Chapter 1
The History of Vascular Neurosurgery: A Journey of Evolution and Revolution

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The history of vascular neurosurgery is as rich and complex as any other field in medicine. Its birth and development emerged from the necessity, creativity, and technology needed to care for patients with potentially life-threatening lesions. Its growth and technological changes have influenced many other subdisciplines of our field. As a matter of fact, of the numerous evolutionary and revolutionary advances in the practice of neurological surgery, most have arisen from this need to treat and cure vascular disease of the brain and spinal cord. From anatomy to pathophysiology, from preoperative imaging to intraoperative optics, from creative microsurgical approaches to innovative endovascular techniques, vascular neurosurgery has brought a plethora of challenges to the practitioners of this art and science, and throughout its history, the neurosurgeon and the many collaborators and scientists have responded.

The historical review of this subject can take many forms. Developments in anatomy, imaging, technology, and techniques influenced the unique histories of each of the vascular diseases that neurological surgeons treat. Though each is deserving of extensive analysis, a brief historical survey of the many technological advances that influenced the growth of vascular neurosurgery will be presented prior to discussing the historical development and growth of the subdisciplines within vascular neurosurgery.

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The Rise of Vascular Anatomy

Galen first introduced the concept that a circulation of arteries and veins (centered on the heart) existed [1, 2]. Though not well conceived, Galen stated that vital spirits were produced in the left ventricle of the heart and traveled to the brain. The concept was further developed by numerous anatomists until the cohesive and correct concept of circulation was introduced by Harvey and elegantly described in the intracranial circulation by Thomas Willis in 1664 (Fig. 1.1) [3, 4].

Unlike the revolutionary change in the understanding of the cerebrovasculature as presented by Willis, there have been many incremental and evolutionary advances in developing a greater understanding of cerebrovascular anatomy. Authors, anatomists, and surgeons such as Krayenbuhl, Seeger, Lasjunias, Berenstein, Yaşargil, and Rhoton provided guidance and insight to every neurosurgeon and endovascular therapist in gaining the intricate fundamental knowledge of the anatomy of the arteries and veins of the brain and spinal cord. However, these authors brought a more important perspective. In addition to providing the detailed anatomy, these authors contributed to our understanding of the surgical anatomy of the surrounding structures. The intricate descriptions of Yaşargil and Rhoton in describing the subarachnoid cisterns and the numerous skull base corridors of approach brought a new understanding of how vascular lesions of the brain could be treated. Lasjunias,

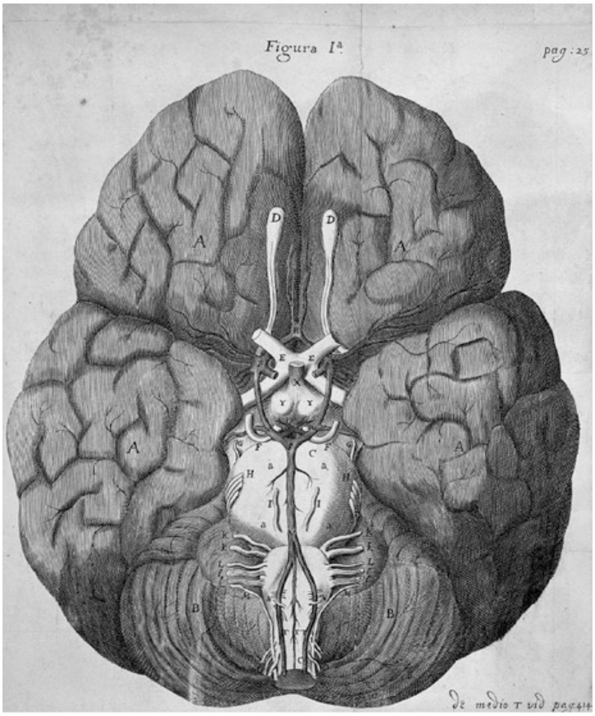

Fig. 1.1 Illustration by Christopher Wren of the basal view of the brain demonstrating the vascular arterial ring to be later named the circle of Willis (Willis, 1664, public domain)

Berenstein, and terBrugge introduced the need to understand the embryology of the cerebrovasculature such that it would become critical in understanding and thus treating some of the most complex vascular lesions. These critical elements have now become the fundamentals for all cerebrovascular and endovascular therapists.

Technological Growth

The History of Cerebrovascular Imaging

Dedicated imaging for the cerebral vasculature was developed long after the first attempts to treat vascular disease. The development of angiography was essentially an extension of the search to better diagnose intracranial lesions. Plain cranial X-rays, pneumoencephalography, and myelography were the basic methods of imaging the central nervous system before 1927 [5–7].

The first images of the human vasculature were obtained by Haschek and Lindenthal in 1896 (Fig. 1.2) [8]. By injecting a mixture of petroleum, quicklime (calcium oxide), and mercuric sulfide, they were able to visualize the vasculature of the hand of a cadaver with X-ray. Antonio Caetano de Abreu Freire Egas Moniz, a Portuguese neurologist, had an interest in developing a technique to image tumors of the brain [9, 10]. Recognizing the sedating effects and imaging qualities of bromine, Moniz hypothesized that injecting bromine compounds would travel to the brain (hence its sedating effects) and thus allow the brain to be imaged with X-ray. Further inspired by Sicard's work on the use of iodized oil myelography, Moniz set out to develop a technique that would improve the diagnosis of intracranial tumors [7]. On June 28, 1927, after several frustrating attempts on cadaver heads and dogs, Moniz and his colleague Almeida Lima successfully demonstrated the displacement of the anterior and middle cerebral arteries in a 20-year-old man with a pituitary adenoma after a direct surgical exposure of the carotid artery [11]. By 1931, Moniz

