Surgical Management of Aneurysmal Subarachnoid Hemorrhage

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KEYWORDS

- Aneurysmal subarachnoid hemorrhage
- Surgical management
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Aneurysmal subarachnoid hemorrhage (aSAH) comprises approximately 2% to 5% of all strokes in the United States, affecting about 30,000 people annually,[1] and the worldwide incidence is approximately 10.5 cases per 1000,000 individuals.[2] Despite advances in diagnostic tools, perioperative management, and definitive surgical or endovascular interventions, aSAH remains a devastating condition. Following aSAH, at least 12% of patients die before receiving medical attention,[3] 46% die within 30 days,[4] and many survivors have significant morbidity and require long term assistance.[1] Cognitive dysfunction is common among aSAH survivors, with up to 50% showing deficits and unable to return to work.[5–7] Because aSAH occurs at a relatively young age and has such a poor prognosis, it is estimated that the loss of productive years from SAH is a significant portion of years lost from ischemic stroke.[8] Outcomes following aSAH are primarily determined by the severity of the initial bleed, early rebleeding, and delayed cerebral ischemia secondary to vasospasm.

Intracranial aneurysm formation and subsequent rupture is a complex multifactorial process that is not well understood. Epidemiology of aSAH is dependent on age, sex, race, and location. Aneurysmal SAH can occur in any age group, but is most common in the fourth to sixth decades. Women have 1.6 times greater risk than men of aSAH[9] and African Americans have 2.1 times the risk of whites.[10] Incidence of aSAH varies greatly among different countries, with Japan (23 to 32 per 100,000) and Finland (22.5 per 100,000) having the highest statistics.[1] Modifiable risk factors include smoking, hypertension, heavy alcohol intake, and use of sympathomimetic agents (eg, cocaine).[1,11] Nonmodifiable risk factors include a family history of SAH and autosomal-dominant polycystic kidney disease, as well as various uncharacterized genetic susceptibility loci.[12,13] Familial intracranial aneurysms tend to rupture at earlier ages than sporadic aneurysms.[12]

Aneurysmal SAH is a life-threatening condition that requires prompt medical and surgical attention. This article reviews the surgical management of aSAH, describing frequently used craniotomies and certain additional techniques and surgical maneuvers that are currently debated in the literature.

HISTORICAL PERSPECTIVE

Early treatment of cerebral aneurysms involved ligation of the proximal parent artery, a technique named Hunterian ligation after John Hunter (1728–1793), who popularized the technique in peripheral arteries in the mid 1700s.[14] Victor

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Horsley (1857–1916) was the first person to apply this technique to the cerebral circulation when he performed internal carotid artery (ICA) ligation for a giant intracranial aneurysm in 1885.[14,15] Norman Dott (1897–1973) subsequently performed the first planned intracranial surgery for treatment of a ruptured cerebral aneurysm in 1931, in which he wrapped the aneurysm with muscle for hemostasis.[16] Dott learned the technique of using muscle pledgets while training under Harvey Cushing (1869–1939), who is thought to be the first surgeon to pack and wrap an unruptured intracranial aneurysm.[15] Dott also pioneered the technique of aneurysm suture ligation in 1933, although this technically challenging maneuver was eventually supplanted by aneurysm clips.[14]

Cushing introduced hemostatic silver vessel clips to neurosurgery in 1911, first using these clips in tumor surgeries to achieve hemostasis on vessels not accessible to suture ligation.[15] Walter Dandy (1886–1946) used a modified Cushing V-shaped silver clip in 1937 to perform the first clipping of an ICA aneurysm.[17] Over the subsequent decades, aneurysm clips underwent many design modifications, particularly with respect to the size and shape of clips suitable for microsurgery and to the materials required for compatibility with magnetic resonance imaging (eg, titanium).[17] In the late 1970s, clipping of ruptured aneurysms was shown to be better than the alternatives of bed rest and carotid artery ligation,[18] and neurosurgical practices shifted toward using clips for routine treatment.

TIMING OF SURGICAL INTERVENTION

Practice regarding the timing of surgery following aneurysm rupture has been historically controversial and has gone through changes over the years.[19] From the 1950s to the mid 1970s, most surgeons advocated delaying surgical intervention for aneurysm clipping at least 1 week until the patient was medically stable. Early surgery was presumed to be more technically demanding due to brain swelling, thought to worsen vasospasm, and was associated with high operative morbidity and worse outcomes.[19–21] While delayed surgical intervention led to excellent operative results, overall patient outcomes remained poor because of high rates of rebleeding and significant vasospasm-related morbidity and mortality in patients waiting for surgery.[22] Rebleeding is a major concern following aSAH, as mortality from such an event reaches 70%.[1] The risk of rebleeding following aSAH without intervention is up to 40% within 30 days,[23] with the rate greatest within the first 24 hours (4%) versus a daily rate of 1% to 2% for the subsequent 4 weeks.[24] Certain studies have demonstrated higher rebleed rates (15%) within the first day, especially within 2 to 12 hours.[25,26] Following the 30-day peak period, the risk of rebleed settles out at about 3% per year.[27]

Interest in early surgery increased in the late 1970s as surgical techniques improved, operations became safer, and as medical management failed to significantly reduce rates of vasospasm and rebleeding before surgery.[19] Following favorable initial results from early surgery, primarily from Japanese groups, the International Cooperative Study on the Timing of Aneurysm Surgery sought to better characterize the relationship between outcomes for early (0–3 days) versus late (11–14 days) surgery after aSAH.[22] This study showed that the overall patient outcome of early surgery was equivalent to that of late surgery. Of note, patients in the late surgery group had better surgical outcomes at 6 months than the early surgery group, most likely secondary to natural selection of survivors. However, up to 30% of patients with aSAH do not survive to have surgery at the later time points, and waiting 2 weeks for surgery was associated with a 30% risk of focal ischemic deficit and 12% risk of rebleeding. Thus, the additional risks associated with delayed surgery negated the better surgical outcomes seen in this group, and early surgery became a feasible option. Additional impetus for early surgery is that these patients, having a secured aneurysm, would greatly benefit from any future advances in vasospasm management. It is now common practice that patients are operated on within 48 hrs of presentation if an aneurysm is present.

