Surgical Treatment of Aneurysms

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Abstract

Although an increasing number of aneurysms are treated with endovascular therapy, traditional surgical treatment continues to be an important therapeutic option for both ruptured and unruptured aneurysms. The goal of aneurysm treatment is to isolate the aneurysm from the circulation while ensuring patency of parent artery and/or perforator branches. With advanced neurosurgical approaches focused on minimizing brain manipulation, careful arachnoid dissection, adjunctive intraoperative monitoring, and imaging techniques, aneurysm surgery can reliably achieve definitive occlusion with low complication rates. In the last decade, the widespread utilization of noninvasive vascular imaging techniques has led to an increased number of unruptured aneurysms that are detected and treated. Noninvasive imaging studies such as MRA and CTA play an ever-increasing role not only for the preoperative assessment but also postoperative monitoring of patients with intracranial aneurysms.

Keywords

Intracranial aneurysms • Cerebral aneurysms • Vascular disorder • Surgical clipping • Surgical treatment • Carotid balloon occlusion • Digital subtraction angiography • Magnetic resonance angiography • Computed tomography angiography • Indocyanine green angiography • Intraoperative angiography • Ruptured

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aneurysm • Unruptured aneurysm • Aneurysmal subarachnoid hemorrhage

Introduction and Historical Overview

Aneurysm rupture and subarachnoid hemorrhage are associated with significant morbidity and mortality. Patients who suffer aneurysmal subarachnoid hemorrhage carry an average case fatality rate as high as 52 %, while as many as 46 % of those surviving the subarachnoid hemorrhage have significant long-term cognitive impairment, and a third of survivors are left dependent on lifelong care [1–4]. For these patients, the imminent danger is rebleeding from the ruptured aneurysm, so the therapeutic goal is to isolate and secure the aneurysm to prevent this catastrophic complication. The mortality associated with ruptured aneurysms has decreased in the last three decades with early surgical intervention, which has been shown to reduce the risk of rebleeding and improve the chance for good recovery in patients with subarachnoid hemorrhage [5–7]. In recent years, advances and widespread utilization of noninvasive imaging have led to a large number of unruptured and often incidental aneurysms to be diagnosed, and this has been associated with an increase in the number of invasive procedures to treat intact aneurysms as well.

Surgical clipping has long been considered the gold standard for the treatment of intracranial aneurysms. Direct surgical clipping excludes the aneurysm from the circulation and removes the risk of growth and rupture. In recent years, parallel to the development of endovascular techniques, there has been a progressive reduction in the number of surgically treated aneurysms. Nevertheless, surgery continues to be an important therapeutic strategy in the treatment of these lesions.

Prior to 1970, the method of treating aneurysms was carotid ligation, which was shown to decrease the risk of rebleeding compared to conservative treatment [8–10]. The high rates of treatment failure and ischemic complications associated with this procedure were greatly reduced with modifications that included the use of preoperative temporary carotid occlusion testing, development of adjustable clamps for gradual carotid occlusion, and introduction of adjuvant extracranial-to-intracranial arterial bypass [8, 9, 11, 12]. Another well-accepted method of carotid occlusion for aneurysm treatment at the time was parent artery sacrifice with permanent balloon occlusion, although the success of treatment was similarly dependent on the degree of collateral circulation available to prevent ischemia [13–16]. Long-term complications of carotid and parent artery occlusion include the risk of immediate or late cerebral ischemia, as well as development of flow-associated aneurysms [11, 17–20]. In a review of patients treated with therapeutic carotid occlusion, 4.3 % of patients were found to have de novo aneurysm formation on average 9.1 years after treatment, thus suggesting the need for extensive follow-up [21]. Nowadays, carotid sacrifice is used only in selected cases of large and giant aneurysms that are not amenable to surgical clipping or endovascular treatment and has shown good outcomes and low mortality rates [20, 22–24].

In the late 1960s and early 1970s with the introduction of the surgical microscope and improvements in surgical clip technology, direct clipping with the use of microsurgical techniques became the modus operandi and led to the development of modern aneurysm surgery as we know it today. The next important step in the treatment of intracranial aneurysms was the introduction of the Guglielmi Detachable Coil in 1992, which represented a dramatic paradigm shift with the eventual establishment of endovascular therapy as an acceptable alternative, and even first-line option, to traditional clip ligation at many centers [25]. However, microsurgery remains the fundamental gold standard for certain aneurysms with complex morphological features such as small size, broad-based neck, those located in small diameter parent arteries. Surgical treatment is also preferred for certain patients such as those of younger age and good functional status, as it provides immediate and long-term aneurysmal obliteration. Given the variety of considerations that factor into decision making for the best therapeutic approach for each individual aneurysm, a multidisciplinary cerebrovascular team is necessary to work together to consider both surgical and endovascular options in every case [26–28]. This chapter provides an overview of the principles of modern intracranial aneurysm surgery.