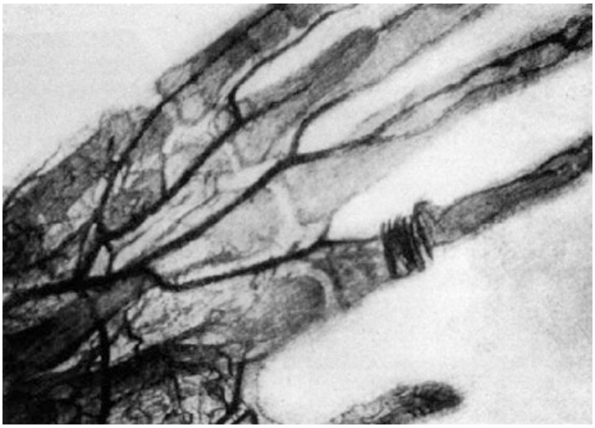

Fig. 1.2 First roentenogram of human vasculature in a postmortem hand by Haschek and Lindenthal 1 year after the discovery of X-ray (1896). The authors used Teichman's mixture injected into the amputated hand (public domain)

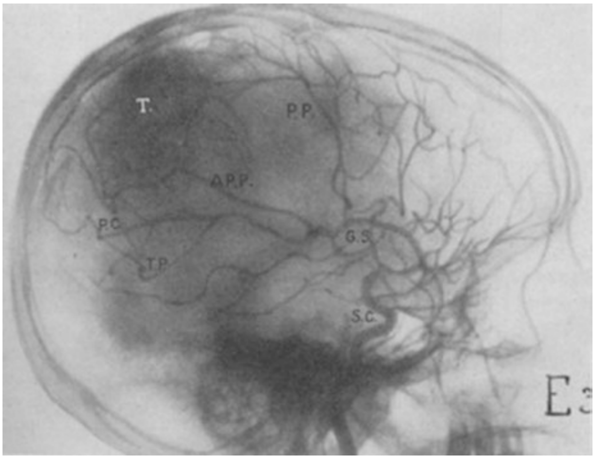

Fig. 1.3 First cerebral angiogram. Egas Moniz performed the first cerebral angiogram demonstrating a lateral view of the intracranial vessels for the first time in a living person (From Moniz [10], with permission)

was able to perform a complete angiogram which included arterial and venous phases (Fig. 1.3) [9, 11]. Angiography's preeminence as a diagnostic tool came in 1936 with Loman and Myerson's percutaneous carotid puncture technique [12]. Interestingly, the *Lancet* foreshadowed the potential of angiographic techniques as early as 1931, when it commented that not only might it be able to diagnose aneurysms but also that "its possibilities as an avenue for therapeutics should not be lost sight of in the future" [13, 14].

This technique became the standard for diagnosing intracranial lesions of all kinds, most significantly vascular lesions for the next 40 years. With better capabilities than standard skull X-ray and while being safer and having better direct imaging capacity than pneumoencephalography, cerebral angiography was used in creative ways that took great advantage of anatomical knowledge. Epidural and subdural hematomas were diagnosed by the notable absence of a capillary blush along the inner table; tumors of various lobes were defined by a notable shift of the Sylvian triangle or the Sylvian point; hydrocephalus was diagnosed by detecting a shift in the true venous angle [15, 16]. These skills became the standard in the image-based diagnosis of all intracranial pathology – until the early 1970s.

Up until 1971, intracranial imaging was limited to the *direct* imaging of the vasculature and ventricles and the *indirect* assessment of the brain parenchyma and its surrounding structures. Diagnosis of parenchymal lesions was by interpretation of surrogate evidence. Sir Godfrey Hounsfield revolutionized this field of imaging. An electrical engineer by training, Hounsfield was given the opportunity to perform independent research funded by EMI and develop the algorithms that would allow him to identify objects by obtaining X-ray images at different angles. This concept rapidly expanded to include the application to medical imaging. Initial studies were performed on a preserved human brain and subsequently on a fresh cow brain. By late 1971, Hounsfield's scanner was able to identify a cerebral cyst in a patient at Atkinson Morley Hospital [17, 18].

The technology and its application exploded. With the development of spiral and later multi-detector CT, higher resolution and greater tissue definition became a reality. The consequent reduction in scan time was a necessary by-product of the technology which created the ideal environment to develop CT angiography. By the late 1990s, the multi-row CT scanner, with thinner slice acquisition and reduced scanning time, now allowed clinicians to obtain long segment scans while injecting intravenous contrast. CT angiography was born [19–21].

In the ensuing 20 years, continued improvements in CT technology and the birth and rise of magnetic resonance imaging have changed the way vascular lesions are diagnosed. Cerebral angiography, initially used to provide clinicians a diagnosis via direct and indirect imaging evidence, has been displaced as a screening tool in favor of these less invasive techniques. As was once predicted, catheter-based angiography has blossomed into a versatile, effective, and safe therapeutic tool that has given birth to numerous new treatment paradigms.

History of the Microscope and Intraoperative Imaging

Neurological surgery in general and vascular neurosurgery in particular have benefited from the technological advances in illumination and magnification. Given that most neurosurgical procedures require dissection of the tissue to depths beyond 3 cm from the surface, proper illumination became the initial priority. Though this was achieved, in part by the use of external light sources with ever-improving efficiency and power beyond natural lighting entering the windows of the operative theater, the ability to provide illumination to the deeper portions of the surgical field remained elusive. The introduction of scopes with lenses to bring light directly to the surgical field began. Contemporaneous to this, there came an understanding and desire to magnify the operative field so as to ease identification of structures and thus render surgery safer [22].