COMMON SURGICAL APPROACHES

Surgery for intracranial aneurysms relies on 2 main principles: gaining access to the aneurysm through a craniotomy and subsequently securing the aneurysm. The basic principles of turning a craniotomy and the microsurgical principles used for the management of acute aSAH (eg, opening of the arachnoid, drainage of cerebral cisterns, use of microinstruments, use of the operating microscope, and brain retraction) have been thoroughly reviewed in numerous articles and textbooks. This section reviews common craniotomies used in most operative cases for acute aSAH. The surgical approach to any given aneurysm depends on a variety of factors, including aneurysm location, morphology, orientation, and neck anatomy. There are 3 main surgical approaches, with possible extensions, required to treat the majority of anterior and posterior circulation aneurysms.[28] Each of these approaches is described briefly below.

Frontosphenotemporal (Pterional) Craniotomy, and the Orbitozygomatic and Subtemporal Extensions

The frontosphenotemporal or pterional craniotomy[29] (**Fig. 1**) is the workhorse of vascular neurosurgery and can be used for most anterior circulation aneurysms and upper posterior circulation aneurysms. For this approach, the head is placed in a radiolucent skull immobilizer, rotated (up to 60 degrees depending on surgical target), and the neck is extended (approximately 30 degrees) so that the malar eminence is the highest point. The scalp is incised from the root of the zygomatic arch, to the linea temporalis, and anteriorly to the midline just short of the patient's hairline. The scalp and temporalis muscles are elevated using a subfascial dissection to preserve the frontalis branch of the facial nerve.[30]

In the authors' practice, the craniotomy is performed using 5 burr holes: keyhole, above the zygomatic root, approximately 1 cm above the temporal squamosa (in line with zygomatic root), intersection of coronal suture with linea temporalis, and frontal bone above frontal sinus and orbit. The burr holes are connected with a Gigli saw (allows for maximum beveling and superior aesthetic results) except for the segment between the keyhole and zygomatic root, which is drilled. Additional squamosal temporal bone is removed with a rongeur to expose the floor of the middle cranial fossa. The greater and lesser wings of the sphenoid are then drilled until the dural flap covering the orbitomeningeal artery is exposed. The dura is opened with a semicircular incision and reflected anterior.

To improve access to the basilar apex and upper clivus regions, the orbitozygomatic and subtemporal extensions (see **Fig. 1**) can be performed following a traditional pterional craniotomy. Since Jane and colleagues[31] first described the supraorbital craniotomy, it has evolved considerably through many adjustments.[32–36] The traditional orbitozygomatic craniotomy as described by Zabramski and colleagues[37] and the modified orbitozygomatic craniotomies as described by Lemole and colleagues[38] are commonly used today. For the traditional orbitozygomatic craniotomy, the temporal fascia is elevated to expose the zygoma and superior orbital rim, and the periorbita is detached from the orbital roof with the use of an Adson elevator. The orbital and zygomatic osteotomies are then performed using a series of 6 bone cuts involving the orbital roof, lateral orbit,

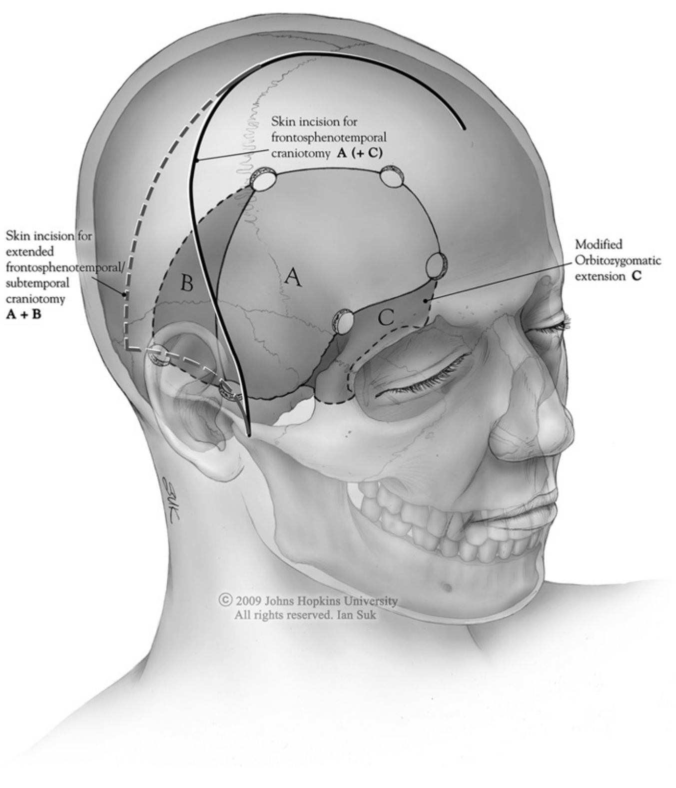

Fig. 1. Frontosphenotemporal craniotomy (A) with subtemporal (B) or modified orbitozygomatic (C) extensions. The skin incision for the frontosphenotemporal craniotomy with or without the modified orbitozygomatic extension (*solid line*) is curvilinear and extends from the root of the zygoma to the hairline in the midline. The frontosphenotemporal craniotomy (A) is centered on the sphenoid wing and keyhole. For the modified orbitozygomatic extension (C), the orbital rim and frontal process of the zygomatic bone are removed. For the frontosphenotemporal craniotomy with subtemporal extension, the skin incision extends posteriorly from the root of the zygoma to the region of the mastoid (*dashed line*) and then arcs superiorly to the hairline in the midline. The craniotomy for the subtemporal extension (C) includes removal of more temporal and parietal bone. (*Courtesy of* Johns Hopkins University, Baltimore, MD.)

