Endovascular technology for aortic arch repair: from innovation to integration

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Treatment of aortic arch pathology is one of the most challenging areas in cardiovascular surgery due to the complex anatomy and proximity to critical cerebral vessels. Open aortic arch replacement with cardiopulmonary bypass and deep hypothermic circulatory arrest remains the gold standard but can be associated with significant perioperative morbidity and mortality, particularly in elderly and comorbid patients. Over the past two decades, thoracic endovascular aortic repair (TEVAR) has become the gold standard for most descending aortic pathologies. As a result, TEVAR use has expanded into the aortic arch, facilitated by hybrid approaches that combine supra-aortic vessel debranching with endovascular stent-grafting. Following this approach, TEVAR, in combination with the use of chimney and snorkel grafts, was developed in an attempt to treat the aortic arch with a complete endovascular approach. However, these techniques have been associated with complications such as stent-graft occlusion, collapse, endoleaks, and strokes. Further developments have led to *in situ* laser fenestrations, and branched and fenestrated endografts, thus enabling total endovascular reconstruction. Contemporary series demonstrate high technical success with acceptable early outcomes in selected high-risk patients. In addition, an increasing experience has been reported with hybrid approaches to the aortic arch, often involving a zone 2 arch replacement followed by completion TEVAR when indicated. While hybrid and endovascular strategies expand the therapeutic armamentarium, careful patient selection, meticulous procedural planning, and preservation of cerebral and spinal perfusion are paramount to minimizing neurological complications. Emerging device technologies, including off-the-shelf branched systems and modular delivery platforms, along with advanced imaging and computational planning, continue to improve procedural safety and feasibility. Lastly, the impact of stiff stent-grafts on the cardiovascular system is largely unknown but raises concerns, as it diminishes the Windkessel function of the proximal aorta. This appears to lead to increased left ventricular afterload, new-onset hypertension, adverse cardiac remodeling, and increased strain in adjacent aortic segments. This keynote lecture reviews the evolution of endovascular technology for aortic arch repair from innovation to integration, discusses current treatment strategies, and highlights future directions that may further optimize endovascular therapy in modern aortic practice.

Keywords: Thoracic endovascular aortic repair (TEVAR); aortic arch; total endovascular aortic arch repair; branched endovascular aortic repair

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Introduction

Treatment of aortic arch pathology, including aneurysms, dissections, penetrating aortic ulcers, and pseudoaneurysms, remains a complex field within cardiovascular surgery. The anatomical configuration of the arch, the presence of the supra-aortic vessels supplying the cerebral circulation, and the highly pulsatile environment pose substantial technical challenges for both open and endovascular interventions. Open surgical repair has historically been considered the gold standard treatment for complex aortic arch pathology with historically better long-term outcomes (1). Modern surgical techniques incorporating cardiopulmonary bypass, hypothermic circulatory arrest, and selective antegrade cerebral perfusion have significantly improved outcomes (2,3). Although recent improvement has been observed, open arch surgery remains associated with considerable perioperative morbidity and mortality, particularly in elderly patients and those with significant comorbidities due to its invasiveness (4,5).

The introduction of thoracic endovascular aortic repair (TEVAR) in the 1990s revolutionized the management of descending thoracic aortic pathology, demonstrating reduced perioperative mortality and morbidity in selected patients with aneurysms, dissections, and traumatic injuries (6,7). As a result, TEVAR has become the preferred treatment modality for many descending thoracic aortic pathologies, leading to a Class 1b recommendation for TEVAR (8,9). As device technology improved and operator experience expanded, the concept of extending TEVAR into the aortic arch followed. However, the unique anatomical and physiological characteristics of the arch, including proximity to the coronary and cerebral vessels, the curvature of the arch, and variable supra-aortic vessel anatomy, initially limited the feasibility of total endovascular approaches. Early hybrid strategies therefore emerged, combining open surgical debranching of the arch vessels to create proximal landing zones followed by endovascular exclusion of the aortic pathology (10). This approach currently carries a Class 2b recommendation (8).