Indications for Treatment

Invasive treatment of an intracranial aneurysm is dependent on many different conditions, the most important one being the rupture status. A patient who presents with intracranial hemorrhage from a ruptured aneurysm has a greater than 60 % risk of re-rupture over the next 6 months, with the risk being much higher during the first 2–3 weeks after the original bleed [29]. Therefore, treatment of a ruptured aneurysm is indicated in the vast majority of cases except in the very elderly who present with impaired neurological condition and those patients in deep coma who fail to improve after maximal neurological and systemic resuscitation. While the decision to treat is fairly clear in a patient with a ruptured aneurysm, the decision-making process is much more difficult in the patient who is found to harbor an unruptured intracranial aneurysm. Detailed analyses of the factors that play a role in the decision to treat unruptured aneurysms are beyond the scope of this chapter.

In general, treatment of an unruptured aneurysm is recommended for patients harboring aneurysms that are symptomatic, those documented to have increased in size on serial imaging, those larger than 6 mm, and aneurysms in certain locations that seem to harbor a worse natural history (e.g., posterior communicating artery (PComm), the posterior circulation, and the anterior communicating artery complex). Patient age, presence of risk factors such as smoking and hypertension, as well as family history of a ruptured intracranial aneurysm also play a pivotal role in the decision to treat an unruptured aneurysm. The patient's overall attitude about the knowledge of having an aneurysm and whether or not this has impacted negatively their quality of life is yet another factor to take into account. Although generalizations cannot be made and each patient and aneurysm should be considered individually, a consensus group of international experts has recently come up with a scoring system that can be used in deciding whether or not an unruptured aneurysm should be considered for invasive treatment [30].

Choice of Treatment Modality

Surgical clipping of intracranial aneurysms has long been considered the modality of choice and the gold standard for the treatment of intracranial aneurysms. However, since the introduction of the Guglielmi detachable coil in clinical practice in 1992, endovascular treatment has emerged as a valid alternative to direct surgical clipping. Due to technological advances, an increasing number of aneurysms are treated nowadays by endovascular means. Three prospective studies have been conducted in patients with ruptured aneurysms comparing surgical clipping to endovascular coiling [31–33]. A meta-analysis of these studies showed similar results in the three studies, demonstrating unequivocally that the percentage of patients with unfavorable outcome (modified Rankin score of 4–6) is significantly lower in patients treated endovascularly compared to those treated with surgical clipping. This conclusion indicates that for patients with ruptured intracranial aneurysms amenable to either treatment, endovascular coiling is associated with a better functional outcome and should be the preferred treatment modality [34]. However, concerns exist about the long-term durability of endovascular coiling with the risk of recurrence, need for retreatment, and underlying risk of long-term risk of re-rupture of the aneurysm. Because of these concerns, surgical clipping might be preferred for very young patients with ruptured aneurysms [35].

There are no available randomized studies comparing endovascular to surgical treatment in patients with unruptured intracranial aneurysms. Overall, given the perceived less invasiveness of endovascular treatment, an increasing number of unruptured aneurysms are treated by endovascular means rather than surgical clipping.

More recent developments in endovascular techniques, such as stent assisted coiling [36] and flow diversion [37], have further expanded the indications for endovascular treatment of unruptured aneurysms. In general, endovascular treatment is preferred for unruptured aneurysms that are amenable to safe treatment using this modality. However, surgical clipping continues to have an important role when treating certain aneurysms of very small size or those with a geometry and location (particularly MCA (middle cerebral artery) bifurcation aneurysms) that is unfavorable for endovascular treatment.

Preoperative Imaging

The diagnosis of a ruptured intracranial aneurysm is often suggested by the presence of subarachnoid hemorrhage on non-contrast head computed tomography (CT) in patients with the typical clinical presentations [38, 39]. However, many aneurysms are detected incidentally during brain imaging studies performed in the workup of neurological complaints. In order to confirm the diagnosis and accurately characterize these lesions, proper vascular imaging techniques are necessary to accurately guide treatment decisions. From the surgical point of view, it is of particular interest to assess the anatomy of the aneurysm particularly with attention to the orientation, diameter, neck width, and presence of perforator branches derived from the sac or neck of aneurysms. It is also useful to determine the relationship of the aneurysm to the parent vessel and surrounding neural or osseous structures. Other features such as the presence of calcifications at the neck level are also important, since this can imply a more challenging treatment.

Many different imaging techniques are available to evaluate intracranial aneurysms. Digital subtraction angiography (DSA), computed tomography angiography (CTA), and magnetic resonance angiography (MRA) have been implemented in the evaluation of these vascular lesions [38]. Unquestionably, catheter angiography remains the gold standard for the diagnosis of intracranial aneurysms [39]. This modality provides high-resolution images and allows for accurate characterization of the aneurysm anatomy (Fig. 1). Moreover, it allows immediate treatment if endovascular therapy is considered suitable. Despite its invasive nature, the complication rate in hands of experienced neuroradiologists is very low [40]. Classically, a two-dimensional digital subtraction angiography with three different projections is obtained to provide appropriate detail. However, three-dimensional reconstruction (Fig. 1b) is increasingly being used to obtain a better morphological visual depiction with the advantage of manipulation and free rotation of the vascular tree, which is very useful for treatment planning. This technique has also been shown to improve the detection of additional small aneurysms when compared to the classic two-dimensional angiography [41].

