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Review Article

Evolving Concepts in the Perioperative Management of Acute Stanford Type-A Aortic Dissection

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ABSTRACT

Aim of review: Acute Stanford Type A aortic dissection involving the ascending aorta or aortic arch remains a surgical emergency associated with high morbidity and mortality. Recent improvements in diagnosis, schemes to identify subtypes based on end-organ complications, increased number of options for operative repair, and advances in perioperative organ protection have had a major impact in the management of this condition.

Methods: Evidence for the past dacades was compiled from published investigations, clinical experience, and expert opinion to provide recommendations for the management of acute Stanford type A aortic dissection.

Recent findings: Operative mortality for acute type A aortic dissection depends largely on the presence of malperfusion, circulatory compromise, or both at the time of presentation. Operative repair requires determination of the extent of aortic root involvement, extent of aortic arch involvement, the location of intimal tears, and the presence of malperfusion. The availability of endovascular grafts and increased experience with endovascular therapy has increased the options for both open- and closed-chest repairs for acute type A aortic dissection. The development and refinement of intraoperative organ protection using deep hypothermic circulatory arrest and selective antegrade cerebral perfusion have decreased the risk of neurologic complications and permitted complex repair or replacement of the aortic arch to be performed with a reasonable degree of risk.

Summary: Understanding recent advances in detecting complications associated with aortic dissection, the full range of surgical options for repair, and strategies for intraoperative organ protection are important for the comprehensive perioperative management of patients with acute Stanford type A aortic dissection.

Within the last decade, the international registry of aortic dissection (IRAD) estimated the incidence of aortic dissections to be 5-30 per 1 million people per year. Acute type-A aortic dissection (ATAAD) is a highly lethal condition if left untreated and is considered a surgical emergency. Increased public awareness and widespread availability of computed tomographic angiography (CTA) have led to earlier and more frequent diagnosis (1). Currently, 2,000 new cases are diagnosed yearly in the United States alone. Comprehensive perioperative management of ATAAD spans multiple medical fields including surgery, anesthesiology, radiology, and critical care medicine. Significant improvements have occurred across the spectrum of healthcare deliverance, including reduced mortality. However, despite these gains, ATAAD remains a condition associated with significant mortality and morbidity. The last decade has seen dramatic changes in the surgical approaches to manage this life-threatening condition, including techniques to preserve the aortic valve, use of advanced neuro-circulatory techniques for brain protection,

Evidence Based Communications

trends towards warmer circulatory arrest temperatures, more frequent use of a myriad of total and extended arch repairs, and application of adjunct endovascular interventions (2-4).

History and Early Classification

In 1965, Michael De Bakey published the results of his ten-year experience with the surgical treatment of aortic dissection (5). When compared to the higher reported mortality in a contemporary group of aortic dissection patients managed non-operatively, it was concluded that aortic dissection is a surgical emergency (6). At this time a classification scheme was introduced that is widely known and still used today. Type I aortic dissections originate in the ascending aorta and extend into the aortic arch, often involving the full length of the aorta and its major terminal branches. Type II dissections also originate in the ascending aorta but do not extend past the innominate artery. Type III dissections arise distal to the left subclavian artery (i.e., isolated to the descending aorta). At the time, this classification scheme also determined the surgical approach. Type I aortic dissections were treated by transection of the ascending aorta and re-approximating the inner and outer walls of the vessel to obliterate the false lumen. The objective of this repair was to restore mural integrity, prevent further progression of the dissection, and redirect blood flow into the true lumen of the aorta. Treatment of Type II dissections involved complete replacement of the ascending aorta with an interposition graft. In Type III dissections, the proximal descending aorta was replaced with the graft, including aortic wall re-approximation at the distal anastomosis to obliterate the false lumen downstream.

In 1970, the cardiovascular surgery group at Stanford University published a small case series that demonstrated survival and responses to treatment options depended on whether the dissection involved the ascending aorta or was limited to the descending aorta (7). Patients with acute Type-A aortic dissections (ATAAD) involving the ascending aorta had better survival in response to surgical repair (72%) compared to medical management (28%). In contrast, those with acute Type-B aortic dissections (ATBAD) confined to the descending aorta, the survival rate with surgical repair was no better than those who were medically managed (72% vs. 80%). These findings led to the Stanford Classification that forms the basis of our modern paradigm for treating aortic dissection. Primarily addressing ATAAD with surgery and ATBAD with medical therapy is an approach that remains supported by modern data. In 1996, the IRAD was formed to collect epidemiologic data on acute aortic dissection. In their report published in 2000, IRAD verified that 30-day mortality was improved when patients had an operation for ATAAD instead of conservative management (27.4% vs. 58.0%). The survival outcomes were reversed in ATBAD, where medical therapy alone had lower mortality than surgical intervention (10.7% vs. 31.4%) (8). Not only is ATAAD a surgical disease, but it is a surgical emergency as the reported mortality accelerates as time passes from the moment of diagnosis: 20% at 24 hours, 30% at 48 hours, and 40% at 7 days (9).

Additional Classification Schemes

Since the introduction of the De Bakey and Stanford classification systems, there have been additional methods to differentiate ATAAD to predict mortality or guide surgical options. The early mortality from ATAAD is driven by 1) proximal complications of the dissection process such as pericardial tamponade or acute aortic regurgitation, 2) proximal malperfusion of the coronary arteries, cerebral or spinal cord circulation, and 3) distal malperfusion of the viscera or limbs. The early application of gated CTA together with TEE has not only improved the ability to diagnose and classify ATAAD, but also provides detailed information on the anatomic extent of the disease together with the presence of vascular or circulatory complications associated with the dissection (1, 9).

Clinical features of hypotension, shock, migrating pain, cardiac tamponade, pulse deficits, or myocardial ischemic changes on EKG, in addition to advanced patient age and history of prior cardiac surgery, can be used to predict surgical mortality (10). More recently, the Penn Classification, based on retrospective data from the University of Pennsylvania, has been described as a predictive tool and independently validated (11). The classification is based on the absence or presence of two variables: circulatory shock and branch vessel malperfusion. Penn Class A (patients with neither) had a low mortality rate of 3.1%. Mortality increased significantly with branch vessel malperfusion (Penn B; 25.6%), circulatory shock (Penn C; 17.6%), or both (Penn BC; 40%) (12).