Over the past decade, continuous technological innovation has led to the development of dedicated branched and fenestrated endografts, designed specifically for the aortic arch. These devices allow incorporation of the supra-aortic vessels and have made total endovascular arch reconstruction technically feasible in selected patients (11,12). Multicenter registries and institutional series have reported encouraging technical success rates and acceptable short-term outcomes (13-15). Alongside these procedural developments, attention has focused on the physiological effects of implanting such stiff stent-grafts on the cardiovascular system, leading to increased left ventricular afterload, new-onset hypertension, adverse cardiac remodeling, and increased strain in adjacent aortic segments (16,17).

This keynote lecture summarizes the evolution of endovascular arch repair strategies, from hybrid procedures to contemporary branched endograft systems, and discusses the current role and future potential of endovascular therapy in the treatment of aortic arch disease.

Anatomical and technical considerations in the arch

The aortic arch differs fundamentally from the descending thoracic aorta in morphology and hemodynamics. The anatomy of the aortic arch may vary greatly between patients, from a normal arch to a bovine arch, an arch with an isolated vertebral artery, or aberrant right subclavian arteries. In addition, there are different types of arches described based on their angulation and anatomical dimensions (18,19), which may complicate endovascular aortic surgery. Achieving secure proximal fixation and optimal graft apposition is technically demanding due to the arch's curvature, branch vessel origins, and high pulsatile forces. Incomplete apposition of a stent-graft against the inner curvature can result in bird-beaking, predisposing the patient to type I endoleaks and device instability. In many patients with arch pathology, an adequate sealing zone requires coverage or revascularization of one or more of the supra-aortic branches (10). Preservation of perfusion through both carotid arteries is essential to avoid neurological complications. Similarly, the preservation of the left subclavian artery (LSA), with the left vertebral artery originating from it, is also important to reduce the risk of stroke, spinal cord ischemia, and arm ischemia (20). This has led to a Class 1b recommendation for LSA preservation or revascularization (9).

Preoperative planning must determine whether the proximal seal can be achieved without supra-aortic branch coverage or whether revascularization via surgical or endovascular means is required. The Ishimaru classification was developed to provide a standardized anatomical framework for describing where stent-grafts are deployed during TEVAR (21). This nomenclature provides a common language for describing the extent of coverage and necessary adjunctive procedures and has become widely adopted in TEVAR planning and reporting.

In addition to the complex anatomy of the aortic arch, a significant atherosclerotic burden in the arch adds risk. Manipulation of guidewires and catheters in an atheromatous arch increases the risk of plaque disruption and cerebral embolization. Therefore, cautious surgical handling, embolic protection strategies when feasible, and careful patient selection are paramount to mitigate stroke risk.

Finally, the ascending aorta and arch are exposed to significant pulsatile forces generated by cardiac output. Therefore, it is recommended to achieve permissive hypotension during deployment to optimize stent-graft positioning in the aortic arch, which may be accomplished by rapid pacing. However, in patients without hypertrophic left ventricles, this may require very high rapid pacing, risking malignant arrhythmias. Preload reduction using an occlusion balloon (e.g., Medtronic Reliant™ Balloon) in the inferior vena cava provides a safe alternative, which is our preferred strategy. In the longer term, devices deployed in the proximal aorta must withstand substantial hemodynamic stress while maintaining long-term structural integrity.

Evolution of arch repair strategies

Hybrid arch repair—debranching

Hybrid arch repair emerged as an early strategy to extend endovascular therapy into the arch, while maintaining cerebral perfusion. Such surgical strategies were developed to debranch the supra-aortic vessels to a more proximal part of the ascending aorta, creating a landing zone for TEVAR (11,22). In selected patients, hybrid arch repair may avoid the need for circulatory arrest and reduce operative risk compared with open arch replacement (22). Series of hybrid repairs report high technical success, with perioperative morbidity and mortality comparable to open repair in high-risk cohorts (11,22,23). Despite these benefits, central surgical debranching is not without limitations. These techniques involve a (partial) sternotomy, side clamping of the ascending aorta with a beating heart, risking stroke, and the development of aortic dissection, particularly in dilated aortas (24). The most common hybrid solution is surgical extra-anatomic bypassing of the supra-aortic vessels. There are several options, including carotid-subclavian bypass or subclavian transposition, carotid-carotid bypass, or even carotid-carotid-subclavian bypass. Such debranching is associated with excellent long-term patency (25,26), and is then completed directly, or in a staged approach, with TEVAR. Nevertheless, open surgical debranching does involve surgical trauma, associated with complications such as stroke, nerve palsy, chyle leakage, bleeding, or graft occlusion (25,26). Therefore, options to avoid surgical debranching were explored.