CTA (Fig. 2) is a fast and widely available modality that can be performed quickly in the acute setting after subarachnoid hemorrhage. The sensitivity and specificity of this modality are reported as 98 % and 100 %, respectively [42]. It is possible to derive three-dimensional renderings of the aneurysm, and this is particularly useful in depicting the relationship of the aneurysm to its surrounding bony structures [38]. The use of CTA has greatly increased during the last years [43], and some authors support its role as the sole preoperative study for intracranial aneurysms [42]. Technical advances including increased field strength (from 1.5 to 3-T) and refinement of techniques such as time of flight (TOF) have improved the diagnostic value of MRA over time [44]. Although this modality is not appropriate for the acute setting, it is widely utilized in the diagnosis and characterization of unruptured aneurysms and is the method of choice in patients with absolute contraindications (pregnancy, anaphylactic reactions, etc.) to contrast administration.

Surgical Principles

The goal of surgical treatment of intracranial aneurysms is complete obliteration with minimal brain manipulation, while preserving flow in

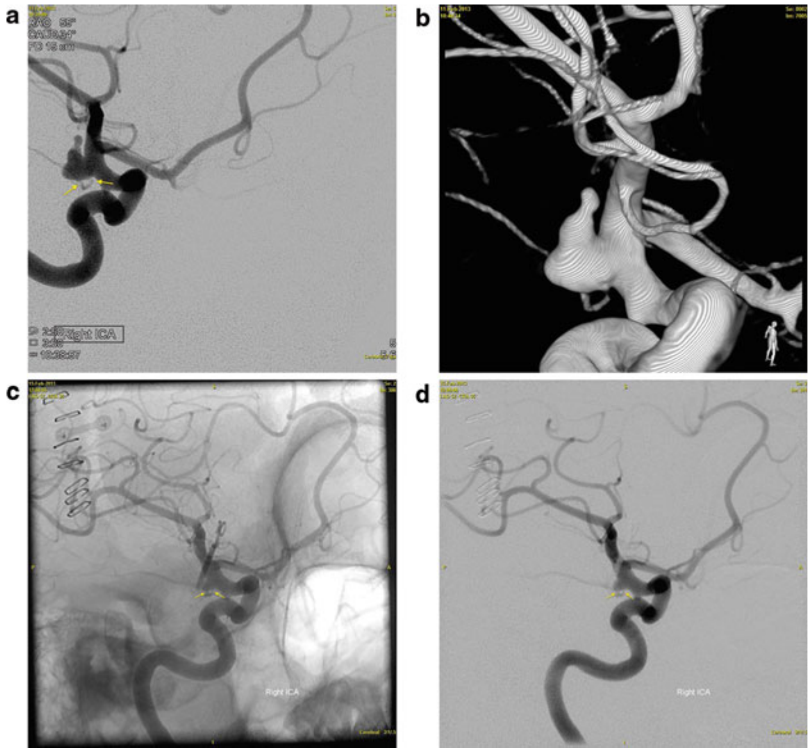

Fig. 1 (**a**) Selective right internal carotid artery (ICA) digital subtraction angiography injection, oblique projection, showing a complex aneurysm arising from the takeoff of the anterior choroidal artery (*arrows*). (**b**) 3-dimensional reconstruction of the digital subtraction angiogram showing the irregular shape of the aneurysm. (**c**) Unsubtracted right ICA angiogram, oblique projection, showing an aneurysm remnant after clipping (*arrows*). (**d**) Selective right ICA injection shows the postoperative remnant. At surgery, it was found that the origin of the anterior choroidal artery was duplicated (*arrows*), and therefore a small remnant was intentionally left to protect the more distal duplicated anterior choroidal artery

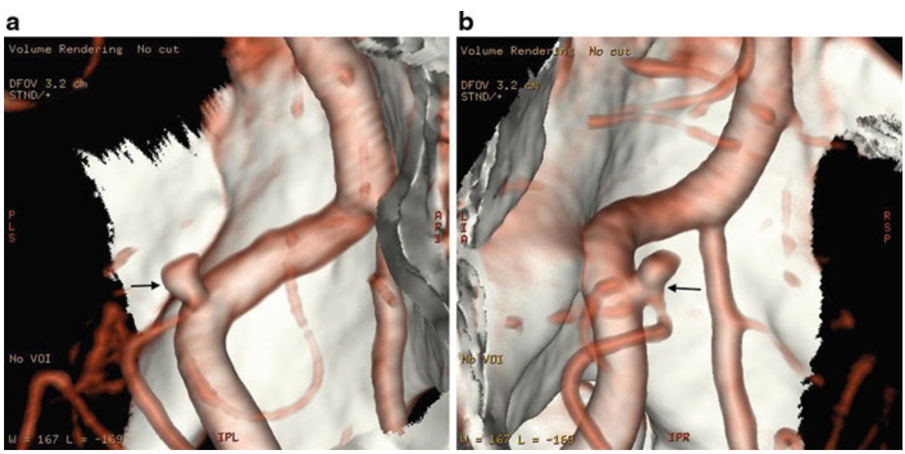

Fig. 2 (**a**) 3D reconstruction of computed tomography angiogram in a patient with a small, 2.6 mm, posterior inferior cerebellar artery aneurysm (*arrows*), showing a detailed profile of the aneurysm. (**b**) Rotational manipulation shows a different projection of the aneurysm. Here, the relationship of the neck of the aneurysm and the origin of the posterior inferior cerebellar artery is well identified (*arrows*)