maxillary root, and zygomatic root as previously described.[37] Subtemporal and supraorbital modifications of the traditional orbitozygomatic craniotomy can be performed to better tailor the craniotomy to treat lesions in the temporal fossa or the anterior/middle cranial fossae, respectively.[38] In general, the authors favor the modified orbitozygomatic craniotomy over the full version of this extension.

The subtemporal craniotomy was popularized by Charles Drake in 1961[39] as an approach to the basilar apex. In brief, the subtemporal approach is performed through a horseshoe-shaped incision starting at the zygoma in front of the ear, extending superiorly and posteriorly along the linea temporalis, and then inferior behind the mastoid. The craniotomy flap is turned using burr holes at the corners of the intended boney exposure and by drilling a trough across the base of the bone flap. Once the bone flap is removed, the inferior edge of the craniotomy is drilled flush with the floor of the middle cranial fossa, and a horseshoe-shaped dural flap is reflected inferiorly. The limitations of this approach include a narrow surgical corridor, the need for significant brain retraction, and difficult access to the contralateral P1 segment and nearby perforators. In the setting of aSAH, a swollen temporal lobe can be problematic when this approach is used.

Most neurosurgeons today use the subtemporal craniotomy as an extension of the frontosphenotemporal craniotomy. The "half and half" approach, originally mentioned by Drake in 1978[40] and popularized by Batjer and Samson,[41] combines the pterional craniotomy with a subtemporal craniotomy. This combined approach essentially eliminates the disadvantages of a pure subtemporal approach, and it provides good access to the basilar bifurcation, the superior cerebellar artery takeoff, and the P1 segment.

As with all surgical procedures, cosmetically superior reconstruction following craniotomy for aSAH is paramount to prevent disfigurement and negative psychosocial effects on the patient and the family. Patients undergoing pterional craniotomies for aneurysm clipping commonly have depression of the frontozygomatic fossa 6 to 12 months after surgery secondary to atrophy of the temporalis muscle. Such cosmetic defects can be avoided by careful dissection to maintain the neurovascular supply to the temporalis muscle[42] and by a simple use of a frontozygomatic fossa titanium cranioplasty.[43] Raza and colleagues[43] described the use of a frontozygomatic titanium cranioplasty in 194 patients who underwent a pterional craniotomy with average follow-up of 9.5 months. In this series, 93% of patients had excellent cosmetic outcomes with virtually no evidence of surgery, and the remaining 7% had only slight depression of the temporalis fossa. This method and other such techniques should be used when possible to achieve outstanding cosmesis in aSAH patients.

Anterior Parasagittal Craniotomy

The anterior parasagittal craniotomy (**Fig. 2**) is used for interhemispheric approaches to distal anterior cerebral artery aneurysms as described by Tamargo and colleagues.[44] For this approach, a radiolucent skull immobilizer is placed and then the head is distracted, flexed, and rotated to the contralateral side. Many variations in positioning have been described, with some surgeons preferring more lateral head position to facilitate gravity retraction and increased exposure of the interhemispheric fissure.

The scalp is incised in a bicoronal fashion and the flap is reflected anteriorly. Following identification of the coronal and sagittal sutures, a pentagonal craniotomy is planned with 5 burr holes so that the craniotomy straddles the midline and extends 4 to 5 cm in front and 2 to 3 cm behind the coronal suture. The anterior-posterior position of the craniotomy in relation to the coronal suture can be modified depending on the location of the aneurysm. Two burr holes are placed ipsilateral to the lesion, 2 burr holes directly over the sagittal sinus, and a single burr hole is placed on the contralateral side. The burr holes are connected with a Gigli saw. A semicircular incision is made for the dural flap with its base along the sagittal sinus.

Lateral Suboccipital Craniectomy and the Far-Lateral Transcondylar Extension

Although there are many different described approaches to aneurysms of the posterior circulation, most aneurysms of the vertebral trunk, the mid and lower basilar trunk, and their associated branches (superior cerebellar artery, anterior inferior cerebellar artery, and posterior inferior cerebellar artery) can be approached by a lateral suboccipital craniectomy with or without the far-lateral extension as described (**Fig. 3**).[28]

For the lateral suboccipital craniectomy, the patient is placed in a skull clamp and is positioned in either the park-bench or lateral position. The incision starts 3 cm behind the posterior margin of the pinna and extends in a sigmoid fashion to the spinous process of C2. After reflection of the suboccipital musculature, the asterion is identified (landmark for junction of transverse and sigmoid