Magnification in the form of operating loupes entered the surgical theater in the mid-nineteenth century [23]. Though initially used as corrective lenses, single-lens spectacles were designed with magnifying properties to be used for surgery. It wasn’t until 1876 that Saemisch, a German ophthalmologist, wore the first true binocular compound magnifying loupes in the surgical theater [23]. Though this solved the initial problems with magnification, it failed to address other important issues for proper visualization during surgery: illumination, the depth of field, and the field of view. For the neurosurgeon, the use of loupes has been of great benefit in the initial stages of most cranial operations and for some spinal surgeries to this day.

By the early 1900s, microscopes had become well-entrenched in the realm of experimental and animal research. In 1921, research on live animals describing the flow of endolymph in pigeons was reported [24]. Taking note of this, Carl Nylen, a Swedish otolaryngologist, subsequently developed and constructed an operating monocular microscope to treat a case of chronic otitis media (Fig. 1.4) [24, 25].

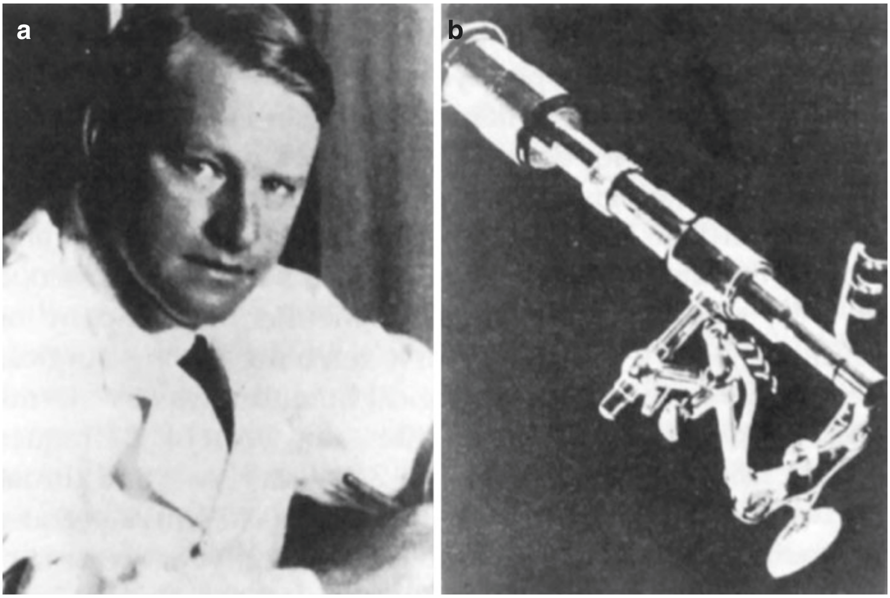

Fig. 1.4 Carl Nylen and the first monocular operating microscope (From Kriss and Kriss [25], with permission)

The field of otolaryngology through the work of Nylen's chairman, Gunnar Holmgren, and others provided the environment upon which further developments to the microscope could be made. By the 1950s, the field of otolaryngology (specifically otology) enjoyed the early rewards of technological improvements in lens crafting, fiber optics, and illumination.

Theodore Kurze was the first neurosurgeon to bring the operating microscope to the neurosurgical theater [25]. Having watched a film depicting surgery of the stapes as performed by William House, Kurze spent a year with House practicing microsurgery in the laboratory. In August 1957, Kurze was the first neurosurgeon to resect a neurilemoma from the facial nerve of a 5-year-old patient [25]. In the ensuing years, Kurze trained Drs. Pool, Rand, and Drake in the use of the surgical microscope, each of whom introduced the technology and techniques at their own institutions.

The surgical microscope provided much that was necessary to succeed in vascular and skull base surgery. The ability to provide excellent illumination, controlled magnification, and an excellent depth of field within an adequate field of view made the surgical microscope indispensible in the realm of neurovascular surgery. Adjunctive devices such as neuronavigation, fluorescence-enhanced microscopy, ultrasound, and intraoperative angiography have thus created an impressive armamentarium of techniques by which the neurosurgeon can ensure a safe, successful operation with a minimum risk of complications.

Endovascular Origins

Being able to visualize neurovascular pathology, both from the diagnostic perspective as rendered by cerebral angiography and noninvasive imaging and from the therapeutic perspective in the form of the surgical microscope and all its adjunctive devices, is certainly mission-critical in effecting success. Within vascular neurosurgery, each of these technologies was incorporated in unique and sometimes subtle ways that helped surgeons expand their skills and treat progressively more complex lesions with better outcomes.

The concept of endovascular treatment grew from attempts to treat aneurysms endovascularly since the nineteenth century [13]. Careful observations and subsequent experiments in animals by Velpeau suggested that metallic objects, such as needles, could result in local thrombosis sufficient to occlude an artery [26]. Independently, Phillips demonstrated that the use of a needle with an applied electric current also resulted in thrombosis within a vessel. These concepts were first studied in humans for the treatment of aortic aneurysms. It wasn't until approximately a century later that the technique was attempted for intracranial lesions [27, 28].

As previously discussed, neuroendovascular therapy has an extensive history. Although there were many approaches at endosaccular occlusion of aneurysms, true catheter-based endovascular approaches to vascular diseases of the central nervous system did not take place until 1960 [29].

Prior to Luessenhop, the direct intravascular approach to treatment of vascular pathology preceded Gardner's resourceful, yet inadvertent, "intravascular" approach to intracranial vascular pathology. Brooks has been incorrectly credited with the first such attempt when he placed a piece of muscle intravascularly to obliterate a traumatic carotid fistula in 1930 [30, 31]. When reviewing his commentary to Noland and Taylor, Brooks appropriately (and perhaps for the first time) points out the rationale for failure of Hunterian ligation in the treatment of carotid-cavernous fistulae, pointing out that the fistulous site must be obliterated for success. He reports having placed the muscle into the carotid artery to attempt to obliterate a fistula in a patient but never reported the free flow of such a piece of muscle to the distal circulation to do so [32]. Arutiunov and Burlutsky expanded upon this concept in the ensuing years and presented their important findings in 1964 [33].