parent artery and associated perforator vessels. The success of the surgical procedure depends on a variety of factors, including appropriate anesthetic management and an organized surgical technique. All of the procedures, regardless of the location, involve certain critical steps that allow adequate exposure and obliteration of the aneurysm. Further principles have to be taken into account depending on the particular anatomic location. Once the aneurysm has been surgically treated, there are tools available in the intraoperative setting to confirm proper obliteration of the aneurysm and ensure patency of the parent artery and perforator branches.

Anesthetic Management

Appropriate anesthetic management plays a very important role in the surgical treatment of intracranial aneurysms. The baseline clinical condition of the patient and the rupture status of the aneurysm often dictate the anesthetic plan. While early surgical treatment is the best measure to reduce the risk of rebleeding in patients with aneurysmal subarachnoid hemorrhage, tight control of hemodynamics and certain precautions must be implemented to minimize the risk of periprocedural rupture. The transmural pressure gradient should be minimized while an adequate cerebral perfusion pressure should be maintained. Appropriate prophylactic measures should be adopted to prevent excessive hypertension that can be present during procedures such as tracheal intubation or surgical stimuli such as skin incisions or pinning for the craniotomy. During the surgical procedure, pharmacologic measures can be established in order to increase brain relaxation, minimize brain retraction, and facilitate dissection. Osmotic diuresis with mannitol reduces the brain tissue volume, while changes in the ventilatory parameters such as controlled hyperventilation can achieve mild hypocapnia and reduced cerebral blood volume to provide additional brain relaxation. These latter maneuvers are especially important in patients with acutely ruptured aneurysms who often have a tight and edematous brain. Additional measures have to be considered when a prolonged temporary clipping is necessary, such as pharmacologic metabolic suppression. The role of moderate hypothermia to extend the duration of tolerable occlusion was felt to be protective as it theoretically reduces the release of excitotoxic amino acids. However, a randomized trial failed to show an effect of mild intraoperative hypothermia on neurologic outcome in patients with favorable clinical grade subarachnoid hemorrhage [45].

Critical Steps in Aneurysm Surgery (Table 1)

Table 1 Critical steps for the surgical treatment of intracranial aneurysms

1. Subarachnoid dissection	Opening of cisterns and arachnoid planes during initial exposure can help drain CSF
	Dissection of arachnoid fissures exposes proximal parent artery and allows proximal vascular control
	Sharp dissection along artery frees aneurysm neck with focus on avoiding damage to arterial perforators
	Trans-sylvian veins should be preserved in order to limit venous congestion and edema
2. Minimize brain retraction	CSF drainage can help brain relaxation via opening of basal cisterns, fenestration of lamina terminalis, or placement of external ventricular drain in patients with acute hemorrhage from aneurysm rupture
	Osmotic diuretics and steroid administration minimizes cerebral edema
	Suction device should be used for applying gentle retraction and countertraction during aneurysm dissection
	Avoid excessive parenchymal retraction to decrease risk of ischemic injury or avulsion of an adherent aneurysm

(*continued*)

Table 1 (continued)

3. Bony exposure	Advanced skull base approaches and modification of traditional approaches remove bony structures (e.g., sphenoid ridge, anterior and posterior clinoid, etc.) to extend the available operative corridor and minimize brain retraction that is required
4. Vascular control	Avoidance of dome manipulation and careful exposure of afferent and efferent arteries are important to establish proximal and distal control for temporary clipping
5. Temporary clipping	Temporary clipping can soften the aneurysm and reduce risk of rupture during aneurysm manipulation
6. Permanent clipping	Clip selection depends on size and direction of the aneurysm dome and neck
	Select proper blade length to avoid poor visibility and inadvertent occlusion of perforating vessels or nearby cranial nerves
	Booster clips can be utilized in atherosclerotic calcified aneurysms
7. Clip inspection	Clip blades should be placed completely across neck and parallel to branch vessel or bifurcations to avoid small remnants