A systematic approach to evaluating anatomic pathology and generating a surgical plan using a combination of pre-operative CTA and intra-operative transesophageal echocardiography (TEE) has been developed by Sun et al., from the Fuwai Hospital in Beijing, China (13). In this scheme the aortic root is divided into three subtypes while the distal aorta is divided into two. Aortic root subtype A1 has minimal aortic regurgitation, a normal sinotubular junction (STJ) and sinus of Valsalva, and no more than one commissural detachment. Subtype A2 has mild to moderate aortic regurgitation, a normal STJ, and 1-2 commissural detachments. Finally, subtype A3 has severe aortic regurgitation, enlargement of the sinus of Valsalva, and disruption of the STJ. Patients with subtype A1 can have preservation of the native aortic valve and sinus of Valsalva, A2 would need replacement or reconstruction of the root +/- the intervention of the valve, and A3 would generally require a Bentall procedure. With respect to the distal aorta, patients were categorized into subtype S (simple) or C (complex). Subtype C patients included those whose arch or descending aorta was the primary tear site or dilated > 40mm, or the innominate artery was occluded. In these patients, a total arch procedure was performed with concomitant stented elephant trunk graft into the descending aorta.

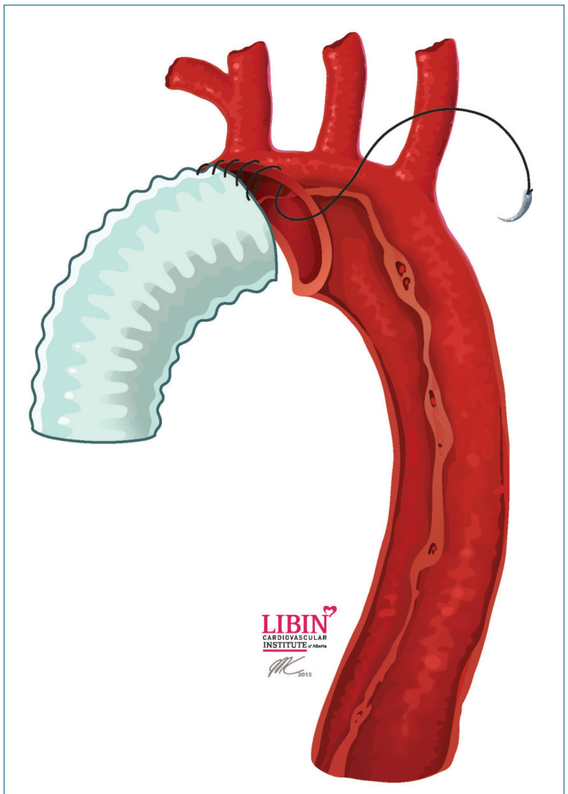

Figure 1. Standard Hemiarch Repair with an Open Distal Anastomosis.

Trends and Developments in Surgical Approaches to ATAAD

Aortic Valve and Root

The aortic valve complex can be viewed as a series of sequential rings. Beginning with the basal attachments of the cusps, through the crown-shape of the cusps themselves within the aortic root, and ending with their distal attachments at the sino-tubular junction (STJ) (14, 15). The dissection process can involve any of these components, resulting in varying degrees of aortic insufficiency. Often, the aortic valve cusps themselves are normal and the regurgitation is due to aortic root dilation or impairment of the more distal components of the complex such as the STJ. If this is the case, then a valve-sparing approach may be warranted. As more experience has been gained in valve-sparing repair for elective procedures (such as bicuspid valvulopathy or aortic root aneurysm), the comfort level with applying these techniques in the setting of ATAAD has grown. This is demonstrated in a nearly 10-fold increase in the frequency of valve-sparing procedures in the IRAD data over the past 20 years (3). If the dissection process involves the aortic root, then this will also need to be addressed. Traditionally the native sinuses of Valsalva were left intact, with the aortic valve resuspended (or replaced) in conjunction with the supra-coronary aorta. In a review by El-Hamamsy et al., it was suggested that in certain scenarios a more complete repair or full replacement of the root

Table. Classification System for Surgical Techniques of Extended Aortic Arch Repair for Acute Type A Aortic Dissections

I. Total Arch Replacement.
Surgical resection of the aortic arch and head vessel re-attachment with or without a dacron elephant trunk inserted into the true lumen
II. Total Arch Replacement & Frozen Stented Elephant Trunk.
A covered endograft is deployed through the open arch during circulatory arrest and head vessel re-attachment to dacron graft. Usually involves a single prosthesis with endograft attached to dacron.
III. Hemi Arch Replacement & Frozen Stented Elephant Trunk.
A covered endograft is deployed through the open arch during circulatory arrest, a residual segment of native dissected arch is left behind, and an open distal anastomosis is done in a “hemi arch” fashion without head vessel attachment.
IV. Total Arch Replacement & “Warm Stent Graft”.
Head vessels are anastomosed more proximally, and a Dacron proximal landing zone is created. Endograft is deployed after coming off CPB with use of fluoroscopy to identify landing zones.

may be required (16). Severe damage to one or more sinuses of Valsalva, a known connective tissue disorder, a severely aneurysmal root, and significant annulo-aortic ectasia were suggested by these authors as indications for a complete replacement of the root with coronary re-implantation. Although much of the surgical decision making will be based on the visualization and physical examination of the root and valve, the pre-operative TEE is a vital source of additional information in this decision-making process (see “Monitoring: TEE” below).

Approach to the Ascending Aorta and Arch

The traditional surgical repair for ATAAD involved a hemiarch replacement. However, there is current debate regarding whether a more extensive approach to the arch should be undertaken at the index operation. The decision should be tailored to the clinical context, anatomic details on pre-operative imaging, intraoperative findings and surgeon/center experience. Important anatomic details to consider include the location and extent of the intimal tear, the size of the aortic arch and distal aorta, collapse of the distal true lumen, and the presence of static or dynamic obstruction of the branch vessels of the aortic arch or abdominal aorta.

Standard Hemiarch Replacement

The current standard for the surgical treatment of ATAAD is hemiarch repair with an open distal anastomosis performed under circulatory arrest (16-18). For patients with a tear localized to the ascending aorta who have a normal caliber aortic arch without distal malperfusion, the standard surgical repair involves a hemiarch replacement with an open distal anastomosis under circulatory arrest (Figure 1). The layers of adventitia, media and intima are reconstituted with some combination of prolene, Teflon felt strips and surgical adhesive. For a De Bakey Type II dissection, the standard hemiarch repair is often curative whereas for the more common De Bakey Type I dissection, this repair requires long-term surveillance imaging to ensure the stability of the distal aorta, particularly during the early post-operative period. Contemporary operative mortality while trending lower remains as high as 12-20% in large registries (1). Those who survive their dissection and emergency surgery may still suffer from medium- and long-term complications including distal aortic malperfusion, need for aortic re-intervention and death. Although more limited repairs of the ascending aorta performed with the clamp in place have historically been described, these should generally be avoided as they do not allow for direct inspection of the arch and invariably leave a significant remnant of the diseased ascending aorta.