In-situ laser fenestration

In-situ laser fenestration is an endovascular technique used to preserve flow to supra-aortic vessels when standard TEVAR would otherwise cover critical branches. Using a controlled laser fiber, small fenestrations are created in the stent-graft at the exact location of the branch vessel, allowing deployment of bridging stents to maintain perfusion (27). This approach is particularly valuable in urgent or emergent cases, such as acute dissections or aneurysms, where custom-made fenestrated devices are unavailable. Preoperative imaging, intraoperative fluoroscopy, and careful alignment are essential to avoid branch occlusion or type I endoleaks. Early multicenter registry data demonstrate high technical success and acceptable early mortality rates, though long-term durability and the risk of branch stent thrombosis remain under evaluation (28). *In-situ* laser fenestration offers a flexible, minimally invasive alternative to hybrid or open arch repair, expanding TEVAR applicability in anatomically challenging scenarios. Nonetheless, stent-graft integrity is altered and its long-term effects remain to be determined, with reintervention rates of approximately 5–10% (27,28).

Snorkels and chimneys

Other options to provide endovascular treatment of the aortic arch include the use of snorkels or chimneys. Initial reports in the late 2000s described the use of such parallel covered stents to preserve supra-aortic branch perfusion while extending proximal landing zones in high-risk patients unsuitable for open repair (29). These early case series established technical feasibility but raised concerns regarding gutter-related type Ia endoleaks and long-term durability. As experience expanded, multicenter registry data provided more robust evidence. Such registries reported high technical success and acceptable early outcomes, while confirming gutter endoleaks as the principal limitation (30,31). Longer-term follow-up data are limited, with most studies reporting a follow-up duration of 2 to

3 years. However, one cohort showed acceptable chimney graft patency (~90% at 5 years) and survival, supporting durability in selected patients (32). More recent systematic reviews and meta-analyses confirm that chimney/snorkel TEVAR remains a valuable and rapidly deployable option, particularly in urgent settings, but is associated with higher proximal endoleak rates compared with branched and fenestrated arch devices (33-35). Consequently, while purpose-built branched technologies are increasingly preferred in elective cases, chimney and snorkel techniques continue to play a complementary role in contemporary endovascular aortic arch repair.

Scallops

Scallops in TEVAR are pre-fabricated U-shaped cutouts in the proximal stent-graft designed to align with branch vessels, typically the LSA or left common carotid artery, allowing blood flow while achieving a secure proximal seal. Scalloped stent-grafts are particularly useful in elective cases with predictable anatomy, offering a simpler alternative to fenestrations or chimney grafts. They reduce procedural complexity and the risk of gutter-related endoleaks compared with parallel graft techniques. Precise preoperative imaging and planning are essential to ensure correct orientation of the scallop relative to branch ostia. Clinical series report high technical success, low perioperative mortality, and excellent branch patency, though the approach is limited to single or widely spaced branches and is less suitable for multiple closely spaced supra-aortic vessels (36,37). TEVAR with scallops may provide a valid solution for aortic lesions in the aortic arch located at the inner curvature. For lesions in the outer curvature it is less attractive, as the scallop would reduce proximal sealing significantly (37).

Fenestrated TEVAR

Fenestrated TEVAR for the aortic arch was developed to further increase the possibilities of total endovascular aortic arch repair. Early experience was driven by custom fenestrated devices, creating fenestrations for supra-aortic arteries, offering a total endovascular alternative to hybrid debranching or open arch repair in high-risk patients (38,39). These initial series demonstrated feasibility and improved proximal sealing compared with parallel graft techniques, though they were limited by manufacturing delays, technical complexity, elevated reintervention rates (approximately half of the included patients), and challenges in achieving precise alignment within the dynamic arch. Subsequent advancements in device design, preoperative planning with high-resolution imaging, and intraoperative guidance have improved accuracy and reproducibility. Multicenter registries and prospective studies have since reported high technical success rates (>90%), low stroke rates (~3–10%), and favorable mid-term durability, establishing fenestrated TEVAR as a viable option in selected patients (38-40). Nevertheless, this approach has been associated with higher rates of type I and III endoleaks when compared with branched TEVAR. On the other hand, fenestrated TEVAR has been associated with significantly lower stroke rates than branched TEVAR, probably due to less wire manipulation in the supra-aortic vessels. Comparable to scallops, fenestrated TEVAR is not recommended for lesions in the outer curvature of the arch, as appropriate sealing is compromised. Therefore, branched TEVAR is more often anatomically suitable for arch lesions than fenestrated TEVAR (41).