1. **Subarachnoid dissection** (Fig. 3a–c): Intracranial aneurysms are commonly located along the circle of Willis within the subarachnoid space, so the surgical treatment is entirely extraparenchymal. By opening the arachnoidal planes and respecting the pia-arachnoid covering the brain, there is no violation of the cortex. Progressive opening of the subarachnoid cisterns en route to the aneurysm allows CSF drainage, and a wide opening of the surgical corridor allows mobilization of the brain without transmitting traction or undue forces on the surrounding structures. The dissection usually follows the path of a major artery with special caution to avoid damage of small perforators.
2. **Brain retraction**: Proper view of the surgical corridor occasionally requires some degree of brain retraction. However, this should be applied in a delicate fashion to avoid local ischemia or damage to neurovascular structures. The suction device can be used to apply gentle retraction as the dissection progresses as well as to provide countertraction when cutting tissue (Fig. 3a, c). If fixed retractors are necessary, these should be placed only after thorough dissection to maximize brain relaxation and minimize retraction pressure. Drainage of cerebrospinal fluid by opening the basal cisterns, fenestrating the lamina terminalis, lowering an existing external ventricular drain (EVD), or placement of a new EVD intraoperatively (in ruptured cases) are all acceptable maneuvers. In addition, osmotic diuretics, as previously described, can be given to decrease the brain tissue volume, and steroids can be administered to minimize edema from retraction.
3. **Maximizing exposure through bone resection**: Bone removal might be necessary to maximize the exposure and decrease brain manipulation, for example, the drilling of the sphenoid ridge for pterional approaches. A variety of advanced skull base approaches have been used in the treatment of intracranial aneurysms. While these are not necessary in the majority of cases, they continue to have a role in selected patients with aneurysms at challenging locations such as the mid-basilar trunk.
4. **Vascular control** (Fig. 3d–f): The afferent and efferent arteries that supply anterograde or retrograde blood flow to an aneurysm should be exposed in case temporary clipping is necessary. Proximal control should be established as early as possible, and the most appropriate point is defined according to the location of the aneurysm; the most complete and preferable is that located adjacent to the aneurysm. Avoidance of the aneurysm dome while establishing proximal and distal control is critical in order to prevent intraoperative rupture. If vascular control cannot be established, a careful dissection focused on the aneurysm neck should be made, and the dome should be avoided to prevent rupture.
5. **Temporary clipping** (Fig. 3d, e): Temporary clips are often placed to facilitate aneurysm

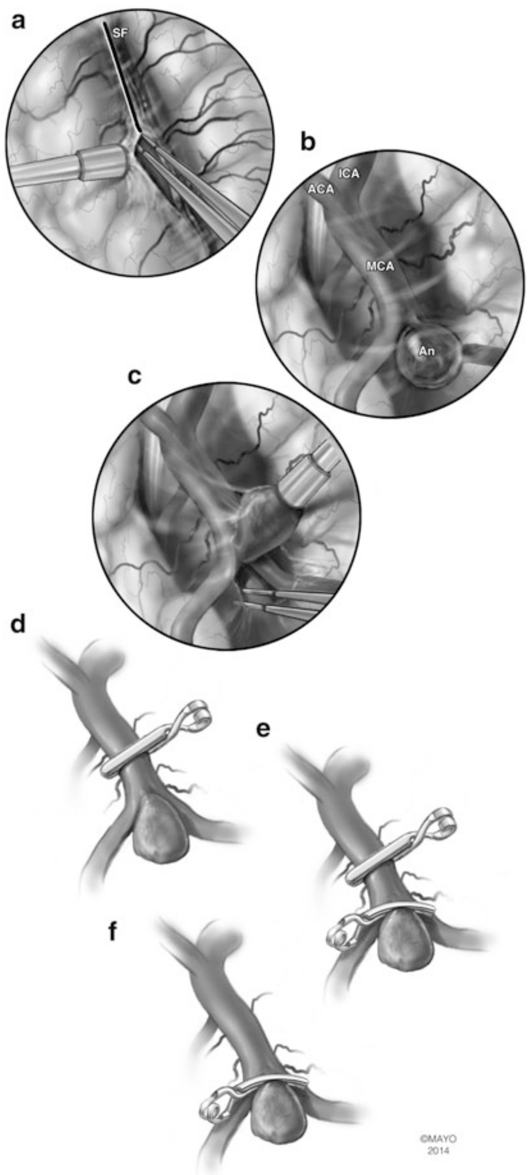

Fig. 3 Artist depiction of the basic steps of microsurgery for intracranial aneurysms. (**a**) The arachnoid surrounding the aneurysm and its parent artery is widely opened. (**b**) The proximal portion of the feeding vessel is exposed in order to obtain proximal control. (**c**) The aneurysm neck is circumferentially separated from surrounding tissues and carefully inspected prior to clipping. (**d**) Temporary clipping can be used to "soften" the aneurysm and facilitate definitive clipping. In addition, presence of the temporary clip protects from massive bleeding in the case of intraoperative aneurysm rupture. When applying the temporary clip, the utmost care is exercised to avoid any compromise of small perforating vessels. (**e**) The permanent clip is applied while the temporary clip is in place; the

manipulation and to optimize visualization of its anatomy, including small perforating arteries and efferent vessels. In the case of complex aneurysms, temporary clipping is especially helpful for softening of the neck to allow for more aggressive permanent clipping. In a minority of cases, such as thrombosed or previously coiled aneurysms, the use of both proximal and distal temporary clipping allows for complete trapping of the segment harboring the aneurysm.