Emerging Extended Arch Options

Alternate repair strategies, such as extended-arch, total arch techniques, or endovascular adjuncts, have been proposed to improve the mid- and long-term outcomes of ATAAD patients. Up to 30% of patients may have a dissection entry tear that is distal to the ascending aorta, which would be ineffectively treated with a standard hemi-arch approach (19). Based on emerging data, mostly from centers in Europe and the Far East, both the 2014 European Society of Cardiology, and 2016 Canadian Cardiovascular Society guidelines recommend that an extended-arch technique should be considered in ATAAD patients with 1) primary intimal entry tear in the aortic arch, 2) evidence of distal malperfusion, 3) aneurysmal arch or descending aorta, or 4) young patients (17, 20). The goals of an extended distal repair are to seal tears extending beyond the transverse arch and to improve false lumen obliteration of the thoracic aorta. Theoretical benefits include a reduction in early malperfusion and prevention of late distal aortic dilatation, reintervention, and mortality.

A meta-analysis of the extended arch for ATAAD identified 2, 140 patients from 38 studies from 2003 to 2015 (21). The pooled operative mortality rate was 8.6%, stroke 5.7% and spinal cord ischemia 2%. It should be noted that a significant geographical bias with only 3 of the 38 studies arising from North America. The authors of this meta-analysis concluded that these perioperative results were encouraging and demonstrated the feasibility of this extended arch repair techniques compared to the traditional hemiarch repair. It also led to a proposed classification system to categorize the various extended arch surgical approaches currently being used (Table and Figure 2) (22). While these extended arch procedures for ATAAD are not yet widely adopted, there are some centers that advocate a strategy for acute type A dissection whereby all diagnostic and therapeutic measures are available within a hybrid operating room (23). Ideally, this treating team should consist of some combination of a cardiac surgeon, cardiologist, interventional radiologist, cardiac anesthesiologist, and vascular surgeon depending on expertise in individual centers. Further follow up will clarify whether long-term outcomes will be improved when an extended arch strategy is selected at index operation.

Malperfusion

End-organ malperfusion is reported in 18% - 33% of cases with acute type A aortic dissections (24). Malperfusion may involve all major aortic branches and thus potentially result in coronary, brain, spinal cord, visceral organ or limb ischemia. With advanced age and hemodynamic instability on arrival, malperfusion constitutes one of the major risk factors for mortality in acute type A aortic dissection. A 2015 multicenter European registry showed that operative mortality increased by an additional 10% for each organ system involved with malperfusion. Patients presenting with 3 organ systems affected by malperfusion had an operative mortality >40% (25). Malperfusion may be described as either dynamic, static or mixed. In dynamic malperfusion, which is the most frequent type of malperfusion, the over pressurized false lumen pushes the septum towards the true lumen and may ultimately collapse the true lumen and obstruct the origin of one or more arterial branches. Static malperfusion results from stenosis or occlusion of an organ arterial branch owing to a local process within the organ artery such as a dissection flap, intramural hematoma or thrombosis.

The importance of managing malperfusion syndromes in driving patient outcomes has led some centers to adopt a strategy of delaying central aortic repair until malperfusion has been treated first with endovascular interventions (26-28). Although primary endovascular repair is an interesting concept, it has not been universally accepted because 1) there are techniques to manage both the primary dissection and malperfusion, and 2) the risk of proximal complications or rupture remains a constant threat. An example of this balance of risk can be found in a review that showed the reported limb reperfusion rates range from 60% to 100% following primary dissection repair while 30% of patients did not survive to surgery when limb malperfusion was addressed first (29).

Intraoperatively, several adjuncts can be used to deal with organ malperfusion. Institution of cardiopulmonary bypass (CPB) can move the dissection flap and affect which organs are perfused. Monitoring should include arterial blood pressure in upper and lower extremities (and sometimes both upper extremities), bilateral cerebral oximetry to assess adequate flow to both cerebral hemispheres while cooling and TEE to assess compression of the true lumen in the descending aorta. The institution of CPB can help with organ malperfusion. Sometimes both the true and false lumen need to be cannulated to perfuse vital organs. Ensuring that the primary entry tear is resected may resolve distal malperfusion. At some centers, the presence of distal malperfusion is a clinical indication for an extended arch replacement. After coming off CPB, an on table aortogram can be performed done to assess for resolution of malperfusion. If radiologic malperfusion persists, the endovascular covered stent graft with or without bare metal stents can be deployed to re-expand the true lumen and treat branch vessel compromise, an approach that has been shown to improve true lumen expansion and false lumen regression in a small case series (30, 31). For example, extended arch replacement with the placement of a short endograft at time of surgery was used to treat a young patient with ATAAD presenting with a collapsed distal true lumen. Incomplete restoration of the true lumen that remained collapsed was later treated by expanding it further with bare metal stents for aortic remodeling (Figure 3).

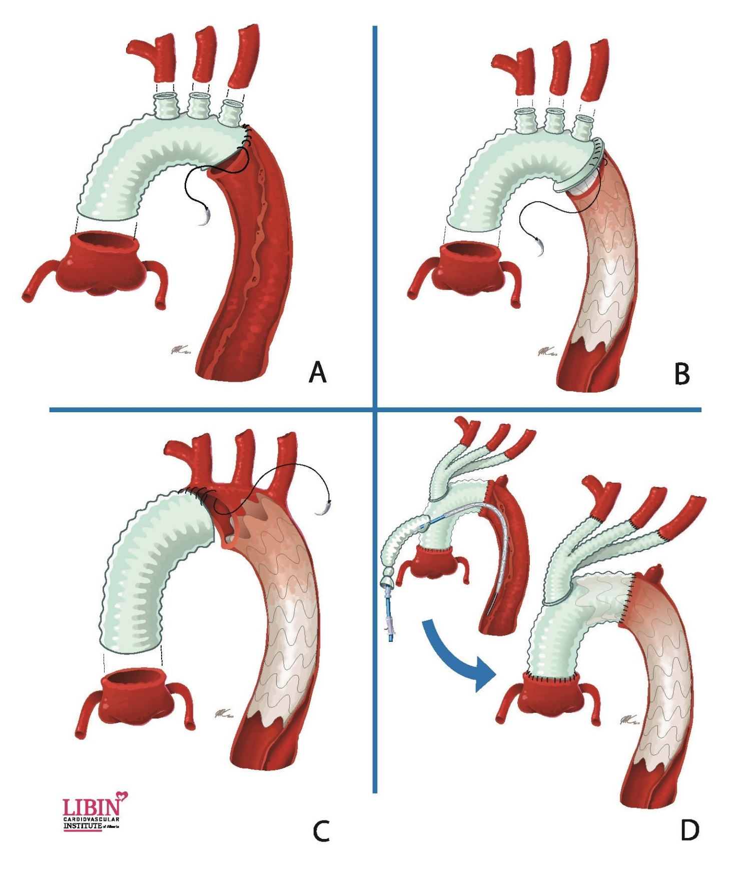

Figure 2. Proposed Classification Scheme for Extended Arch Techniques.
A. Total arch replacement +/- standard elephant trunk without descending thoracic aortic stent grafting. B. Total arch replacement and descending thoracic aortic stent grafting with frozen stent graft placed under circulatory arrest. C. Hemi-arch replacement and descending thoracic aortic stent grafting with the stent graft placed under circulatory arrest. D. Total arch replacement with stent graft placed after coming off cardiopulmonary bypass and with the use of fluoroscopy to identify landing zones. (Reprinted with permission from www.aorta.ca)