Catheter technology had developed sufficiently by 1960, such that Luessenhop and Spence were able to intraoperatively cannulate the internal carotid artery [34]. They were the first to successfully deposit silastic spheres into the internal carotid circulation to treat an arteriovenous malformation in the operating room. Two years later, Rothenberg et al. introduced the concept of using balloons in the treatment of intracranial aneurysms when he developed the angiotactic balloon [35]. A polyester sleeve wrapped around a neoprene balloon was attached to a 4-French delivery system. This sleeve could then be deployed in situ, with inflation of the balloon, as was demonstrated in their animal model, substantiating that the intravascular use of balloons might be helpful in the treatment of intracranial vascular disease – a concept that would become important in endovascular therapy.

The remainder of the history of neuroendovascular therapy as well as vascular neurosurgery remains entwined with the history of the treatment of specific vascular diseases. Each lesion presents unique challenges and hence unique solutions developed by creative, evolutionary steps and at times revolutionary leaps. What is evident throughout this rich, colorful history is the overriding passion and drive that was demonstrated by the pioneers and the courage of the patients. Additionally, it is intriguing to note that in most cases, the concepts and logic on how to approach the clinical issues were clear and at times obvious. It was the need for technology to "catch up" with the ideas that at times delayed the progress.

History of Aneurysm Therapy

Intracranial aneurysms were first thought to be a cause of subarachnoid hemorrhage (SAH) in the seventeenth century [36]. Morgagni likewise emphasized the concept that intracranial aneurysms could be the cause of hemorrhage [37]. He was also the first to report the presence of incidental "dilatations" of both posterior cerebral arteries in 1725, possibly making this the first description of an intracranial aneurysm. The first documented account of an unruptured intracranial aneurysm did not occur until 1765 by Francesco Biumi in Milan [38]. In 1814, the first verified account of an aneurysmal rupture was reported by Blackall [39].

Despite recognizing these lesions during the mid-eighteenth century, there is no mention of any treatment being offered. Indeed, the reports at this time were based on postmortem findings. Treatment of vascular lesions of the head and neck did not begin until the late nineteenth century, several years after Hunter's description of proximal femoral artery ligation for popliteal aneurysms as an alternative to leg amputation [40, 41].

Building upon the success of Hunterian ligation in the peripheral circulation, the concept of carotid artery ligation for intracranial vascular pathology began to take form. The first successful carotid sacrifice for an indication other than hemorrhage was by Cooper in 1808 for an aneurysm of the left cervical internal carotid artery (Cooper's first carotid ligation in 1805 was unsuccessful) [42]. Cooper, interestingly, surmised at the time that the partial resolution in pulsations was attributed to retrograde filling from distal collateral circulation. Benjamin Travers first reported successful treatment of an intracranial lesion (carotid-cavernous fistula) in 1809 [43].

The years that followed were filled with clinical reports of carotid ligation for numerous nontraumatic indications. A full century after Hunterian ligation was first described; carotid occlusion for an intracranial aneurysm was performed. During surgery for resection of a middle fossa tumor in a 48-year-old woman, Victor Horsley identified a pulsating tumor, most likely an aneurysm. Horsley subsequently ligated her right common carotid artery. She was reported to be doing well 5 years later [44].

The following years were then devoted to developing more sophisticated methods of carotid occlusion progressing from various types of suture to mechanical clamps that would allow for progressive, controlled narrowing of the artery to the point of occlusion in an attempt to encourage collateral flow and allow for aborting the procedure in case of new neurological deficits [13].

Reports demonstrated mortality rates generally below 20% [45–48]. Unfortunately, successful obliteration of the aneurysm was low, with success usually occurring for aneurysms of the internal carotid artery (ICA) itself. Winn's report evaluating the rehemorrhage rate in 34 patients with posterior communicating artery aneurysms essentially found no difference between those treated with carotid occlusion and the conservatively managed nonoperative group [49].

Because of the difficulties noted and because of significant concerns regarding delayed thrombotic/embolic events from cervical carotid occlusion, the methods of cervical carotid occlusion were superseded by intracranial methods. The first successful intracranial carotid occlusion was described by Hamby and Gardner in 1932 [50]. Zeller was the first to attempt this procedure in 1911, but his patient died from hemorrhage after an assistant accidentally avulsed the ligated artery by pulling the ligature [51]. In 1935, Dandy introduced the use of the Cushing silver clip (developed in 1911) to achieve proximal supraclinoid ICA occlusion for the treatment of intracranial aneurysms [52].

Direct Approaches to Aneurysm Therapy

By the early 1900s, it was clear that, although a significant amount of knowledge had been gained on the pathology of aneurysms and some technical advances toward the treatment of these lesions had taken place, the overall outcomes were still dismal. Indeed, Harvey Cushing thought that the aneurysm was "a lesion having such remote surgical bearings, whether there are surgical indications further experience alone can tell" [53]. Ayer later echoed these sentiments by stating that subarachnoid hemorrhage "has little interest from a standpoint of active surgical procedure" [54].

Because of the many difficulties encountered with the indirect approaches of cervical carotid ligation, more direct approaches were sought. Although there were real concerns with a direct attack on the neck of an aneurysm, there were significant benefits. The technology in the 1930s made securing an aneurysm at the neck rather dangerous, as ligatures and silver clips were the only devices developed at the time. Thus, risks of exsanguination secondary to avulsion of the aneurysm at the neck were quite real. However, preservation of the parent vessel and a higher chance of cure for aneurysms beyond the carotid terminus were sufficient reason to embolden surgeons in their quest for new techniques.