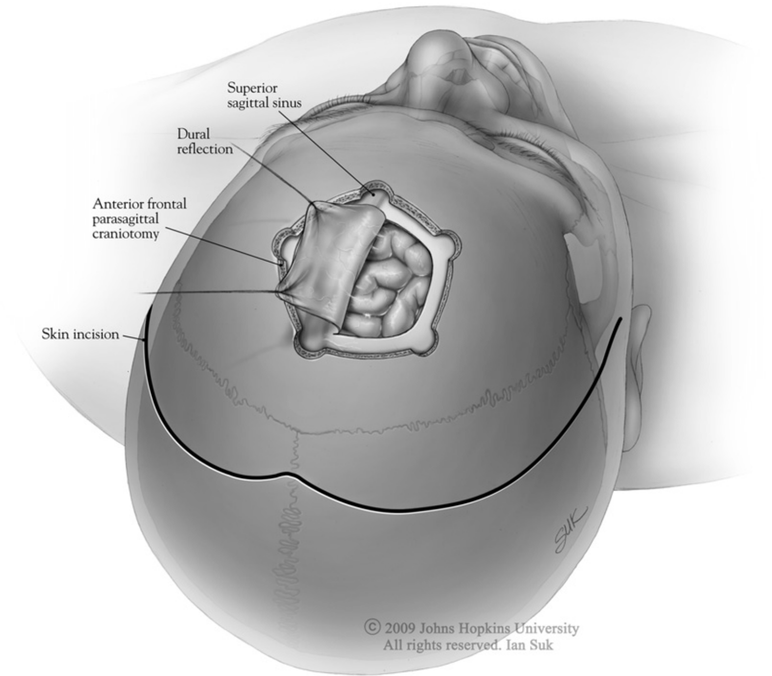

Fig. 2. Anterior parasagittal craniotomy. A bicoronal skin incision is made (*solid line*). The pentagonal craniotomy straddles the midline. The anterior-posterior position of the craniotomy in relation to the coronal suture is tailored to the location of the aneurysm. A semicircular dural incision is made with its base along the superior sagittal sinus and is reflected toward the midline. (*Courtesy of* Johns Hopkins University, Baltimore, MD.)

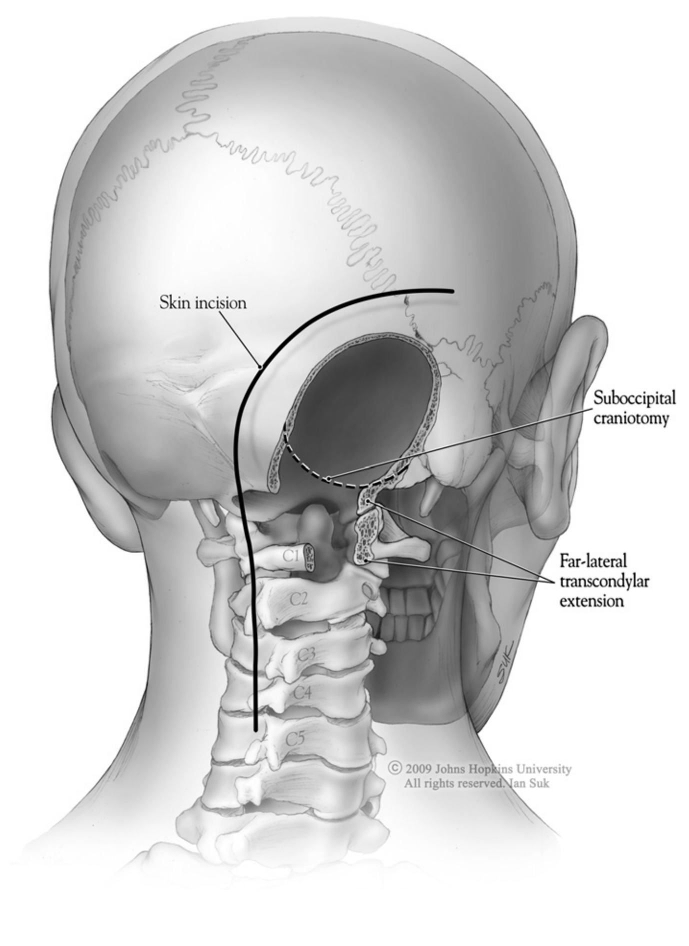

Fig. 3. Lateral suboccipital craniectomy and the far-lateral transcondylar extension. A "hockey stick" skin incision (*solid line*) is made with the lateral arm beginning superior and posterior to the ear, descending medial, and ending midline in the upper to mid cervical level. The suboccipital craniectomy extends from the asterion to just above the foramen magnum (*dashed line*). For the far-lateral extension, the lip of the foramen magnum, the C1 arch, and the posteromedial third of the atlanto-occipital joint are removed. (*Courtesy of* Johns Hopkins University, Baltimore, MD.)

sinuses). A craniectomy is then performed that extends from the asterion (supralateral margin), to just above the foramen magnum (inferior), and medially to expose the lateral cerebellum. The dura is opened in a lambdoid incision with respect to the sigmoid and transverse sinuses.

For the far-lateral extension, a "hockey stick" incision is performed with the lateral arm beginning superior and posterior to the ear, descending to the superior nuchal line, crossing medial to the midline, and then descending to the spinous process of C2 or C3. A musculocutaneous flap is then elevated to expose the foramen magnum, the mastoid, and C1 from the arch to the transverse process. The vertebral artery is identified at the point where it enters the dura and then traced to the sulcus arteriosus. The main additions of the far-lateral are removal of the C1 arch, the lip of the foramen magnum, and the posteromedial third of the atlanto-occipital joint. Following completion of the craniectomy, the dura is opened from the transverse sigmoid junction to the arch of C1 and reflected laterally.