Advancements in Endovascular Options

As EVAR, TEVAR and TAVR (transcatheter aortic valve replacement) are now well-established therapies for a wide range of aortic pathologies, several groups are giving renewed attention to the application of stent graft technology into diseases of the ascending aorta and arch. Closed chest repair of ATAAD is attractive for several theoretical reasons, primarily due to the potential for a minimally invasive repair of a massively morbid disease process, particularly in those patients with co-morbidities and are not suitable for open repair.

The goal of ATAAD stent graft repair is to exclude antegrade false lumen flow via coverage of the primary intimal tear, ideally with 2 cm of landing zone on either side, without covering critical side branches or causing a stent graft-induced new entry (SINE).

There are many hurdles unique to the ascending aorta that need to be crossed before this approach gains widespread application.

At present, there is relatively little worldwide experience in the setting of closed chest repair of ATAAD. A recent systematic review identified 59 reported cases of closed chest repair of Type A aortic dissection in patients unsuitable for open repair, a mix of acute / sub-acute / chronic cases, the majority being single case reports (32). While the composite aorta-related mortality and all-cause mortality was impressive at 5% and 15% respectively, experience to date highlights the importance of appropriate patient selection when utilizing this approach.

Confident characterization of the primary intimal tear, adjacent landing zones and side branches such as the coronary arteries is a pre-requisite to appropriate patient and device selection. The inherent mobility at the aortic root and ascending aorta often result in motion blurring at these regions on the commonly utilized non-gated preoperative CTA, precluding definitive characterization in up to 25% of patients (33). The absence of ATAAD specific devices also limit which patients are candidates due to the short length (often < 10 cm) and large caliber of the ascending aorta relative to the existing available devices (shortest device length 10 cm and largest caliber 45 mm). The absence of suitable landing zones is a common limiting factor when considering anatomic suitability for closed-chest ATAAD repair. An intimal tear near the sinotubular junction (and coronary arteries) is a hurdle that will not be easily overcome, and these patients are not appropriate candidates for endovascular repair. Distal landing zones can be extended into the arch utilizing either a branched device or a chimney technique in combination with surgical bypass of the arch vessels. Additional limitations specific to existing devices include long nosecones, with resultant potential for ventricular rupture or acute aortic insufficiency, and delivery systems which are too short, necessitating creative access routes such as axillary or transapical. Accurate deployment of a large caliber stent graft in the harsh flow dynamics associated with the ascending aorta present another hurdle. Temporary reduction of the cardiac output can be accomplished via temporary rapid ventricular pacing, pharmacologically using adenosine or by using a balloon to achieve partial right atrial inflow occlusion.

Initial CT feasibility studies estimated that approximately 35% of ATAAD patients are theoretical candidates for closed-chest repair utilizing existing off-the-shelf devices, however these did not account for the risk of a SINE (34). A more recent feasibility study out of Japan looking at the next generation ascending aorta and arch-specific devices in the setting of ATAAD concluded that only 1/5 ATAAD patients were a theoretical candidate primarily due to the potential for a SINE at the aortic root and the associated potential for rupture and tamponade (33).

Neurocirculatory and Temperature Strategies for HCA

Deep Hypothermic Circulatory Arrest (DHCA)

The brain has a high metabolic rate and utilizes 20% of the total cardiac output to meet its oxygen and glucose requirements for neuronal function and cellular integrity (35). In most cases, surgery for ATAAD will require opening the aortic arch for inspection and repair. This requires that the delivery of blood to the brain via the arch branch vessels while on CPB is temporarily stopped. Hypothermia provides neuroprotection during periods of circulatory arrest by 1) reducing the metabolic requirements (thus raising the ischemic threshold) for both neuronal activity and cellular integrity, 2) suppressing many of the complex excitotoxic, inflammatory, immune, and genetic pathways that result in neuronal injury and death when ischemia does occur, and 3) attenuating the secondary insult which occurs during reperfusion following ischemia (36-38). The use of DHCA for ATAAD has been used extensively for decades, is simple, and has a proven track record of success.

Selective Antegrade Cerebral Perfusion (SACP)

Though the neuroprotective properties of hypothermia are well known, preservation of cerebral blood flow while operating on the aortic arch theoretically avoids the need for any neuroprotection as the brain's oxygen supply is maintained throughout. This is the basis for many of the selective antegrade cerebral perfusion (SACP) strategies that are currently applied in a majority of operating rooms worldwide (2-4). Success in neurocirculatory management for ATAAD requires comprehensive knowledge of cerebrovascular anatomy, the planned surgical approach(es), and information regarding the extent of the dissection's involvement of the arch branch vessels.

The circle of Willis (COW) provides connections between the cerebrovascular inputs of the right and left hemispheres, as well as the anterior and posterior circulation (Figure 4). The left and right internal carotid and vertebral arteries are the 4 main sources of blood flow to the brain and spinal cord. Under normal physiologic