Norman McComish Dott, a pupil of Cushing and one of the several men to help establish neurosurgery in Great Britain, was the first surgeon to be credited with the first direct attack on an intracranial aneurysm [13, 55]. On April 22, 1932, in treating a middle-aged man who had sustained three subarachnoid hemorrhages secondary to an aneurysm of the ICA terminus at the origin of the proximal middle cerebral artery, Dott encountered "formidable" bleeding during the exposure. He harvested the muscle from the patient's thigh and placed it on the exposed aneurysm dome. He reported that hemorrhage stopped after approximately 12 min. He applied further muscle pledgets in the region and surrounding the parent artery. The patient was reported to have made an excellent recovery with no further hemorrhagic events. Additional reports by Tonnis, Dandy, and Jefferson added to the early literature of wrapping [46, 56, 57].

The next advance in aneurysm treatment was aneurysm trapping, which was initially described by Walter Dandy in 1936 [45]. He performed cervical internal carotid ligation and clipping of the supraclinoid carotid artery for a cavernous aneurysm. Logue clipped the A1 segment to trap an anterior communicating artery aneurysm in 1956, and Tindall et al. added contralateral common carotid artery narrowing to assist in thrombosis [58, 59].

The Aneurysm Clip

On March 23, 1937, a new era in cerebrovascular surgery began. Walter Dandy reported exposing an aneurysm of the posterior communicating artery via his hypophyseal approach in a 43-year-old man presenting with a third nerve palsy. Having identified the neck of the aneurysm, he placed a silver clip across its neck and cauterized its dome. By 1944, he had amassed sufficient cases that he published his observations and results in the first monograph of aneurysm surgery, *Intracranial Arterial Aneurysms* [46].

This first clip used by Dandy was a malleable Cushing- or Mackenzie-type silver clip. Simple, yet important, modifications to the concept followed with the development of a U-shaped clip to allow the tips of the clip to approximate first and essentially trap the aneurysm neck within the clip, thus obliterating the aneurysm.

Further modifications to the clip came quickly [13]. Developments such as adjustable clips, cross-action "alpha" clips, and Drake's fenestrated clips for basilar tip aneurysms have enabled surgeons to treat aneurysms that were previously deemed unclippable [60]. Sundt's encircling clip-graft was another significant innovation in aneurysm clip technology that allowed for repair of vessel tears or small irregularities that are untreatable by ordinary clipping methods [61].

Currently, modifications to the aneurysm clip are based on metallurgy and different design configurations. Concurrent with the development of the aneurysm clip came many other developments in techniques and parallel technologies that helped improve the surgical treatment of patients with cerebral aneurysms [62]. As discussed, the introduction of the surgical microscope revolutionized the approach to treating aneurysms. The elegant microsurgical techniques of Yaşargil and Fox helped to redefine the surgical approaches to aneurysms, emphasizing the importance of understanding cisternal anatomy and microvascular anatomy in maximizing patient results [63]. During this period, others, such as Drake, set the standards for surgery of posterior circulation aneurysms, along with the development and use of the first fenestrated aneurysm clip [60].

Endosaccular Alternatives to Clipping

As aneurysm clip technology continued to develop, surgeons continued to reflect on alternative techniques for the management of aneurysms. The concept that aneurysms could be treated endoluminally was serendipitous. In 1936, Gardner opened a giant ICA aneurysm, thinking it to be a large tumor. He subsequently packed it with five cotton sponges [64]. The patient did well until 2 years later when the sponges were removed because of infection.

Thereafter, endosaccular attempts to thrombose aneurysms included the use of silk suture, electrothrombosis with copper wire, magnetically guided iron filings, and horse or hog hair through a transfundal approach [13]. Except for a few select procedures, the aforementioned techniques all involved transcranial approaches to the aneurysm. The technology for safe navigation intravascularly was not far behind. By 1962, Rothenberg et al. developed an intravascular catheter that could release an expandable sleeve and occlude an aneurysm in an experimental animal model [35]. Two years later, modern endovascular therapy for aneurysms was born.

Endovascular Therapy for Aneurysms

Though revolutionary in appearance, technique, and devices, the historical record suggests that perhaps endovascular therapy for aneurysms was an inevitable evolution. Luessenhop continued to build on his work with Spence. In 1964, Luessenhop and Velasquez demonstrated that balloons could be safely introduced into the internal carotid artery and actually demonstrated temporary exclusion of an aneurysm from the circulation during balloon inflation [29].

Though additional trials with magnetically guided iron filings via an intravascular route were attempted, subsequent years of research focused on the use of intravascular balloons to endovascularly occlude aneurysms [13]. During this period, a tremendous amount of research in the field of materials science enabled biomedical engineers to bond soft shapeable tubing of different compositions in such a way as to provide proximal catheter support with distal catheter flexibility and softness, resulting in a vast improvement in the navigation properties of the catheter. With the birth of the microcatheter, endovascular surgery's explosive growth paralleled that which was seen with the advent of the aneurysm clip.

Unlikely to have been greatly influenced by work in the Western Hemisphere, Serbinenko began searching for the endovascular treatment of intracranial vascular disease as a young neurosurgeon training at the N. N. Burdenko Institute in the mid-1950s. By 1969, Khilko and Zubkov demonstrated that stable thrombus could be formed within an aneurysm by saturation with coagulants and reduction of flow to the aneurysm by temporary parent vessel constriction [65].