6. **Permanent clipping** (Fig. 3e, f): Permanent clipping is certainly the most important and critical part of the surgical treatment of intracranial aneurysms. The goal is to achieve complete occlusion of the aneurysm while preserving adequate flow through the parent vessel and small perforating branches. Therefore, complete visualization of the aneurysm and its surrounding structures is essential before proceeding with the permanent clip application (Fig. 3c). Small aneurysms with narrow necks are often treated with a single clip. However, large aneurysms with broad necks and complex anatomy often require multiple clips in order to achieve complete obliteration.
7. **Clip inspection**: Once the permanent clips are in place, the aneurysm can be mobilized in order to confirm the patency of the parent artery as well as the efferent branches and perforating vessels. In addition, complete aneurysm obliteration can be confirmed with visual inspection and by palpating the aneurysm sac looking for the absence of pulsatile flow. Puncture of the dome is often done at this stage to confirm complete exclusion by the clip.

Fig. 3 (continued) ideal placement of the clip blades will completely cross the neck of the aneurysm while preserving patency of the parent artery. (**f**) The temporary clip is removed and the blades of the permanent clip are inspected to ensure that clip blades completely cross the aneurysm neck without compromising the parent artery. It is important to check for any small perforators that may have inadvertently been included inside the clip blades

Intraoperative Assessment of Aneurysm Occlusion

Visual inspection alone is often insufficient to confirm proper clip placement. Therefore, various techniques have been developed to assess aneurysm occlusion as well as parent artery and perforating branch patency. In the intraoperative setting, these techniques can be used alone or in combination to further adjust surgical clips. Adjustments are undertaken to avoid vessel stenosis, occlusion, and subsequent cerebral ischemia or aneurysm remnant, which may predispose to aneurysm recurrence and rupture.

Intraoperative Angiography

Intraoperative digital subtraction angiography (DSA) is considered by many as the gold standard for assessment of aneurysm occlusion and vessel patency. The rate of clip readjustment after intraoperative angiography is highly variable and ranges between 8 % and 34 %. Images in different projections can be obtained for comparison with the preoperative studies and to ensure proper clip placement. Despite its invasive nature, the complication rate is minimal in experienced hands, and many authors advocate the routine use of intraoperative angiography in all cases of aneurysm clipping. However, it is not widely available, requires the presence of trained personnel during the surgical procedure, and is time-consuming. Moreover, some small perforators are beyond its resolution and cannot be visualized. With the availability of newer techniques of intraoperative imaging to verify proper clip placement, this technique is now used in selected cases, particularly when treating large and complex aneurysms.

Microvascular Doppler Ultrasonography

Micro-Doppler ultrasonography is a noninvasive method often used during intracranial aneurysm surgery for the assessment of parent vessel patency and complete aneurysm occlusion. This method is inexpensive, easily performed, does not significantly prolong the operative time, and can be used repeatedly if clip adjustments are required. Although partial aneurysm occlusion can be easily detected due to persistent flow in the aneurysmal dome, the residual neck of a partially obliterated or thrombosed aneurysm cannot be detected with this modality because of the lack of flow in the dome.

Indocyanine Green Fluorescent Videoangiography

Near-infrared indocyanine green (ICG) fluorescent videoangiography is a relatively new method for intraoperative assessment of blood flow during aneurysm surgery. ICG is a near-infrared fluorescent compound that is injected intravenously and binds to plasma proteins to reach the cerebral vasculature within 30 s. A near-infrared light source and a near-infrared-sensitive video camera, which are included in most modern surgical microscopes, are necessary to visualize ICG in the vasculature. This technique allows for real-time visualization of aneurysm filling and patency of efferent vessels or perforating branches within the surgical field (Fig. 4). This method of intraoperative assessment is especially useful for evaluating patency of very small perforating branches (Fig. 4c–e), as many of these are beyond the resolution of standard DSA. Recent studies have shown similar rates of clip readjustment when comparing intraoperative ICG videoangiography to intraoperative DSA, supporting the routine use of ICG videoangiography while DSA is utilized only in selected cases.

Surgical Approaches

The goal of aneurysm surgery is to attain occlusion of the aneurysm while preserving flow in the associated vasculature. The majority of aneurysms involve proximal arterial branches at or close to the base of the brain. A handful of surgical approaches along with some of their variations are