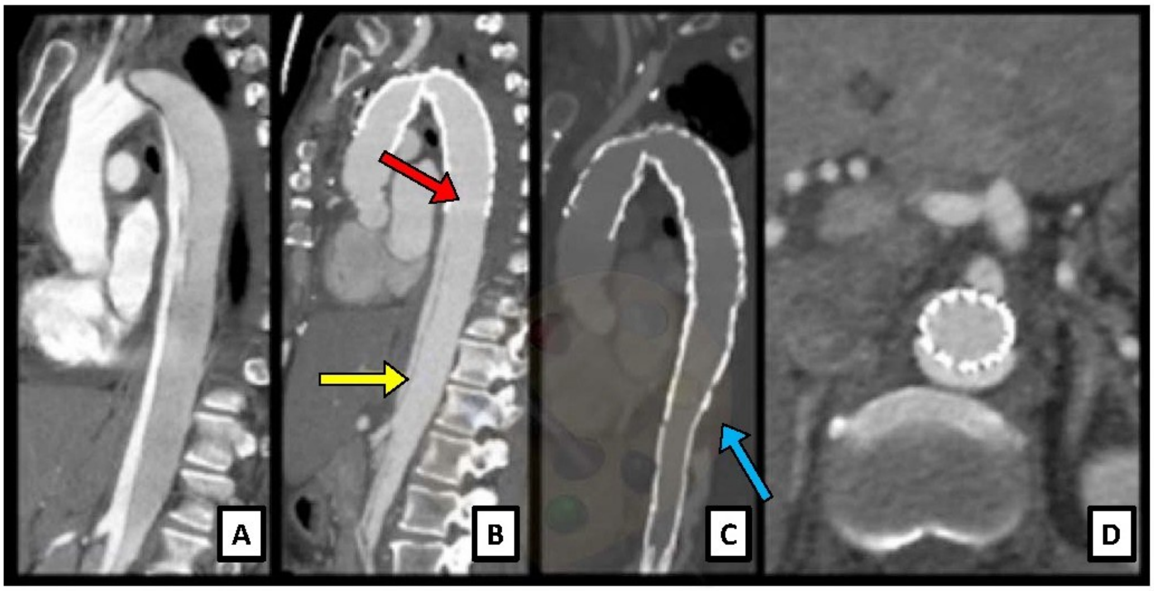

Figure 3. A 48-year-old woman with ATAAD treated with a hybrid arch and staged bare metal stent.
A. CT image demonstrating primary intimal tear distal to the left subclavian origin. Note the thrombosed false lumen in the ascending aorta and the severely effaced true lumen in the descending aorta. B. CT image 1-week post-hybrid arch demonstrates an entry tear at the distal landing zone of the endovascular device in the mid-thoracic descending aorta (red arrow). The true lumen was severely narrowed at the level of the celiac trunk and superior mesenteric artery (yellow arrow). C. CT image after second operation consisting of coverage of the entry tear with a shortly covered graft followed by a 46 × 164-mm Cook Dissection bare metal stent. The bare metal stent was deployed from the mid-thoracic aorta to the abdominal aorta just below the renal arterial origin. Note the successful true lumen expansion (cyan arrow). D. Axial CT image at 6 months demonstrating excellent perfusion of the visceral arteries and reduced false lumen perfusion.

circumstances all 4 vessels provide perfusion to the brain and the COW acts as a "back-up" mechanism should one or more of these vessels fail in their task. A scenario of "perfusion failure" will occur during SACP if the vessel is not being included in the perfusion strategy or if the aortic dissection process has disrupted a vessel being relied upon for cerebral perfusion. As one can imagine, the fewer cerebrovascular inputs being used during SACP, the more dependence is placed on the COW or other collaterals to prevent neurologic ischemia and injury.

Generally, SACP can be divided into two main categories: unilateral or bilateral (Figure 5). Unilateral ACP (uACP) is most commonly performed through either an axillary artery graft or direct innominate artery cannulation. The axillary graft approach involves a small incision on the right chest, below the clavicle, exposure of the axillary artery, placement of occluding ties or clamps, and anastomosing a length of graft to the artery. This is usually done prior to sternotomy and a small dose of heparin (5000 units or 50-100 units/kg) is often administered. One of the benefits of this technique is that the axillary graft can itself be cannulated and used for both full CPB and uACP. Two disadvantages of this technique are that it takes additional time to perform and it may not be efficacious if the dissection extends into the innominate artery. Direct innominate artery cannulation is another technique for delivering uACP that has been previously described, appears to be safe, and may begin to grow in popularity (39, 40). This approach is much faster and simpler than the axillary method, however it cannot be used for CPB, so another technique will be required to initiate CPB such as central or femoral cannulation. Like the axillary artery, its effectiveness for delivery uACP may be impaired if the innominate artery is severely dissected. Finally, care needs to be taken not to place the cannula in too far. If it is placed past the right common carotid, then no ACP will be delivered. Alternatively, if it is placed directly into the carotid then the right vertebral artery is excluded, and the posterior circulation will be completely dependent on collateral blood flow.

Bilateral ACP (bACP) is less commonly used in most centers, but has the benefit of less reliance on the collateral blood flow to provide adequate perfusion. A wide variety of techniques have been described, but the principles are similar: bACP is performed by perfusing simultaneously both the right and the left common carotid arteries. This may or may not be supplemented by perfusion of the left vertebral artery via the left subclavian artery. Though the potential benefits of more natural physiologic cerebral blood flow seem clear, bACP is a more complicated neurocirculatory technique involving manipulation of the branch vessels that may increase the risk of thromboembolic stroke.

Regardless of the SACP technique being used, maintenance of cerebral blood flow has allowed for surgical procedures in the setting of ATAAD to be performed under warmer temperatures (2, 4). Hypothermia can be classified as profound (≤ 14.0 °C), deep (14.1-20.0°C), moderate (20.1-28.0°C), or mild (28.1-34.0°C) (41). There have recently been large series in patients with ATAAD who were managed with mild or moderate SACP and had excellent outcomes (42, 43). The most consistent benefit demonstrated with a shift to moderate or mild hypothermia is shorter CPB times. The use of higher temperatures for CPB must be balanced with the increased risk of cerebral ischemia. Based on the measured temperature-based reductions in human cerebral metabolism, cerebral circulatory "safe arrest times" have been suggested (Figure 6). It should be appreciated that there will be population variance in the cerebral metabolic response to hypothermia, that these times cannot be considered as absolute thresholds for neurologic injury, and that there has been no prospective study to confirm the safety profile of applying these times across a large surgical population- let alone patients with ATAAD who suffer from elevated rates of preoperative cerebral malperfusion and perioperative stroke. In selecting a cooling target, it may be wise to consider 1) what is the planned SACP strategy and 2) what is the anticipated cerebral circulatory arrest time in case the SACP is suboptimal or ineffective.