FENESTRATION OF THE LAMINA TERMINALIS

Aneurysmal SAH can cause fibrosis of the arachnoid granulations and leptomeninges,[45,46] leading to altered cerebrospinal fluid (CSF) dynamics and persistent hydrocephalus that requires CSF diversion. Shunt-dependent hydrocephalus occurs in > 20% of patients with aSAH,[47] representing a significant complication. Microsurgical fenestration of the lamina terminalis during aneurysm surgery was proposed in the mid to late 1990s as a means of facilitating CSF dynamics and reducing the incidence of shunt-dependent hydrocephalus in patients with aSAH[48,49]; however, subsequent studies have been inconclusive regarding the benefit of this technique. Komotar and colleagues,[47] in a retrospective study of 582 patients with aSAH, demonstrated greater than 80% reduction in shunt-dependent hydrocephalus if the lamina terminalis was fenestrated at the time of surgery. However, a more recent retrospective analysis of 369 patients[50] and a literature review comparing results from 11 different studies[51] failed to find a significant association between lamina terminalis fenestration and decreased shunt dependency. This latest review, in particular, is limited by unmatched cohorts, and all studies of this technique are limited by lack of prospective, randomized data. Pending more definitive studies, this technique is generally favorable and continues to be used by the senior author of this article.

INTRAOPERATIVE ELECTROPHYSIOLOGICAL MONITORING

Intraoperative neurophysiological monitoring during intracranial aneurysm surgery has become standard practice at the authors' institution as well as other major medical centers. Intraoperative neurophysiological monitoring is an important adjunct to meticulous surgical inspection and intraoperative angiography to detect cerebral ischemia from temporary clipping, unintentional parent vessel or perforator occlusion, brain manipulation, and retraction injury. Somatosensory evoked potentials (SSEPs), particularly median and posterior tibial nerve SSEPs, are commonly monitored during anterior circulation procedures, whereas dual monitoring with SSEPs and brainstem auditory evoked responses (BAERs) are preferred for posterior circulation aneurysm surgeries.[52,53]

The rationale for employing electrophysiological monitoring during aneurysm surgery is the significant correlation between alterations in electrical signals and regional cerebral blood flow (rCBF), with transient electrophysiological changes generally corresponding to good outcomes[52] and permanent changes corresponding to postoperative deficits.[54,55] However, SSEP false-negative rates can reach up to 25% in some studies, and patients with unchanged SSEPs can still have new postoperative motor and other neurologic deficits.[53,56] Motor deficits with the false-negative SSEP results are commonly attributed to subcortical (internal capsule or brainstem) strokes.[57–59] Monitoring of motor evoked potentials (MEPs) has been evaluated for efficacy in detecting impending motor deficits. Studies by Neuloh and Schramm,[56] using transcranial electrical stimulation, and Horiuchi and colleagues,[60] using direct cortical stimulation, have demonstrated that MEP deterioration is a more sensitive and reliable predictor of postoperative motor paresis than SSEPs. This technique is promising, but further evaluation in a controlled trial is needed to assess if monitoring with MEPs can reduce morbidity from aneurysm surgery in patients with aSAH.

Electroencephalography (EEG) is also commonly used during surgery for intracranial aneurysm clipping. Prior to temporary clip application, the neuroanesthesia team titrates the brain-protective anesthetic regimen to achieve burst suppression on EEG. Burst suppression helps to decrease metabolic demand so that the cerebral tissue can better tolerate induced ischemia, such as during temporary clipping. EEG is less commonly used to detect ischemia during such surgeries because the airspaces between the dura and arachnoid as a result of the craniotomy and brain relaxation can interfere with scalp EEG recordings.[53,61] Intraoperative multilobar EEG using subdural electrodes are more sensitive than scalp EEG for detecting ischemic events during aneurysm surgery,[62] but these are not currently in widespread use.

DIGITAL SUBTRACTION INTRAOPERATIVE ANGIOGRAPHY

Egas Moniz (1874–1955) developed cerebral angiography in 1927,[17] but it was not until 1933 when the first angiogram to demonstrate an intracranial aneurysm was performed by Norman Dott.[16] The technology to perform intraoperative angiography was available by the 1960s,[63] however, its routine use did not occur until the 1990s. The interest for intraoperative evaluation of aneurysm clip placement stemmed from reports of routine postoperative angiography that demonstrated unexpected rates of residual aneurysms and major vessel compromise.[64–66] In such studies, the incidence of residual aneurysms and incidence of parent or branch vessel occlusion were as high as 12% and 19%, respectively, for a possible combined 31% total incidence of unexpected findings. Incompletely treated aneurysms are dangerous as they are prone to regrowth with a 20% to 80% risk of rehemorrhage and 10% to 30% risk of mass effect over 10 to 20 years.[64,67–69] These reports, combined with improvements in portable digital subtraction (DS) angiography equipment and practitioner expertise led to more widespread use of intraoperative angiography and subsequent studies evaluating its efficacy.

Various groups have evaluated and demonstrated the efficacy of intraoperative angiography during surgery for aneurysm clipping as an adjunct to methodical surgical technique and clip inspection.[70–72] In a series of 337 aneurysms by Chiang and colleagues,[71] findings on intraoperative angiography led to clip repositioning in 37 (11%) of aneurysm cases, with 22 (6.5%) being related to residual aneurysm, 10 (3%) parent vessel occlusion, and 5 (1.5%) a combination of residual aneurysm and vessel occlusion. Intraoperative angiography is particularly useful in large (>10 mm) and giant (>25 mm) aneurysms, as these lesions are more likely to be unsatisfactorily clipped and require revision than smaller aneurysms.[70–72] It is also particularly useful in peri-clinoidal, basilar apex, and anterior communicating region aneurysms. Complications from intraoperative angiography include vessel occlusion, embolic events, and dissection. Chiang and colleagues[71] reported an overall complication rate of 2.6%, with stroke in 1 of 303 (0.3%) operations, whereas Tang and colleagues[72] reported 2 strokes in 517 aneurysms treated (0.4% stroke risk). The false-negative rate of intraoperative angiography ranges from 5% to 8%,[70–73] but this number is limited by the lack of routine postoperative angiography in such cases. In general, intraoperative angiography is an important tool to evaluate for aneurysm residuals and vessel occlusion, and it is used routinely at the authors' institution. Drawbacks are that, it is not available in all centers, it is an invasive technique, and it does not provide immediate feedback.