Branched TEVAR

The development of branched stent-grafts for the aortic arch represents a major step toward fully endovascular treatment of the aortic arch. Building on early experimental concepts of endovascular arch reconstruction, initial clinical applications in the early 2010s focused on custom-made, inner-branched devices designed to incorporate one or more supra-aortic vessels. Early feasibility studies demonstrated high technical success but highlighted challenges related to device complexity, vascular access (often requiring upper extremity or cervical exposure), and the risk of cerebral embolization (41,42). Additionally, one longer-term cohort including both fenestrated and branched TEVAR patients reported a reintervention rate of approximately half of the patients (38). With increasing experience, multicenter series and registries reported improved outcomes, with technical success rates exceeding 90%, stroke rates generally ranging from 3–10%, and encouraging mid-term durability (39-43). The subsequent introduction of standardized and off-the-shelf branched devices, such as single- (*Figure 1*) and double-branched arch endografts, has expanded applicability, particularly in urgent or emergent settings where custom manufacturing is not feasible (44). Contemporary data suggest that branched TEVAR provides superior proximal sealing and lower rates of type Ia endoleak compared with parallel graft techniques,

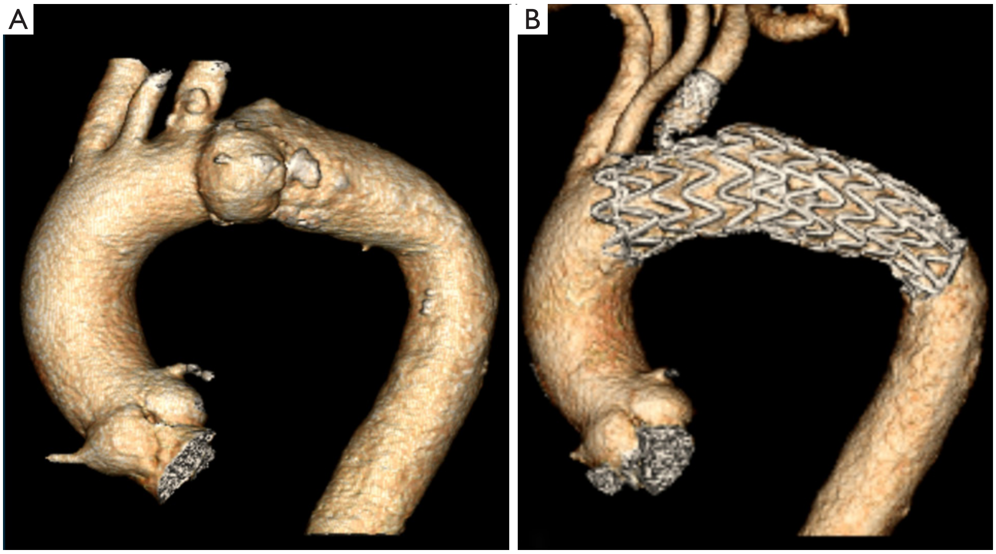

Figure 1 Three-dimensional reconstruction of pre- (A) and postoperative (B) CTA scan of a patient with a saccular distal aortic arch aneurysm treated with a single branched stent-graft (GORE TBE). CTA, computed tomography angiography.

while avoiding some of the alignment challenges of fenestrated devices (45). As a result, branched stent-grafts are increasingly considered the preferred endovascular option for elective aortic arch repair in suitable anatomy at experienced centers (*Figure 2*). However, procedural complexity, access requirements, and stroke risk remain important considerations (45).