Comparison of Neurocirculatory and Temperature Strategies

In a multi-center study of 324 patients over 10 years, there was no significant difference in operative mortality, stroke, acute kidney injury, prolonged ventilation, or re-exploration for bleeding patients who had surgery for ATAAD under deep hypothermia, regardless whether or not SACP was used (44). In another study of 280 patients from a single institution there was a trend towards lower mortality in patients who had moderate hypothermia with uACP compared to DHCA (9.2% vs 14.6%, $P = 0.17$), but there was no difference in any adverse outcomes such as stroke, temporary neurologic dysfunction, or dialysis-dependent renal failure (45). A retrospective review of 157 ATAAD patients by Preventza et al., compared the use of uACP to bACP under moderate hypothermia (46). Their results showed no difference in mortality, postoperative stroke, or temporary neurologic dysfunction between the two groups. Tong et al. compared the same techniques in their series of 203 patients (47). Interestingly, though not meeting statistical significance, they did find trends in 30-day mortality (bACP 11.6% vs uACP 20.7%, $P = 0.075$), and permanent neurologic dysfunction (bACP 8.4% vs uACP 16.9%, $P = 0.091$) favoring bACP. There were also shorter postoperative ventilation times in the bACP group (bACP 95.5 +/- 45.3 hours vs uACP 147.0 +/- 82.0 hours, $P < 0.001$).

Determining the superiority of one approach over another is challenging for several reasons. First, there has been much less experience in the application of SACP or use of warmer circulatory arrest temperatures in the setting of ATAAD compared to elective surgery for other aortic pathology. Second, all studies that do exist are retrospective in nature and suffer the typical limitations of this form of analysis. Third, there is no consensus on the definition of the various options for SACP and even the current definitions for hypothermia have only existed since 2013. Finally, even with the long-standing experience of DHCA, there is still significant variance in the reported mortality and morbidity making it difficult to assess the outcomes of these newer techniques.

Monitoring

Arterial Pressure Line

Selection of the site(s) for invasive arterial monitoring will be based on several patient and surgical factors. It is important to consider which sites will best determine the perfusion pressure of the brain, heart, and vital organs once CPB has been initiated. This is usually best done by identifying which aortic branches are perfused by the true lumen as well as looking for clinical and radiographic evidence of branch vessels malperfusion. The nature of the aortic dissection, true lumen and false lumen flow, and branch vessels malperfusion can be dynamic throughout the operation. Sometimes, particularly in the setting of a complex dissection and/or malperfusion pattern, it is ideal to monitor invasive pressure from multiple sites. The planned neurocirculatory and surgical repair strategies will also determine which invasive pressure monitoring sites should be chosen. For example, if uACP through either an axillary or innominate artery approach is to be used, then the right radial artery can help guide the adjustment of cerebral perfusion flow and pressure. Or if an axillary graft is to be used for both CPB and uACP then a right radial and left radial (or femoral) arterial line will be needed. The variety of considerations and permutations regarding arterial pressure monitoring highlight the importance of a careful examination of the preoperative CTA and thorough discussion with the surgeon prior to the operation.

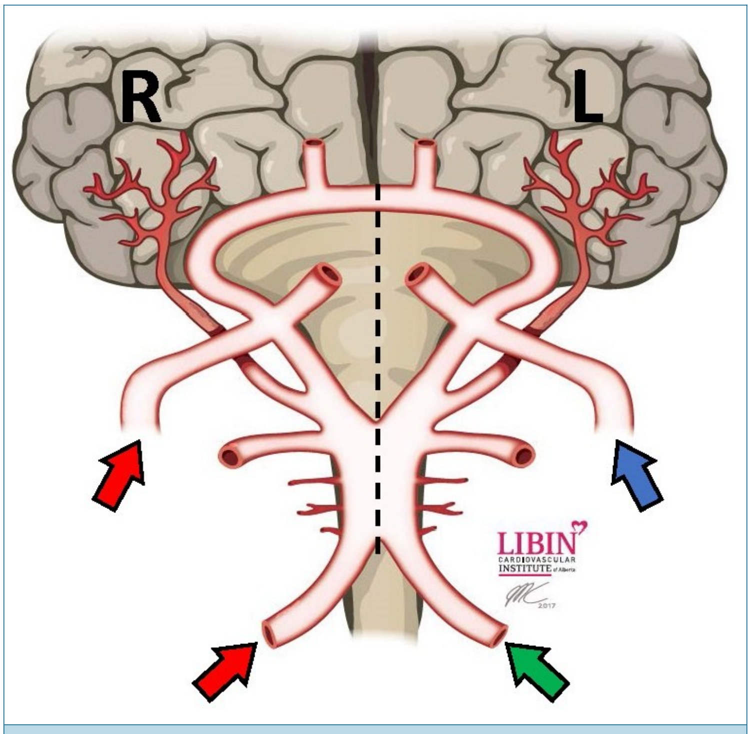

Figure 4. Circle of Willis and Cerebrovascular Inputs for SACP.
If uACP is used, either with axillary graft or direct innominate cannulation, the brain is perfused through the right common carotid and right vertebral arteries (red arrows). The left cerebral hemisphere is dependent primarily on perfusion via the Circle of Willis. If left common carotid perfusion is added it would be considered bACP and the left hemisphere would receive antegrade perfusion (blue arrow). Normal physiologic cerebral perfusion occurs when all 4 main input vessels are perfusing the brain. This would occur during lower body circulatory arrest only once the left subclavian is perfused in addition to the other arch branch vessels, directing blood to the left vertebral artery (green arrow).

Neurophysiologic Monitoring

The use of near infrared spectroscopy (NIRS) and electroencephalopathy (EEG) is important in the management of hypothermia and neurocirculatory techniques. To achieve maximal cerebral metabolic suppression during deep or profound hypothermic circulatory arrest, EEG electoral cortical silence can be used as a cooling endpoint. It is valuable because there is a large population variance in the cooling time and nasopharyngeal temperature at which EEG silence is reached. In a study by Stecker et al., electoral cortical silence was observed at temperatures ranging from 12.5-27.2 °C (48). Without EEG guidance, and choosing a commonly used target of 18 °C, it would seem that a significant proportion of patients would have either suboptimal hypothermic neuroprotection or be excessively cooled.

Both NIRS and EEG can be helpful in determining the effectiveness or managing the cerebral perfusion parameters in SACP. Both can be used to identify a lack of contralateral cerebral perfusion in the setting of hypothermic circulatory arrest with uACP. Once uACP is initiated, if there is evidence of bilateral hypoperfusion then the uACP cannula should be checked and flow/pressure/oxygen content parameters optimized. A more typical scenario involves detection of hypoperfusion to the contralateral side (left cerebral hemisphere). If this occurs there are two general causes, the determination of which is critical since they require different actions to correct the problem. The first cause is inadequate flow across the circle of Willis (COW) to the left side. This can be due to insufficient uACP pressure/flow, an anatomically abnormal COW, or obstructive vascular disease within a communicating artery. It should be suspected if examination of the aortic arch orifice of the left common carotid artery does not demonstrate robust retrograde flow. This problem is corrected either by increasing the uACP pressure/flow or converting to a bACP strategy. The second cause is adequate flow across the COW with retrograde steal through the left carotid and left vertebral arteries. This should be suspected if examination of the aortic arch demonstrates significant retrograde flow from either left-sided branch vessels orifice. This may be corrected by placing a clamp on or occlusive balloon in the left carotid and left subclavian to redirect flow into the cerebrovasculature. Conversion to bACP would also correct this issue.

