroke* 2012; 43(6): 1657–1659. doi: 10.1161/strokeaha.111.640011
35. Saver JL, Jahan R, Levy EI, et al. Solitaire flow restoration device versus the Merci Retriever in patients with acute ischaemic stroke (SWIFT): A randomised, parallel-group, non-inferiority trial. *Lancet* 2012; 380(9849): 1241–1249. doi: 10.1016/S0140-6736(12)61384-1
36. Nogueira RG, Lutsep HL, Gupta R, et al. Trevo versus Merci retrievers for thrombectomy revascularisation of large vessel occlusions in acute ischaemic stroke (TREVO 2): A randomised trial. *Lancet* 2012; 380(9849): 1231–1240. doi: 10.1016/S0140-6736(12)61299-9
37. Dawbarn RHM. The starvation operation for malignancy in the external carotid AREA: Its failures and successes. *JAMA* 1904; XLIII(12): 792–795. doi: 10.1001/jama.1904.92500120002g
38. Dotter CT, Judkins MP. Transluminal treatment of arteriosclerotic obstruction. *Circulation* 1964; 30(5): 654–670. doi: 10.1161/01.cir.30.5.654
39. Vaidya S, Tozer K, Chen J. An overview of embolic agents. *Seminars in Interventional Radiology* 2008; 25(3): 204–215. doi: 10.1055/s-0028-1085930
40. Brassel F, Meila D. Evolution of embolic agents in interventional neuroradiology. *Clinical Neuroradiology* 2015; 25(S2): 333–339. doi: 10.1007/s00062-015-0419-6
41. Pierot L, Gubucz I, Buhk JH, et al. Safety and efficacy of aneurysm treatment with the WEB: Results of the WEBCAST 2 study. *AJNR. American Journal of Neuroradiology* 2017; 38(6): 1151–1155. doi: 10.3174/ajnr.a5178
42. Spiotta AM, Turner RD, Chaudry MI, et al. Carotid sacrifice with a single Penumbra occlusion device: A feasibility study in a swine model. *Journal of Neurointerventional Surgery* 2014; 8(1): 99–102. doi: 10.1136/neurintsurg-2014-011461
43. Roubin GS, New G, Iyer SS, et al. Immediate and late clinical outcomes of carotid artery stenting in patients with symptomatic and asymptomatic carotid artery stenosis. *Circulation* 2001; 103(4): 532–537. doi: 10.1161/01.cir.103.4.532
44. Cremonesi A, Manetti R, Setacci F, et al. Protected carotid stenting. *Stroke* 2003; 34(8): 1936–1941. doi: 10.1161/01.str.0000081000.23561.61
45. Bosiers M, Deloose K, Verbist J, Peeters P. Carotid artery stenting: Which stent for which lesion? *Vascular* 2005; 13(4): 205–210. doi: 10.1258/rsmvasc.13.4.205
46. Mathias K. A new catheter system for percutaneous transluminal angioplasty (PTA) of carotid artery stenoses. *Fortschritte der Medizin* 1977; 95(15): 1007–1011.
47. Mathias K, Mittermayer C, Ensinger H, Neff W. Percutaneous catheter dilatation of carotid stenoses—Animal experiments (Cerman). *RöFo: Fortschritte auf dem Gebiete der Röntgenstrahlen und der Nuklearmedizin* 1980; 133(3): 258–261. doi: 10.1055/s-2008-1056722

48. Bergeron P, Becquemin JP, Jausseran JM, et al. Percutaneous stenting of the internal carotid artery: The European CAST I study. Carotid Artery Stent Trial. *Journal of Endovascular Surgery* 1999; 6(2): 155–159. doi: 10.1583/1074-6218(1999)006<0155:PSOTIC>2.0.CO;2
49. Wholey MH, Wholey MH, Jarmolowski CR, et al. Endovascular stents for carotid artery occlusive disease. *Journal of Endovascular Surgery* 1997; 4(4): 326–338. doi: 10.1177/152660289700400402
50. Raymond J, Guilbert F, Weill A, et al. Long-term angiographic recurrences after selective endovascular treatment of aneurysms with detachable coils. *Stroke* 2003; 34(6): 1398–1403. doi: 10.1161/01.str.0000073841.88563.e9
51. Ferns SP, Sprengers MES, van Rooij WJ, et al. Late reopening of adequately coiled intracranial aneurysms. *Stroke* 2011; 42(5): 1331–1337. doi: 10.1161/strokeaha.110.605790
52. Geremia G, Haklin M, Brennecke L. Embolization of experimentally created aneurysms with intravascular stent devices. *AJNR. American Journal of Neuroradiology* 1994; 15(7): 1223–1231.