Off-the-shelf *vs.* custom-made

An increasing number of dedicated aortic arch stent-grafts are available off-the-shelf, as TEVAR is often urgent or emergent. Off-the-shelf platforms, such as the W. L. Gore TBE and the Artivion NEXUS, offer rapid availability and standardized inner-branch configurations, making them particularly attractive in urgent or emergent settings. These devices enable timely intervention while maintaining adequate technical success in selected anatomies. However, their fixed designs may limit applicability in patients with complex arch geometry or variant supra-aortic vessel anatomy. In contrast, custom-made platforms, including the Terumo Aortic Relay Branch, Artivion NEXUS DUO and NEXUS TRE, and Cook Medical CMD devices, allow tailored configurations (such as dual/triple branches, scalloped or fenestrated designs) that enhance anatomical conformity and sealing. Similarly, systems such as the MicroPort Endovastec Cratos and Hector platforms provide customized or semi-customized multibranch options, while devices like the SB Kawasumi Najuta offer pre-shaped fenestrated alternatives. Custom-made stent-grafts offer personalized solutions, optimizing alignment and potentially reducing endoleaks. On the other hand, they are constrained by manufacturing delays and limited availability, restricting their use in acute scenarios. For such acute settings, it is advisable to have an off-the-shelf device available in specialized aortic centers.

Staged hybrid zone 2 arch replacement followed by TEVAR

Hybrid zone 2 arch replacement followed by TEVAR when indication has emerged as a solid staged strategy for managing acute type A aortic dissection, as well as complex aortic arch and proximal descending thoracic aortic disease (46). The initial open procedure establishes a durable proximal repair with supra-aortic debranching, creating an optimal landing zone for potential endovascular completion (*Figure 3*). This approach builds on the evolution of hybrid arch repair and staged elephant trunk techniques and is conceptually aligned with the frozen elephant trunk (FET) paradigm, which integrates open and endovascular principles to promote favorable aortic remodeling (47,48). However, the FET technique continues to be associated with elevated rates of spinal cord ischemia (~5%), particularly in acute type A aortic dissections (49). This is likely caused by the coverage of intercostal arteries

Figure 2 Three-dimensional CTA reconstruction of a patient with a distal aortic arch aneurysm treated with a total aortic arch endovascular repair (Terumo Relay Triple Branched prosthesis). CTA, computed tomography angiography.

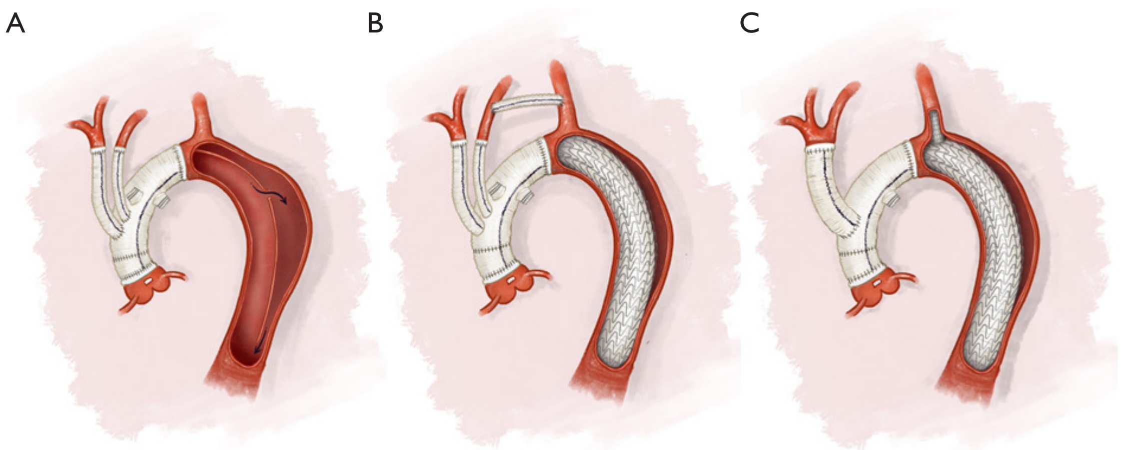

Figure 3 Illustrations of staged hybrid approach of zone 2 arch replacement with residual aortic dissection (A), followed by completion TEVAR with a straight stent-graft and cervical debranching (carotid-subclavian bypass) (B), or with a single branched stent-graft (C). TEVAR, thoracic endovascular aortic repair.