The use of emitted near-infrared light, which can pass through the skull, allows for NIRS monitors to help gauge cerebral perfusion. The benefits of using NIRS include its ease-of-use, accessibility, functionality in the absence of pulsatile flow allowing it to be used for CPB or SACP, and ability to use it during deliberate hypothermia. The disadvantages of NIRS is that diminished cerebral blood flow does not necessarily indicate neuronal ischemia. Also, placement of the NIRS optodes on the forehead results in near-infrared light passing through tissue usually supplied by the anterior and middle cerebellar arteries. Therefore, there is no measurement of perfusion to the posterior circulation or spinal cord. The use of EEG can overcome some of the limitations of NIRS however it too has limitations. If the brain becomes ischemic one of the first defense mechanisms is to cease electrical activity. This can be observed on an EEG and therefore ischemia can be identified regardless of the current level of cerebral perfusion. Since the EEG electrodes can be placed over the entire surface of the skull, it can also be used to identify ischemia in the territory supplied by the posterior circulation. Its disadvantages include inaccessibility at many centers (particularly the middle of the night) and its loss as a monitor for cerebral perfusion if hypothermic temperatures produce electrocortical silence. If a center has the capacity and expertise, then an optimal neuro-monitoring strategy may be to use both NIRS and EEG.

Transesophageal Echocardiography (TEE)

The importance of TEE in the setting of ATAAD has been established since its introduction as a standard monitor for cardiovascular surgery and has been previously reviewed (49-54). The use of TEE will always be valuable to 1) confirm or diagnose the presence of a type A dissection, 2) detect pericardial tamponade, aortic regurgitation, ventricular dysfunction, or regional wall motion abnormalities, and 3) identify the true and false lumens. Beyond this, there have been more recent developments in 3D technology as well as changes in surgical approaches which have created new areas for TEE to help in the management of ATAAD patients. Coronary artery malperfusion is a well-known potential complication of aortic dissection. The dissection process can involve the coronary ostia or cause obstruction of a coronary ostium. This complication is usually suspected when patients complain of angina, ST changes are evident on EKG, regional wall motion abnormalities are seen on an echocardiogram, and there are signs of heart failure.

As described earlier, there is a shift towards performing more aortic valve-sparing procedures in addition to a more nuanced approach to aortic root pathology. These trends have developed in parallel with a greater focus on developing a more systematic and comprehensive approach to the TEE evaluation of aortic regurgitation and the aortic root. A classification system for aortic regurgitation has been described

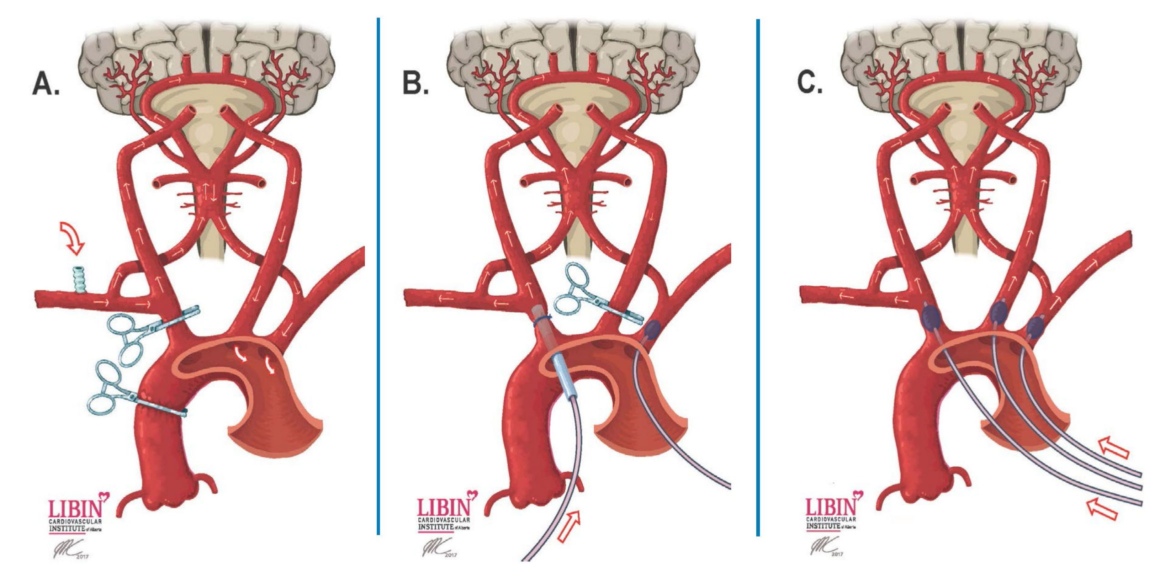

Figure 5. Examples of Common SACP Techniques.
A) uACP via an axillary graft. Note that there is retrograde blood flow exiting the origins of the left common carotid and left subclavian arteries. B) uACP with direct innominate cannulation. In this example, a clamp has been placed on the left common carotid artery and an occlusive balloon catheter inserted into the left subclavian artery. In both instances this is to eliminate retrograde steal and left cerebral hemisphere ischemia. C) bACP with direct insertion of balloon cannulae into all three arch branch vessels. This provides normal physiologic cerebral perfusion.

and has since become an accepted method to describe the mechanism of regurgitation (56-58). The strengths of this classification system were that it was based on a previously well-known approach to mitral regurgitation put forward by Carpentier decades ago and that categorization within the system led to a recommended surgical strategy. More recently, the similar approach has been applied to aortic regurgitation in the setting of ATAAD (59). In this classification scheme, Type I pathology is a result of dilation of the aortic root, sinotubular junction, and ascending aorta. Type II indicates aortic cusp prolapse due to the dissection tearing the cusp at its insertion point in the STJ. Type III is failure of cusp coaptation due to restricted aortic valve closing caused by the dissection flap prolapsing through the aortic valve annulus. The specific echocardiographic details go beyond determining the mere presence and severity of aortic regurgitation. It requires the anesthesiologist to be able to perform detailed TEE analysis and communicate the results to their surgical colleague.