INTRAOPERATIVE FLUORESCENT ANGIOGRAPHY

Intraoperative fluorescent angiography has been a recent addition to the neurosurgical armamentarium to assess intraoperative blood flow dynamics, aneurysm sac obliteration, and vessel patency. Angiography using fluorescein sodium has been used by some groups[74,75] in the treatment of cerebral aneurysms; however, the near-infrared dye indocyanine green (ICG) has emerged as the preferred agent for microsurgical use[76–82] secondary to superior contrast of vessels during primary and subsequent dye applications.[81]

ICG has been evaluated in several studies of aneurysm clipping,[76–80,82] and integration of ICG near-infrared video technology into the surgical microscope[79] has greatly facilitated its application. ICG use is noninvasive, safe, simple, and provides the surgeon with rapid feedback after clip application. ICG provides high resolution imaging of vessel anatomy, arterial and venous blood flow, and incomplete aneurysm clipping. Raabe and colleagues[78] demonstrated that ICG angiography correlated with intraoperative or postoperative DS angiography in 90% of cases, and it provided significant information in 9% of cases, many of which led to clip repositioning. This technique is also unique in that it can visualize perforating arteries with good resolution.[78,80]

ICG videoangiography is not without limitations and is not suited for all applications. Only vessels within the microscope field can be visualized with ICG. Blood clots (subarachnoid, intramural, or intraluminal), vessel wall calcification, atherosclerotic plaque, and arachnoid scarring can all obscure visualization.[78,82] For the aforementioned reasons, ICG angiography is not currently a replacement for intraoperative DS angiography, but rather a complement to it.

TEMPORARY CLIPPING

Temporary arterial occlusion, or induced reversible arrest of local arterial flow, is an important adjunct technique used in the management of cerebral aneurysms. This technique was developed in the 1940s by Norman Dott,[21] and has been a vital tool for cerebrovascular neurosurgeons since that time. Temporary arterial arrest can be useful to decrease the risk of rupture during dissection of cerebral aneurysms ranging from those that are seemingly mundane to those that are complex and giant. The technique softens the aneurysm neck and sac, facilitates microdissection of aneurysms that are adherent to efferent vessels or perforating arteries, and allows for evacuation of calcified larger aneurysms before definitive clip placement. In the event of an intraoperative rupture, targeted temporary clip placement halts flow to the involved vessel and provides the neurosurgeon with critical minutes to enact a definitive treatment plan. Temporary arterial occlusion on vascular territories at greatest risk for infarction following temporary clipping are those with significant numbers of perforating arteries, such as the distal basilar artery and the proximal middle cerebral artery.[83]

The goal of temporary clip placement is to limit the duration of occlusion so that iatrogenic ischemia is not converted to permanent infarction. Prior to temporary clipping, intravenous brain-protection anesthesia titrated to EEG burst suppression is initiated to increase tolerance of brain tissue to temporary ischemia by decreasing cellular metabolic demand. Hypertension is also commonly induced to increase collateral perfusion.

Although temporary clipping of parent vessels is routinely used in the operating room, reported "safe limit" times of occlusion are variable, mostly secondary to the wide variety of patient, technical, and anesthetic factors involved. Various studies have tried to determine the occlusion time tolerable before infarction occurs; however, the acceptable occlusion time depends on the location of the aneurysm, the presence of nearby perforating arteries, the degree of collateral flow, and the anesthetic regime used to achieve brain protection. Samson and colleagues,[83] in a study of 100 patients undergoing temporary arterial occlusion under normothermic, normotensive conditions with etomidate-mediated burst suppression, demonstrated that temporary ischemia converted to fixed infarction within 15 to 20 minutes of temporary clip time. In this study, none of 49 (0%) patients with temporary clip time less than 14 minutes developed an infarction linked to the temporary clipping, whereas 5 of 27 (19%) patients with temporary clip times between 14 and 21 minutes developed an infarction. Furthermore, patients over 61 years of age and those with poorer preoperative neurologic condition (Hunt and Hess Grade III to IV) developed permanent infarction after shorter periods of arterial occlusion. Ogilvy and colleagues,[84] using mild hypothermia, hypertension, and mannitol for brain protection also found that the risk of stroke increased after approximately 15 to 20 minutes, with a stroke rate of 1 in 67 (1.5%) in patients with temporary clipping duration less than 20 minutes and stroke rate of 12 in 65 (18%) for longer clip durations. Tolerable temporary ischemia varies depending on the vascular territory. For example, Lavine and colleagues[85] demonstrated that infarction was more common after only 10 minutes of occlusion time for middle cerebral artery aneurysms despite the use of brain-protection anesthesia, as the middle cerebral artery (MCA) territory is particularly sensitive to ischemia.

One modification of the temporary clipping technique is the use of intermittent reperfusion, or short periods of temporary occlusion separated by reperfusion periods. Although intermittent reperfusion is beneficial in decreasing ischemia in rat[86–88] and rabbit[89] stroke models, few clinical studies have addressed this question. Samson and colleagues[83] did not show any benefit to the use of intermittent reperfusion.