Serbinenko began to research and develop skills and techniques for the use of balloons in earnest [66]. By 1974, Serbinenko reported the use of selective catheterization to deliver and deploy detachable balloons filled with a hardening agent (liquid silicone) for the treatment of a variety of vascular lesions in 300 patients at the Burdenko Institute. He began in 1963 with balloon exploration of the intracranial circulation and first occluded the internal carotid artery with a balloon via an approach through the external carotid artery in 1964. Most important to this historical review, he reported the successful detachment of balloons within a basilar tip aneurysm and supraclinoid carotid aneurysm.

Encouraged by this, Debrun et al. made minor modifications to Serbinenko's concept by introducing contrast into the balloon and an elastic band at its neck, which tightened to prevent leakage of contrast upon detachment [67]. DiTullio et al. developed the one-way valve for balloons, whereby contrast injection opened the valve, and the internal hydrostatic balloon pressure, once inflated, would prevent outflow of contrast [68].

In 1982, Romodanov and Shcheglov reported their results in the treatment of 119 patients with detachable, silicone-filled latex balloons [69]. They reported 108 occlusions with 93 parent vessel preservations and 4 deaths. Higashida et al. and Moret et al. used hydroxyethyl methacrylate as the filling solution for the balloon, further refining this technique [70–72]. Although initially promising, significant complications were reported with this technique, which included intraoperative and delayed rupture, as well as recanalization.

The use of coils for endovascular vessel occlusion began in earnest almost a century after its initial use for aortic aneurysms, with the introduction of the Gianturco coil [73]. In 1985, Braun et al. reported the first intracranial aneurysm treated with coil embolization [74]. Interestingly, the use of coils in this setting was the result of an unsuccessful balloon occlusion for a giant internal carotid artery aneurysm. The introduction of platinum coils with Dacron (E.I. duPont de Nemours and Co., Wilmington, DE) fiber to induce thrombosis for the treatment of vascular malformations and aneurysms was reported by Hilal et al. in 1988 [75]. Although some successes were reported, the inability to precisely control these pushable coils resulted in a significant incidence of parent vessel occlusion and distal embolization. A controllable delivery system with the ability to retrieve, reposition, and redeploy the coil to a satisfactory configuration prior to detachment was necessary to increase the safety of the procedure.

Intrigued by Mullan's work on electrothrombosis and Serbinenko's endovascular techniques, Guido Guglielmi began developing techniques that would combine these concepts. Guglielmi first constructed a microwire with a small magnet that would be introduced endovascularly within an aneurysm. He then developed a technique whereby a suspension of iron microspheres would be injected into the circulation and be attracted to the small magnet within the aneurysm, thus inducing thrombosis. The magnet would then be electrolytically detached from the microwire and left in situ [13].

Approximately 1 year later, Guglielmi began working with Ivan Sepetka of Target Therapeutics and developed the first-generation electrolytically detachable coil [76]. In 1990, the first coil was introduced in a patient for a traumatic carotid-cavernous fistula who failed balloon occlusion [77]. One month later, the first aneurysm was treated with this electrolytically detachable coil [78]. Interestingly, the initial reports suggested that aneurysmal thrombosis was a consequence of the thrombogenic properties of the coils in conjunction with electrothrombosis during detachment. This was later found not to be the case.

Since that time, the tremendous explosion in endovascular technology and techniques has challenged the role of microsurgery in the treatment of aneurysms. Early endovascular studies revealed that, although small aneurysms with small necks and a 2 to 1 dome-to-neck ratio had excellent long-term results, outcomes for large aneurysms or those with broad necks (>4 mm) had a significant recanalization rate [79]. To address this, Moret et al. [72] introduced the balloon remodeling technique. By placing a balloon across the neck of the aneurysm during coil deployment from a second microcatheter, better packing was achieved with less risk of coil protrusion into the parent artery.

Because of the limitations of coil embolization for aneurysm treatment, additional advances have been made in an attempt to reduce the recurrence rate of endovascular aneurysm therapy. Numerous studies have been published, evaluating the role of endovascular aneurysm therapy [80].

Similar to the explosion in the various kinds of aneurysm clips in the 1960s and 1970s, this past decade has seen the development of several different generations of the original coil along with variations in basic coil morphology [81]. The addition of bioactive coatings on or within the coil has resulted in a new direction of aneurysm treatment [82]. Such technology may increase the healing at the aneurysm neck, thereby reducing aneurysm recurrence.

Endovascular Hunterian ligation, aneurysm trapping, and parent vessel occlusion have all been reevaluated since being introduced in the early twentieth century [83]. Similar to its surgical predecessors, endovascular Hunterian ligation has a limited role in the current armamentarium of aneurysm therapy.

As with open surgical techniques, these concepts of “indirect” aneurysm therapy have been reintroduced with greater sophistication. Whereas at first the indirect approaches to aneurysm therapy involved flow reversal and trapping of aneurysms, now the indirect approach involves the use of stents for diversion of flow away from the aneurysm inflow zones [84]. First used as adjuncts for broad-necked aneurysms, stents are now being evaluated for their ability to alter flow along the aneurysm neck and, thus, influence recanalization.

History of Vascular Malformation Therapy

The history of resecting the various types of vascular malformations truly resides in the progress of anatomical and physiological knowledge, coupled with the rise of technical expertise and technology. Vascular malformations, specifically arteriovenous malformations, were recognized since the days of the Egyptians (Amenhotep I during the sixteenth century BC), who specifically cautioned physicians to not attempt to treat these lesions when they occurred anywhere in the body [85–87]. Intracranial vascular lesions were first reported by Virchow and Luschka in the late nineteenth century [88]. Subsequently, attempts to resect these lesions in the late nineteenth century to the early twentieth century were clearly fraught with danger given that hemostasis as a technique for the central nervous system had yet to be perfected.