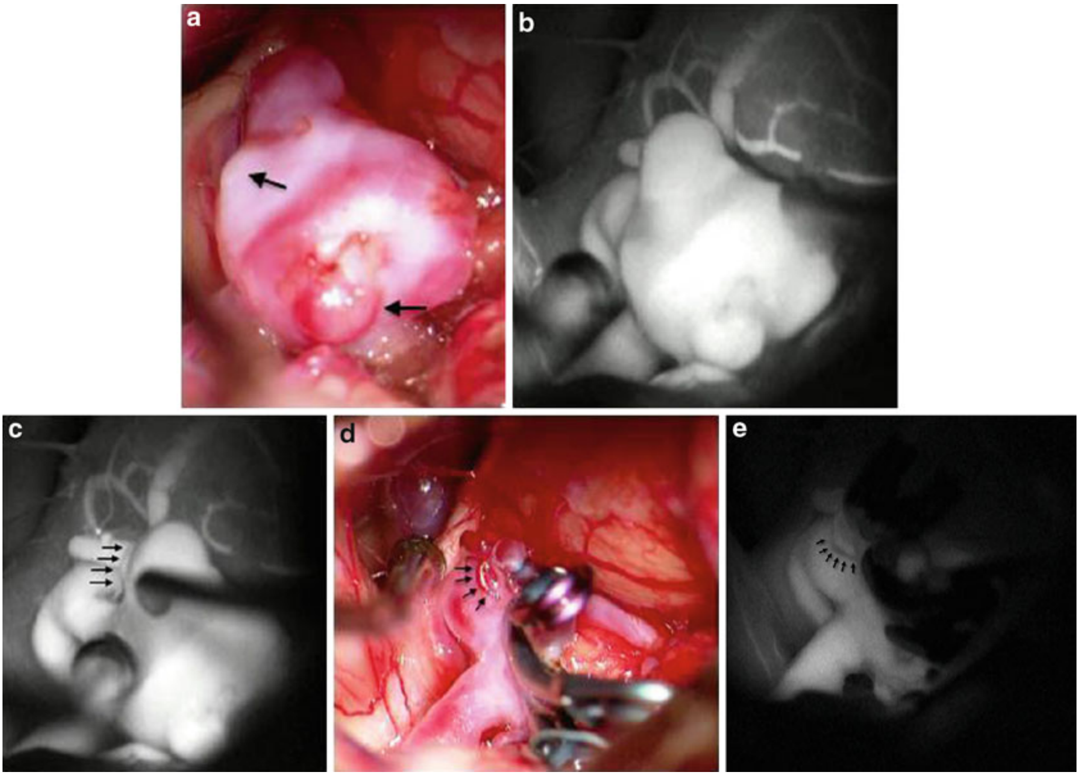

Fig. 4 (**a**) Intraoperative high-magnification view of an irregular anterior communicating artery aneurysm after surgical exposure, with areas of lobulations (*arrows*) indicating possible areas of weakness in the aneurysm wall. (**b**) ICG fluorescent videoangiography view showing the aneurysm prior to clipping. This image is obtained to establish the baseline against which post-clipping ICG fluorescent videoangiography can be compared. (**c**) Baseline ICG fluorescent videoangiography showing presence of a small perforating vessel (*arrows*) that is incorporated in the distal neck of the aneurysm. (**d**) Intraoperative view of aneurysm after multiple-clip reconstruction of this complex aneurysm, with sparing of the associated small perforating vessel (*arrows*). (**e**) Post-clipping ICG fluorescent videoangiography shows no evidence of the previously visualized aneurysm, while patent flow is preserved through the small perforating vessel (*arrows*)

utilized in the treatment of these aneurysms: the pterional (and its numerous variations), the subtemporal, the interhemispheric, and the retrosigmoid/far lateral. A detailed description of these approaches and their pros and cons is beyond the scope of this chapter.

Pterional Craniotomy

The pterional craniotomy, also known as the frontotemporal craniotomy, is the most commonly used approach in aneurysm surgery because of its versatility and access to most anterior circulation aneurysms and many posterior circulation aneurysms. Not only is it the preferred exposure for most aneurysms, but it is also widely utilized to treat other vascular and nonvascular lesions of the sellar/parasellar region, the orbital roof and fissure, the cavernous sinus, as well as the frontal and anterior temporal regions [46]. The patient is positioned supine with the head fixed in three-point fixation, slightly rotated to the contralateral side, and extended so that the ipsilateral zygoma becomes the highest point of the patient's head. This "classic" position maximizes the effects of gravity in allowing the brain to “fall down” after bony opening, thus minimizing the need for mechanical retraction. The skin incision is curvilinear, starting 1 cm anterior to the tragus beginning at the level of the zygomatic arch, and arcs forward behind the hairline.

Over the years, numerous modifications of the “classic” pterional approach have been described and applied to the treatment of intracranial aneurysms. With advances in skull base techniques, some skull base-specific approaches have been proposed to treat intracranial aneurysms. Of these, the orbitozygomatic craniotomy has gained traction in the past as a variation of the pterional approach. With this approach, complete or partial removal of the frontal or temporal portion of the zygomatic arch provides the required exposure to minimize the need for brain retraction. On the other hand, the impetus for less invasive techniques in recent years has led to a progressive reduction of the size of the craniotomy for the treatment of most anterior circulation aneurysms. These include development of the “key-hole” approach and the lateral supraorbital approach. There are a variety of different approaches for the treatment of most anterior circulation aneurysms from which to choose from, and the selection of one modification of the pterional approach over another is often related to surgeon preference, degree of comfort with a specific approach, and aneurysm characteristics or position.

Other Surgical Approaches for the Treatment of Aneurysms

Approaches other than the pterional and its modifications are utilized for aneurysms in specific locations [47, 48]. These approaches and their respective indications include the subtemporal approach for some aneurysms of the upper basilar artery and the proximal posterior cerebral artery, the interhemispheric approach for aneurysms of the pericallosal artery, and the retrosigmoid and the far lateral craniotomy for aneurysms of the lower basilar trunk and the origin of the posterior inferior cerebellar artery (Table 2).