53. Turjman F, Acevedo G, Moll T, et al. Treatment of experimental carotid aneurysms by endoprosthesis implantation: Preliminary report. *Neurological Research* 1993; 15(3): 181–184. doi: 10.1080/01616412.1993.11740132
54. Wakhloo AK, Schellhammer F, de Vries J, et al. Self-expanding and balloon-expandable stents in the treatment of carotid aneurysms: An experimental study in a canine model. *AJNR. American Journal of Neuroradiology* 1994; 15(3): 493–502.
55. Nelson PK, Lylyk P, Szikora I, et al. The pipeline embolization device for the intracranial treatment of aneurysms trial. *AJNR. American Journal of Neuroradiology* 2010; 32(1): 34–40. doi: 10.3174/ajnr.a2421
56. Berge J, Biondi A, Machi P, et al. Flow-diverter silk stent for the treatment of intracranial aneurysms: 1-year follow-up in a multicenter study. *AJNR. American Journal of Neuroradiology* 2012; 33(6): 1150–1155. doi: 10.3174/ajnr.a2907
57. Chong W, Zhang Y, Qian Y, et al. Computational hemodynamics analysis of intracranial aneurysms treated with flow diverters: Correlation with clinical outcomes. *AJNR. American Journal of Neuroradiology* 2013; 35(1): 136–142. doi: 10.3174/ajnr.a3790
58. Becske T, Brinjikji W, Potts MB, et al. Long-term clinical and angiographic outcomes following pipeline embolization device treatment of complex internal carotid artery aneurysms: Five-year results of the pipeline for uncoilable or failed aneurysms trial. *Neurosurgery* 2016; 80(1): 40–48. doi: 10.1093/neuros/nyw014
59. Becske T, Potts MB, Shapiro M, et al. Pipeline for uncoilable or failed aneurysms: 3-year follow-up results. *Journal of Neurosurgery* 2017; 127(1): 81–88. doi: 10.3171/2015.6.jns15311
60. Szikora I, Berentei Z, Kulcsar Z, et al. Treatment of intracranial aneurysms by functional reconstruction of the parent artery: The budapest experience with the pipeline embolization device. *AJNR. American Journal of Neuroradiology* 2010; 31(6): 1139–1147. doi: 10.3174/ajnr.a2023
61. Fischer S, Vajda Z, Aguilar Perez M, et al. Pipeline embolization device (PED) for neurovascular reconstruction: Initial experience in the treatment of 101 intracranial aneurysms and dissections. *Neuroradiology* 2011; 54(4): 369–382. doi: 10.1007/s00234-011-0948-x
62. Shankar JJS, Tampieri D, Iancu D, et al. SILK flow diverter for complex intracranial aneurysms: A Canadian registry. *Journal of Neurointerventional Surgery* 2015; 8(3): 273–278. doi: 10.1136/neurintsurg-2015-011708
63. Murthy SB, Shah S, Shastri A, et al. The SILK flow diverter in the treatment of intracranial aneurysms. *Journal of Clinical Neuroscience* 2014; 21(2): 203–206. doi: 10.1016/j.jocn.2013.07.006
64. De Vries J, Boogaarts J, Van Norden A, Wakhloo AK. New generation of flow diverter (surpass) for unruptured intracranial aneurysms. *Stroke* 2013; 44(6): 1567–1577. doi: 10.1161/strokeaha.111.000434
65. Hornung M, Bertog SC, Grunwald I, et al. Acute stroke interventions performed by cardiologists. *JACC: Cardiovascular Interventions* 2019; 12(17): 1703–1710. doi: 10.1016/j.jcin.2019.05.052
66. Hopkins LN, Holmes DR Jr. Public health urgency created by the success of mechanical thrombectomy studies in stroke. *Circulation* 2017; 135(13): 1188–1190. doi: 10.1161/circulationaha.116.025652
67. Putman CM, Chaloupka JC. Use of large-caliber coronary guiding catheters for neurointerventional applications. *AJNR. American Journal of Neuroradiology* 1996; 17(4): 697–704.
68. Bunt TJ. Complete cerebral angiography in the evaluation of patients with cerebrovascular insufficiency. *The American Surgeon* 1988; 54(10): 617–620.