Though first exposed by Giordano in 1897, his surgical procedure focused on ligating a parietal feeding artery with no sign of cure [89]. The literature does suggest that the first successful resection of an AVM was performed in same year by Jules-Emile Pean [90]. Subsequent case reports of AVM surgery by pioneers such as Bailey, Dandy, and Cushing demonstrated very poor outcomes. Indeed, Cushing and Bailey were more adamant against the neurosurgeons' role in treating AVMs than Cushing was with regard to aneurysms. Most interestingly, it was Cushing himself who observed the positive effects of radiation therapy on AVMs as early as 1928, a finding that was first reported by Vilhelm Magnus in 1914 [91, 92].

The second successful resection of an AVM was reported by Olivecrona [93]. Unique to this report was Olivecrona's systematic approach to the lesion, describing the careful ligation of superficial feeding arteries with circumferential dissection of the nidus. Of note, he echoed the concept of ligating the venous outflow vessels as the last, critical portion of the surgery.

It is interesting to note that the first angiographic diagnosis of the AVM was in 1936, several years *after* the numerous and some successful surgical resections [94–96]. This, in addition to the eventual addition of microscopic surgery, enhanced knowledge in anatomy and physiology, and McCormack's careful stratification of vascular lesions during the 1950s and 1960s brought a greater understanding to vascular malformations of the brain [97].

With the advent of the better methods of illumination, the microscope, and the microsurgical techniques as introduced by Donaghy, Krayenbuhl, and Yaşargil, the systematic approach to AVM resection blossomed. This was the stage of mastery. With Yaşargil's case series of ten patients, AVM surgery became safe and efficacious far beyond the initial attempts to successfully treat these lesions [90, 98]. As the technical microsurgical expertise was maturing, the simultaneous birth of radiosurgery toward the end of the 1960s and the growth of endovascular during the same period brought a new era to AVM therapy [99]. The year 1968 saw the development of the gamma knife by Lars Leksell as a natural outgrowth from recognizing radiation's effects on AVMs [92]. As noted, the very first endovascular procedure in the modern era was in fact to treat a fistula of the carotid artery by Luessenhop [29]. Furthermore, microcatheter technology developed primarily as a means of gaining access distally, and the calibrated leak balloon catheter was developed to gain access to pedicle feeders of AVMs. The historical aspects of radiosurgery and endovascular therapy for these lesions are too rich to describe in this brief overview and are described elsewhere.

Ischemic Therapy and Revascularization

The history of ischemic therapy is the history of our struggle with control. Recognized since the days before Hippocrates, the term apoplexy was used to describe what we today refer to as a stroke [100]. Derived from the ancient Greek to mean "to be stricken from," the term suggests man's helplessness in providing any form of therapy for this disease. It was believed that the hand of the gods was at play, punishing an individual for some bad behavior, and thus humans were helpless to provide any treatment that would interfere with the will of the gods.

Though there was some observational insight as to the function of the carotid artery – Rufus attributed the term "carotid" to mean "fall into a deep sleep" – the true link between the carotid's role in supplying blood to the brain was centuries away [101].

Wepfer, several centuries later, was the first to link the ischemic and hemorrhagic intracranial pathology to the signs and symptoms of stroke [102]. As correlative pathology leads to a greater understanding of the pathophysiology of stroke, clinicians were emboldened to attempt to prevent strokes.

Surgery of the Carotid Artery

Paré was recorded as being the first to treat a traumatic injury of the carotid artery in 1552 [103]. The first to be reported in the English literature occurred several hundred years later, in 1804. Abernethy successfully treated an injury to the carotid artery when he saved the life of a man who was gored in the neck by a cow in 1798 (but was reported in 1804) [104]. Unfortunately the patient died several days later. Petit, however, was the first to suggest that someone could survive in the setting of an occluded carotid, bringing forward the concept that elective surgery of the carotid was feasible [105]. It was thus that a few years later, Hebenstreit electively and successfully occluded a carotid artery [40]. This led the way for the first elective occlusion of a carotid artery to treat an aneurysm (in the form of Hunterian ligation).

As a reconstructive operation for a carotid arteriovenous aneurysm, von Parczewski performed the first end-to-end anastomosis in 1916 [106]. Thereafter, surgery for the carotid, including resection and reconstruction, was developed by oncological surgeons operating for neck cancer. By 1914, Ramsey Hunt reported the clear association of cervical carotid disease with hemiplegia and stroke and urged clinicians to examine the cervical vessels for diminution of pulsations in the setting of neurovascular symptoms [107].

The birth of angiography and the recognition that atherosclerosis of the carotid artery could in fact be the cause of stroke served as the critical elements in genesis of endarterectomy. Dr. DeBakey's landmark carotid endarterectomy for atherosclerotic disease was thus performed by in 1953 [108–110]. Interestingly, DeBakey was also the first to treat carotid disease “endovascularly” in 1967 when he performed a carotid angioplasty for fibromuscular dysplasia, though he performed it through a carotid cutdown procedure [111]. A decade later, percutaneous carotid angioplasty was performed by Mattias with good success [112, 113]. In 1994, Marks and his group introduced the concept of placing a stent across a spontaneous carotid dissection refractory to medical management in two patients with good outcomes [114]. What followed was the explosive growth of carotid angioplasty and the many excellent trials that enhanced our understanding of the benefits and limitations for endarterectomy and angioplasty and stenting in the setting of atherosclerotic disease of the carotid arteries.