DEEP HYPOTHERMIC CARDIOPULMONARY BYPASS

Some aneurysms cannot be safely clipped while fully arterialized. Such aneurysms are typically large, deep in location, have atherosclerotic walls, are partially thrombosed, are intimately associated with critical perforators, or incorporate branch vessels in the wall and the dome. Perforating arteries and the cerebral territories they perfuse do not tolerate temporary clipping well. As such, special circumstances arise when temporary clipping is not sufficient, and reduced blood flow (or complete circulatory arrest) in combination with deep hypothermia for brain protection is necessary to decrease pressure in the aneurysm dome for proper dissection and clipping.

Circulatory arrest, or no-flow deep hypothermic circulatory arrest, was first introduced in the 1960s and subsequently underwent many modifications, including adaptation to the neurosurgical arena. The specifics of this complex technique are described elsewhere.[90] Several series have been published regarding hypothermic circulatory arrest for aneurysm treatment.[91–94] Mack and colleagues[94] published a 15-year, single institution experience with deep hypothermic circulatory arrest for complex aneurysms in 66 patients, 15 (23%) of whom presented as SAH. In this series, aneurysms were clipped in 57 (86%) patients and unclipped in 9 (14%) patients. Unclipped aneurysms were treated by Hunterian ligation (n = 3), trapping (n = 4), or left untreated (n = 2). The surgical mortality was 11% based on 7 perioperative deaths, with 2 of the deaths resulting from complication of the cardiopulmonary bypass. Patient age and duration of cardiac arrest were independent predictors of early clinical outcome ($P<.05$), with patients younger than 60 years and circulatory arrest times less than 30 minutes associated with better outcomes. This group found that the volume of cases requiring hypothermic circulatory arrest decreased over the study period, likely secondary to the increase of endovascular capability and early diagnosis of aneurysms before they reach large sizes necessitating bypass procedures.

During the development and refinement of cardiac arrest protocols over the past several decades, concern for adverse neurologic sequelae as a result of complete circulatory arrest gave rise to the alternative method of low-flow deep hypothermic cardiopulmonary bypass (DHCPB), in which cerebral and body circulation is maintained at a reduced rate. Several early studies, primarily in animals, provided evidence for superior neurologic outcomes using low-flow DHCPB versus cardiac arrest.[95–97] This result was confirmed by Newburger and colleagues[98] in a study of perioperative neurologic effects of no-flow versus low-flow DHCPB open cardiac surgery in 171 infants. Cardiac arrest was associated with higher risk of seizure, longer EEG-based recovery time, and greater release of brain isoenzyme and creatine kinase within 6 hours after surgery compared with low-flow DHCPB. Bellinger and colleagues[99] studied developmental and neurologic function at 1-year follow-up for 155 of the 171 original patients. Compared with the low-flow DHCPB group, patients in the cardiac arrest group scored significantly lower on the Psychomotor Development Index of the Bayley Scales of Infant Development and had nonstatistically significant trends toward poorer results on other tests of development. Furthermore, worse test results and increased risk of neurologic abnormalities correlated with duration of circulatory arrest. Low-flow DHCPB is used extensively in cardiac and general vascular surgery; however, only few reports exist of its use in neurovascular procedures[100,101] despite data indicating superior outcomes versus cardiac arrest. At the authors' institution, the use of low-flow DHCPB is favored for the reasons mentioned. Temporary clipping is used as an adjunct maneuver to achieve local flow arrest as needed during aneurysm dissection and clipping.

All neurosurgical procedures involving either low-flow DHCPB or no-flow hypothermic circulatory arrest require pharmacologic- and temperature-mediated brain protection. Mild (33°C) or deep (15°C) hypothermia and pharmacologic agents such as etomidate, propofol, and isoflurane are used to decrease cerebral oxygen consumption and protect the brain from ischemia. When using deep hypothermia, the surgeon must be aware of its many side effects,[90] especially the common side effect of coagulopathy secondary to platelet dysfunction and slowing of the coagulation cascade.[102] Hemostasis is of critical importance during the craniotomy and dissection not only because of the hypothermic coagulopathy but also because heparin is given prior to cannulation and initiation of bypass. A seemingly small ooze can quickly result in significant bleeding if not given due attention. Once hypothermia is induced and the bypass is setup, blood flow can be titrated down as needed, including turning the pump off for total circulatory arrest. Of note, small vessels can appear as arachnoid bands when devoid of blood, so the aneurysm should be dissected as much as possible before cardiac arrest to limit potential damage to these vessels.

Due to the complexity and significant risk of low-flow DHCPB and circulatory arrest procedures, they should only be done at major centers with advanced neurosurgical and cardiothoracic capabilities.