In the past, identification of a true and false lumen was mainly helpful for confirming the diagnosis of dissection or assisting the placement of arterial cannulae for CPB. Incremental emphasis has since been placed on the importance of the location of the primary entry tear, the presence of reentry tears, and the identification of malperfusion. These features can be important for guiding the primary surgical approach, intraoperative perfusion strategies, or deciding on the need for adjunct endovascular interventions. Unfortunately, if the primary entry tear or reentry tears are in the aortic arch they will unlikely be visible by TEE. If no entry tear is detectable in the root or ascending aorta or if reentry tears are seen in the ascending aorta, then there is an increased chance that the patient may be treated with an extended arch in combination with an endovascular technique. The true lumen and false lumen should be examined throughout the length of the aorta, both before and after surgical repair. Failure to re-expand the true lumen in

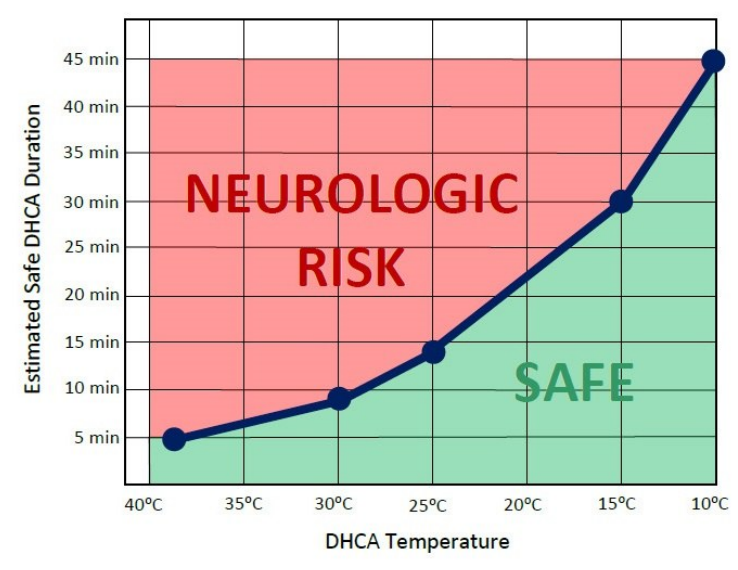

Figure 6. Cerebral Circulatory "Safe Arrest Times". Deliberate hypothermia is effective for brain protection for operations that require circulatory arrest. The safe duration for deep hypothermic circulatory arrest (DHCA) is a function of the target systemic temperature achieved with deliberate hypothermia.

the distal aorta or evidence of malperfusion with color-flow Doppler may be indications to consider additional endovascular stenting. These uses of TEE to help guide management are still in very early phases of development and are not yet supported by any robust studies or guidelines. But its importance in this area may become more prominent over time so anesthesiologists should continue to develop skills and systematic approaches to examining the characteristics of the true and false lumen, as well as detecting evidence of malperfusion.

Future Directions

It is a dynamic era in the surgical management of acute type-A aortic dissection. There have been several advances in the classification, echocardiographic examination, surgical techniques, use of endovascular therapies, neurocirculatory strategies, and temperature management in this patient population. Most of the developments and shifts in trends are in their infancy and our experience, comfort, knowledge, and evidence-based practices will continue to grow over time.

There are some areas that are ideal for future advancements and research. A helpful development would be the formation of an internationally agreed upon classification system to describe the various neurocirculatory techniques. Currently, our ability to assess for differences in cerebral perfusion techniques is hampered by inconsistencies in their reporting. One simple solution is for the acceptance and use of a term to identify the period that the viscera, lower limbs, and to some extent spinal cord are ischemic. At our center we use the term "lower body circulatory arrest" or "LBCA" to describe this period. This would allow for better comparison between techniques when looking for evidence of gut, kidney, liver, and spinal cord ischemia. The use of terminology for SACP also requires some degree of standardization. For example, a surgeon may start with uACP through the innominate artery to begin an extended arch procedure, then technically be performing bACP once the left carotid anastomosis is complete. Another surgeon, performing a hemiarch repair may use uACP for the entire duration of circulatory arrest. It would be incorrect to compare these two techniques head-to-head as uACP. With the large amount of variation in practice it may be difficult to come up with a classification scheme that works for every technique. Despite the challenges, it is a goal worth striving for if we are to better understand the risks and benefits of different neurocirculatory strategies.

Another area of uncertainty is to what extent these newer techniques ought to be applied universally. Much of the data for newer surgical or ACP techniques and warmer circulatory arrest temperatures comes from large high volume aortic centers. It is still unclear how well these techniques will work if adopted by smaller centers or surgeons with less experience in them. This consideration was recently advanced by an experienced group of aortic surgeons who demonstrated excellent results on aortic re-interventions in patients who had a standard hemiarch repair for their original ATAAD (60). Their conclusion was that it may make more sense for low-volume centers to perform a basic operation when faced with an ATAAD than attempting a more complex repair in an effort to avoid aortic re-interventions. Of course, this approach would not impact potential mortality and morbidity associated with malperfusion syndromes which is another possible benefit of the more complex repairs described above.

Randomized control trials are challenging, particularly so in patients with an acute life-threatening disease like ATAAD. This does not mean that opportunities for prospective randomized studies should not be sought out. Areas that could be potential targets for future research should focus on areas that affect key surgical decision-making and perioperative management. With the heightened focus on malperfusion and the adoption of some centers to delay treatment of the aortic dissection until malperfusion has been corrected, this could be an area for future research. As mentioned earlier, there may be potential benefits of avoiding deep hypothermia which must be balanced against the loss of neuroprotection. Although reported case series have demonstrated the safety of various SACP temperatures, this has not been done prospectively. Also, the neurologic outcomes currently reported may not be sufficient to identify meaningful outcomes. A recent consensus document amongst an international group of leading aortic surgeons to standardize outcome reporting is an important first step (61). But the true incidence of neurologic events may change if patients are comprehensively assessed by a neurologist using sensitive tools like a mini-mental status exam (MMSE) or if radiologic findings of silent stroke are included (62, 63). Finally, in current practice the decision to perform a standard hemiarch versus extended arch procedure may be based on how unstable the patient is on presentation or the presence of signs of malperfusion. To date, there have been no prospective randomized studies to test these two approaches and such studies are being designed.

Conclusions

Acute type-A aortic dissection is an old disease with universally acknowledged high rates of death if left untreated. Advancements in the perioperative management of these patients have resulted in decreased mortality and morbidity, though they remain high compared to other cardiac surgical procedures. Recent developments in imaging modalities, new surgical techniques with increasing use of extended arch techniques, warmer circulatory arrest temperatures, advanced neurocirculatory techniques, and intraoperative neurophysiologic monitoring have all added to the complexity in managing these patients. Many of our emerging modern practices remain in their early stages of implementation and evaluation, thereby making the term "evolution" an accurate descriptor. Time, experience, refinement, and further research into the outcomes of these new techniques will improve our understanding of their strengths and weaknesses, allowing us to apply the best management strategy to these high-risk patients.

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