69. Nardai S, Kis B, Gubucz I, et al. Coronary stent implantation for acute basilar artery occlusion with underlying stenosis. *EuroIntervention* 2020; 16(12): e1021–e1028. doi: 10.4244/eij-d-19-00519
70. Sulzenko J, Kožnar B, Peisker T, et al. Stable clinical outcomes when a stroke thrombectomy program is started in an experienced cardiology cath lab. *JACC: Cardiovascular Interventions* 2021; 14(7): 785–792. doi: 10.1016/j.jcin.2021.01.025
71. Campeau L. Percutaneous radial artery approach for coronary angiography. *Catheterization and Cardiovascular Diagnosis* 1989; 16(1): 3–7. doi: 10.1002/ccd.1810160103
72. Park JH, Kim DY, Kim JW, et al. Efficacy of transradial cerebral angiography in the elderly. *Journal of Korean Neurosurgical Society* 2013; 53(4): 213–217. doi: 10.3340/jkns.2013.53.4.213

73. Matsumoto Y, Hokama M, Nagashima H, et al. Transradial approach for selective cerebral angiography: Technical note. *Neurological Research* 2000; 22(6): 605–608. doi: 10.1080/01616412.2000.11740727
74. Han H, Jun I, Seok H, et al. Biodegradable magnesium alloys promote angio-osteogenesis to enhance bone repair. *Advanced Science* 2020; 7(15): 2000800. doi: 10.1002/advs.202000800
75. Zhou C, Li HF, Yin YX, et al. Long-term in vivo study of biodegradable Zn-Cu stent: A 2-year implantation evaluation in porcine coronary artery. *Acta Biomaterialia* 2019; 97: 657–670. doi: 10.1016/j.actbio.2019.08.012
76. Kabir H, Munir K, Wen C, Li Y. Recent research and progress of biodegradable zinc alloys and composites for biomedical applications: Biomechanical and biocorrosion perspectives. *Bioactive Materials* 2021; 6(3): 836–879. doi: 10.1016/j.bioactmat.2020.09.013
77. Wei S, Ma JX, Xu L, et al. Biodegradable materials for bone defect repair. *Military Medical Research* 2020; 7(1): 54. doi: 10.1186/s40779-020-00280-6
78. Xu K, Li S, Dong S, et al. Bioresorbable electrode array for electrophysiological and pressure signal recording in the brain. *Advanced Healthcare Materials* 2019; 8(15): e1801649. doi: 10.1002/adhm.201801649
79. Shin J, Liu Z, Bai W, et al. Bioresorbable optical sensor systems for monitoring of intracranial pressure and temperature. *Science Advances* 2019; 5(7): eaaw1899. doi: 10.1126/sciadv.aaw1899
80. Riaz U, Shabib I, Haider W. The current trends of Mg alloys in biomedical applications—A review. *Journal of Biomedical Materials Research* 2018; 107(6): 1970–1996. doi: 10.1002/jbm.b.34290
81. Cassese S, Byrne RA, Ndrepepa G, et al. Everolimus-eluting bioresorbable vascular scaffolds versus everolimus-eluting metallic stents: A meta-analysis of randomised controlled trials. *Lancet* 2016; 387(10018): 537–544. doi: 10.1016/S0140-6736(15)00979-4
82. Byrne RA, Kastrati A. Bioresorbable drug-eluting stents. *JACC: Cardiovascular Interventions* 2015; 8(1): 198–200. doi: 10.1016/j.jcin.2014.11.010
83. Nevzati E, Rey J, Coluccia D, et al. Biodegradable magnesium stent treatment of saccular aneurysms in a rat model-introduction of the surgical technique. *Journal of Visualized Experiments: JoVE* 2017; 128: 56359. doi: 10.3791/56359
84. Gräter BE, Täschler D, Strange F, et al. Testing bioresorbable stent feasibility in a rat aneurysm model. *Journal of Neurointerventional Surgery* 2019; 11(10): 1050–1054. doi: 10.1136/neurintsurg-2018-014697
85. Zamiri P, Kuang Y, Sharma U, et al. The biocompatibility of rapidly degrading polymeric stents in porcine carotid arteries. *Biomaterials* 2010; 31(31): 7847–7855. doi: 10.1016/j.biomaterials.2010.06.057
86. Wang W, Wang YL, Chen M, et al. Magnesium alloy covered stent for treatment of a lateral aneurysm model in rabbit common carotid artery: An in vivo study. *Scientific Reports* 2016; 6(1): 37401. doi: 10.1038/srep37401
87. Zhang J, Li H, Wang W, et al. The degradation and transport mechanism of a Mg-Nd-Zn-Zr stent in rabbit common carotid artery: A 20-month study. *Acta Biomaterialia* 2018; 69: 372–384. doi: 10.1016/j.actbio.2018.01.018
88. Goyal M, van Zwam W, Moret J, Ospel JM. Neurointervention in the 2020s: Where are we going? *Clinical Neuroradiology* 2020; 31(1): 1–5. doi: 10.1007/s00062-020-00953-8