Table 2 Craniotomy selection for intracranial aneurysms by location

Surgical approach	Aneurysm location
Pterional approach and its modifications	ICA, anterior communicating artery (AComm), middle cerebral artery, proximal anterior cerebral artery, posterior cerebral artery, basilar bifurcation, superior cerebellar artery
Interhemispheric approach	Distal anterior cerebral artery, pericallosal artery, callosal marginal artery
Far lateral approach/ retrosigmoid and suboccipital approach	Vertebral artery, vertebrobasilar junction, mid-basilar artery, anterior inferior cerebellar artery, posterior inferior cerebellar artery
Petrosal approach	Mid-basilar artery, anterior inferior cerebellar artery

Postoperative Care

Following craniotomy and clipping of aneurysms, patients are typically admitted to the neurological intensive care unit. In the absence of complications, patients are awakened and extubated in the operating room. In the presence of immediate postoperative deficits, an immediate CT scan should be performed. If imaging studies show evidence of vessel compromise responsible for these deficits, return to the operating room may be considered. However, this is exceedingly rare with the available tools utilized intraoperatively nowadays.

Patients are usually observed in the neurological intensive care unit overnight, though the patients with ruptured aneurysms are observed for a longer period of time because of the risk of SAH-related complications such as vasospasm and hydrocephalus. With modern neurosurgical techniques and high-power microscopes, surgery for intracranial aneurysms is usually done within the subarachnoid space, which minimizes the amount of brain manipulation that is required. With careful preservation of venous structures, postoperative seizures are uncommon. Therefore, the routine use of anticonvulsant medications is not recommended. Anticonvulsant medications delay recovery due to the high incidence of side effects such as fatigue and drowsiness seen with even the last-generation agents. If there are no postoperative complications, intravenous fluids are discontinued the day after the operation, and the diet is advanced as tolerated. Similarly, Foley catheter and arterial lines are disconnected early and the patient is rapidly mobilized.

Complications

Complications related to surgical treatment of intracranial aneurysms are uncommon due to the use of advanced microsurgical techniques in combination with intraoperative tools such as electrophysiologic monitoring, microvascular Doppler ultrasound, ICG videoangiography, and intraoperative catheter angiography in select cases. However, symptomatic epidural and subdural hematomas can be seen postoperatively in less than 1 % of patients, and ischemic complications are still a risk despite use of these advanced intraoperative tools and microsurgical techniques. Ischemic complications are often related to manipulation of very small perforating vessels during the dissection of the aneurysm or their compromise during clip application. This occurs more frequently in areas rich in small perforating vessels, where the aneurysm sac is often adherent to or in close relationship with vessels like the basilar bifurcation or the anterior communicating artery complex (Fig. 4d).

With advanced microsurgical techniques, postoperative seizures are an uncommon occurrence, but when encountered, an urgent CT scan should be obtained to rule out the possibility of an intracranial hematoma. They can also be the consequence of a subpial dissection and compromise of the cortical mantle. If the patient suffers a postoperative seizure, anticonvulsant medications are started. In the absence of repeated seizures and after an EEG rules out any evidence of an active seizure focus, the anticonvulsants are discontinued after 6 months to 1 year. An aneurysm remnant can occasionally be seen after clipping of an aneurysm. Sometimes, the remnant is left intentionally in order to decrease the risk of compromise to the parent artery (Fig. 1d). At other times, the remnant can be an unexpected finding on postoperative imaging studies. In general, small remnants after clipping of an aneurysm have a benign natural history and can be followed over time, especially if their correction is associated with a high risk of potential complications.

Follow-Up of Surgically Treated Aneurysms

We usually obtain an immediate follow-up vascular study to document completeness of aneurysm exclusion and to rule out complications. Although this was traditionally done using catheter angiography, CTA with 3D reconstruction has been increasingly relied upon in recent years for postoperative imaging. With modern software, artifacts related to the clips can be minimized, and good correlation with postoperative angiography has been shown. Long-term follow-up of surgically treated aneurysm has established surgery as a durable treatment modality with an exceedingly low incidence of recurrence after adequate clipping. Patients who presented with subarachnoid hemorrhage have a higher cumulative incidence of recurrent hemorrhage when treated with coiling as compared to clipped aneurysms (2.6 % vs. 0.4 %). However, recurrent hemorrhage can be also related to de novo aneurysms [1, 49, 50]. Follow-up imaging every 5 years can be considered in patients who presented with SAH in order to rule out de novo aneurysm formation, although no study has definitively shown the validity of this approach in preventing future SAH. In the presence of a known remnant, follow-up imaging study with CTA should be performed approximately 1 year after the original surgery. In the presence of a stable remnant, further follow-up can be considered every 2–3 years thereafter.

Summary

In conclusion, despite rapid advances in endovascular techniques, traditional surgical clip ligation continues to be an important therapeutic option for patients with ruptured and unruptured aneurysms. Surgical clipping provides higher degree of complete aneurysm exclusion when compared to endovascular techniques and carries a lower risk of aneurysm recurrence over time. Strict adherence to microsurgical principles focusing on minimizing brain manipulation, extensive arachnoid dissection, and utilization of intraoperative adjuncts are the key to low complication rates in aneurysm surgery. Noninvasive vascular imaging studies such as MRA and CTA play an ever-increasing role in the preoperative and postoperative assessment of patients with intracranial aneurysms undergoing surgical treatment.

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