Thrombolysis

Though prevention of stroke became an important tactic in treating ischemic disease, there was still the need to better understand and perhaps abort a stroke in evolution. With the NINDS ivTPA trial, a new era in stroke management was born [115]. No longer was there a sense of helplessness among clinicians. It was clear that in the right circumstances, a stroke and its sequelae could be reversed or indeed aborted. Intra-arterial chemical thrombolysis was first used in 1999 which was the result of numerous clinical case series that suggested excellent outcomes with minimal risk. The PROACT II trial confirmed a modest benefit to intra-arterial thrombolysis with urokinase [116]. However, when urokinase was removed from the market, the procedure suffered. Clinicians searched for a different technology to treat acute stroke. Surgical embolectomy first performed in 1963 by Chou, though technically feasible, did not demonstrate significantly good clinical outcomes [117]. However, in performing chemical thrombolysis, occasional mechanical disruption of the clot yielded some anecdotal success. It was thus that a drive to develop dedicated mechanical clot retrieval devices was born. The Merci retriever became the first FDA-approved device for the endovascular treatment of acute ischemic stroke. Subsequent to that, devices such as the Penumbra neurovascular system designed around aspiration of the clot was successfully developed. Finally, the development of stent-retriever devices continues the technological march to treating embolic stroke [118–120].

Hemorrhagic Strokes

The treatment of intracerebral hemorrhage (ICH) would seem to be straightforward: Identify the hematoma and evacuate the hematoma through a minimally directed surgery, leaving the smallest “footprint” possible in order to ensure the best possible outcome. Despite this straightforward directive, and despite the seeming simplicity in the approach to this rather common disease entity, excellent results have eluded the neuroscience community.

Though Piorry is initially credited with discussing trepanation as a means of evacuating an intracerebral hematoma in 1834, the first successful craniotomy for the evacuation of an intracerebral hematoma was performed in 1888 by MacEwen [121, 122]. In the years that followed, there was rather slow progress in understanding how best to maximize outcomes. Though detailed techniques were published, outcomes were inconsistent. In 1961 McKissock et al. published the first randomized trial for the treatment of intracerebral hematomas [123, 124]. This prospective trial failed to identify any significant differences in outcome between those patients treated with maximal medical management compared to those treated by surgery. By the 1980s, it was determined that patients undergoing surgical evacuation of lobar hemorrhages had better outcomes than patients treated for deep, central hemorrhages [125, 126]. Thus, the last 20 years of surgical research in ICH have focused on approaching deep-seated clots through minimally invasive means. Neuroendoscopy, stereotactic aspiration, focal thrombolysis, and aggressive medical management techniques continue to undergo development and evaluation as we struggle to achieve improved outcomes [127, 128].

The Bypass

Attempts to enhance or supplement the intracranial circulation overlap with the history of arterial reconstruction of the carotids. Nonetheless, the first attempts at intracranial revascularization were born from the transposition of the temporalis over the convexity of stroke patients in 1943 [129]. The concept of the indirect bypass blossomed. Creative approaches were undertaken with the use of omental flaps, dural leaflets, burr holes, and the transposition of the superficial temporal artery upon the surface of the brain, termed encephaloduroarteriosynangiosis (EDAS), most commonly used for symptomatic moyamoya disease [130, 131].

The direct approach to revascularization gained a firm foothold in 1960 with the first microsurgical saphenous vein bypass from the cervical carotid artery to the supraclinoid carotid artery by Jacobsen and Suarez [132]. Seven years later, Donaghy and Yaşargil simultaneously completed the first successful superficial temporal artery to middle cerebral artery bypass in Vermont and Zurich [133]. With acceptance of the microscope into the neurosurgical theater, the development and adoption of microsurgical instruments form other specialties, the rise of oncological and skull base neurosurgery and the growth in the passion to advance surgical anatomy; the 1970s and the 1980s became a period of novel approaches to effect extracranial to intracranial bypasses. Though of benefit in the setting of oncological resection and giant aneurysms, the benefits in the setting of cerebral ischemia were not well known. In order to determine its efficacy in this setting, Barnett et al. initiated the Extracranial-Intracranial (EC-IC) Bypass Trial in 1977, the results of which were reported 12 years later [134]. Unfortunately, the results of this prospective, randomized multicenter trial failed to demonstrate any clinical benefit in preventing cerebral ischemia in any group of patients, much to the shock of the neurosurgical community. However, later analysis revealed some substantial flaws in the methodologies. Unfortunately since that time, additional surgical (COSS Trial) and endovascular (SAMMPRIS) trials have not demonstrated significant benefits, though subgroup analysis suggests some benefits in certain populations [135, 136]. Though it would be simple to conclude that such interventions are not of any benefit in preventing cerebral ischemia, additional studies may be required to understand if there are some smaller populations that might show benefit.

Summary

The treatment of cerebrovascular disease has changed dramatically. The historical record reveals tremendous growth and creativity spurred by the seeming hopelessness of the disease process. Striking without warning, killing a large proportion of individuals at some of their most productive times of their lives, affecting families in ways never conceived, clinicians felt compelled to "make things better." The ideas, at times straightforward, lacked the necessary technology to properly implement or execute the treatment. Sometimes, what was truly lacking was the understanding of the disease process itself. Yesterday as today, the vision of curing AVMs and aneurysms drives us forward. We have become bolder over the centuries: We now dare to abort strokes in progress. We now dare to use the body's natural highway (its circulation) to guide us to the site of pathology and treat it through the smallest of footprints. The greatest lessons of this rich history, however, lie with the intrepid individuals and their patients who dared to push the field of anatomy and surgery to gain knowledge. Tomorrow, as today, the field will continue to move forward through the careful evolution of current practices and the eventual revolution in therapy that will follow. One thing is certain: Whether gene therapy, robotics, or computer-brain interface technology expands, its applications in the treatment of cerebrovascular disease are assured.

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