MANAGEMENT OF ACUTE HYDROCEPHALUS

Acute hydrocephalus (ventriculomegaly within 72 hours) is a common manifestation of aSAH that occurs in 20% to 30% of patients, particularly in patients with poor clinical grade and high Fisher Scale scores.[1] In a retrospective study of 433 patients with aSAH, Heuer and colleagues[103] demonstrated increased intracranial pressure (ICP) in approximately 50% of patients with good clinical grade (Hunt and Hess Grades I–III) and more than 60% of patients with poor clinical grade (Hunt and Hess Grades IV–V). Progressive decline in mental status, slow pupillary responses to light, and upward gaze palsy are known presenting signs of acute hydrocephalus,[11] and the diagnosis can be confirmed by computed tomography scan. Patients with acute hydrocephalus following aSAH should receive medical ICP management and be promptly evaluated for external CSF diversion. Elevated ICP following aSAH is associated with poor patient outcome, with higher ICPs leading to worse outcomes.[103] Many centers, including the authors', prefer ventricular drainage, especially when the hydrocephalus is obstructive secondary to intraventricular clot. Other groups prefer lumbar drainage, citing that this technique is more effective than ventricular drainage in washing blood from the basal cisterns,[104,105] and that it may have the added benefit of decreasing vasospasm.[104]

It is generally accepted that timely ventricular drainage for acute hydrocephalus following aSAH in poor clinical grade patients (Hunt and Hess Grades IV–V) is beneficial,[106–109] but is more controversial in good grade patients, particularly Hunt and Hess Grade III.[110] Controversy stems from the belief that CSF drainage before securing a ruptured aneurysm lowers the ICP and, as a result, increases transmural pressure across the aneurysm wall and increases the rebleed risk.[111] Some studies demonstrate an increased rebleed rate with CSF drainage before aneurysm repair,[112–114] whereas other studies demonstrate similar frequency of rebleeding in patients with and without CSF drainage.[105,106,115,116] This topic was recently discussed at a Symposium on the Controversies in the Management of Cerebral Aneurysms,[110] where the audience members preferred noninvasive management for good grade patients.

CEREBRAL REVASCULARIZATION

Some aneurysms are difficult to clip without significant surgical risk of stroke. These aneurysms are often giant or complex, fusiform aneurysms that incorporate the parent artery or other arterial branches into the aneurysm neck and base. Atherosclerosis, calcification, and previous coil embolization[117] can also make aneurysm clipping difficult, if not dangerous. Surgical options for such lesions include parent vessel ligation or aneurysm trapping. However, these maneuvers risk cerebral ischemia and stroke, and extracranial-intracranial (EC-IC) bypass may be necessary to restore distal blood flow. EC-IC bypass procedures were first conceptualized in the early 1950s, but did not become a surgical reality until 1967 when introduced by Yasargil and Donaghy.[118,119] This technique has subsequently been refined by different groups over the decades,[120–123] and many strategies for bypass following parent artery occlusion are currently available for the treatment of aneurysms in the anterior and posterior circulations. Detailed descriptions of these techniques are well described in the literature and in textbooks and are outside the scope of this article. In brief, arterial bypasses have been categorized into 4 main types.[124] Type I is a saphenous vein interposition graft for carotid artery replacement. Type II is a saphenous vein bypass graft from the extracranial carotid artery to the middle or posterior cerebral artery. Type III is a superficial temporal or occipital artery bypass to an intracranial artery. Type IV is the anastomosis of one intracranial artery to an adjacent intracranial artery, or the primary reanastomosis of an artery following aneurysm excision. Important to note is that patients that undergo bypass procedures are commonly on postoperative aspirin, and this might complicate subsequent interventions on sick patients with aSAH.

NOVEL CLIP CONFIGURATIONS AND TECHNIQUES

The neurosurgical literature has numerous technical notes describing novel approaches and maneuvers for treating complex cerebral aneurysms and intraoperative complications, such as aneurysm rupture. Two such reports are described here as examples.

Surgical management of complex multilobed aneurysms, such as those that frequently occur at the MCA bifurcation, presents a challenge to the operator. Many techniques are available to treat these lesions: temporary arterial occlusion, reconstruction with multiple clips in series, coagulation of the aneurysm fundus, wrapping, and in the case of giant aneurysms, hypothermia and circulatory bypass. Novel clip configurations, using combinations of fenestrated and nonfenestrated aneurysm clips, are also effective for obliteration of complex aneurysms and reconstruction of the pertinent normal vascular anatomy.[125,126] Clatterbuck and colleagues[126] reported a series of 15 morphologically complex MCA aneurysms treated successfully with a novel orthogonal interlocking tandem clip arrangement. For this technique, a straight clip is applied to obliterate a portion of the fundus, and then a fenestrated clip is applied to obliterate the residual fundus. The advantage is that the blades of the initial straight clip are incorporated into the fenestration of the second clip, with the angle between the 2 clips 90° or more. This technique can help reduce incidence of aneurysm remnants, while maintaining patency of critical associated normal vasculature.

Intraoperative aneurysm rupture is a known serious complication of surgical intervention for SAH. One type of rupture that can be tricky to manage is partial avulsion of the aneurysm neck.

Lanzino and Spetzler[127] describe the simple, yet effective, technique of clip wrapping to manage this problem. In their case of a woman with SAH from a ruptured anterior communicating artery aneurysm, the aneurysm neck was partially avulsed from the anterior communicating artery during clip placement. The avulsed region was then wrapped, and simultaneously tamponaded, with cotton. The clip was then re-applied to the aneurysm neck so that the clip partially covered the cotton and secured it in place over the avulsion. Novel techniques such as this add to the list of tricks available to the neurosurgeon when dealing with difficult intraoperative situations.

SUMMARY

Aneurysmal SAH is a neurosurgical emergency with significant morbidity and mortality. Successful management of patients with aSAH involves a multidisciplinary team including neurosurgeons, critical care specialists, and in many cases interventional radiologists. Surgical clipping remains a definitive treatment for ruptured cerebral aneurysms, and many techniques have improved over the years to better approach, dissect, and secure both simple and complex aneurysms following aSAH. This report highlights some of these techniques and adjuvant therapies; however, these techniques are constantly evolving and being scrutinized. Future studies, particularly randomized prospective trials, are required to further advance the field and improve outcomes following aSAH.

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