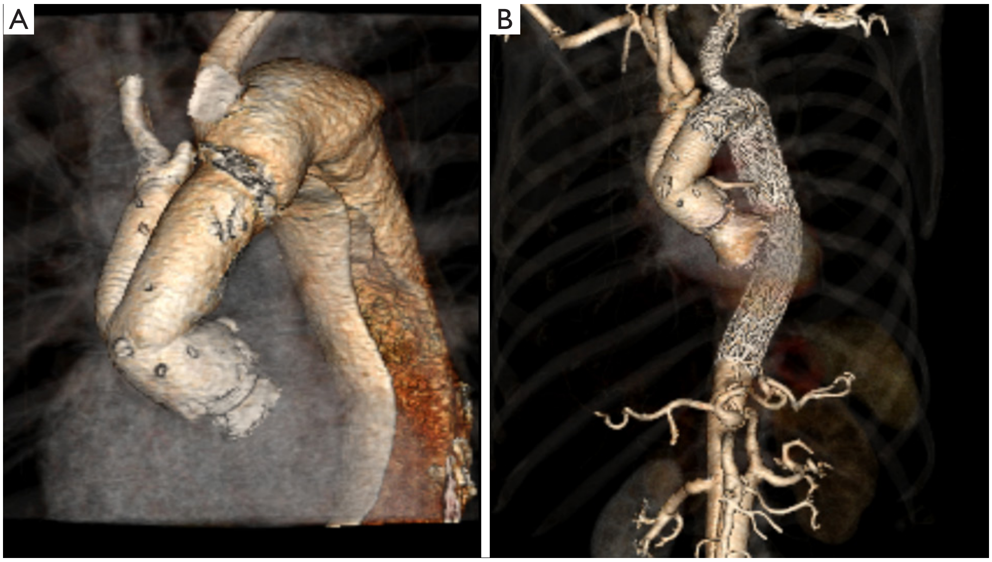

Figure 4 Three-dimensional CTA-reconstruction of a patient managed with a zone 2 arch replacement for type A aortic dissection (A). Due to progressive post-dissection dilatation completion TEVAR was conducted with a GORE TBE, extended with a GORE CTAG to complete the repair and induce further aortic remodeling (B). CTA, computed tomography angiography; TEVAR, thoracic endovascular aortic repair.

by the stent-graft, in combination with hypothermic circulatory arrest, correction of coagulopathy, hypotension, and the dissection extending to the lower extremities. With the staged approach, subsequent TEVAR is reserved only for patients demonstrating progressive distal aortic dilatation, persistent false lumen perfusion, or unfavorable remodeling, consistent with observations from studies on chronic dissection and distal aortic progression (9,50). This strategy offers several advantages, including reduced operative time, avoidance of extensive circulatory arrest, and the ability to individualize treatment based on interval imaging findings. Importantly, not all patients require second-stage TEVAR, supporting a selective, indication-based approach. A recent report shows satisfactory mid-term survival, low neurological complication rates (with 0% spinal cord ischemia), and effective aortic remodeling (46). Furthermore, with the rise of single-branched stent grafts, perfusion of the LSA is ensured without the need for other extra-anatomical bypass procedures. This results in a more straightforward completion procedure. Overall, hybrid zone 2 arch replacement with TEVAR upon indication represents a pragmatic and patient-tailored evolution of modern aortic arch surgery, balancing invasiveness with durable long-term outcomes (*Figure 4*).

TEVAR in the ascending aorta

TEVAR in the ascending aorta represents a rapidly evolving frontier in aortic intervention, driven by the need for less invasive alternatives in patients deemed at high risk for conventional open surgery. Conventional management for ascending aortic pathology, particularly acute type A dissection, has been open surgical replacement with cardiopulmonary bypass, deep hypothermic circulatory arrest, and adjunctive cerebral perfusion. However, in patients with unreasonable surgical risk, endovascular approaches have been explored as alternatives.

Limited by anatomical constraints, including proximity to the aortic valve, coronary ostia, and arch vessels, early experiences of TEVAR in the ascending aorta were confined to case reports and compassionate use scenarios (51-54). Off-label use of thoracic stent-grafts in the ascending aorta has been reported for the treatment of ascending pseudoaneurysms arising at prior surgical graft anastomoses (54). Similarly, single-branched stent-grafts have been applied in selected cases of local acute type A dissections in patients deemed unfit for surgery (*Figure 5*) (53). These early experiences illustrate the potential for expanding endovascular therapy into the proximal aorta. Dedicated device design, including

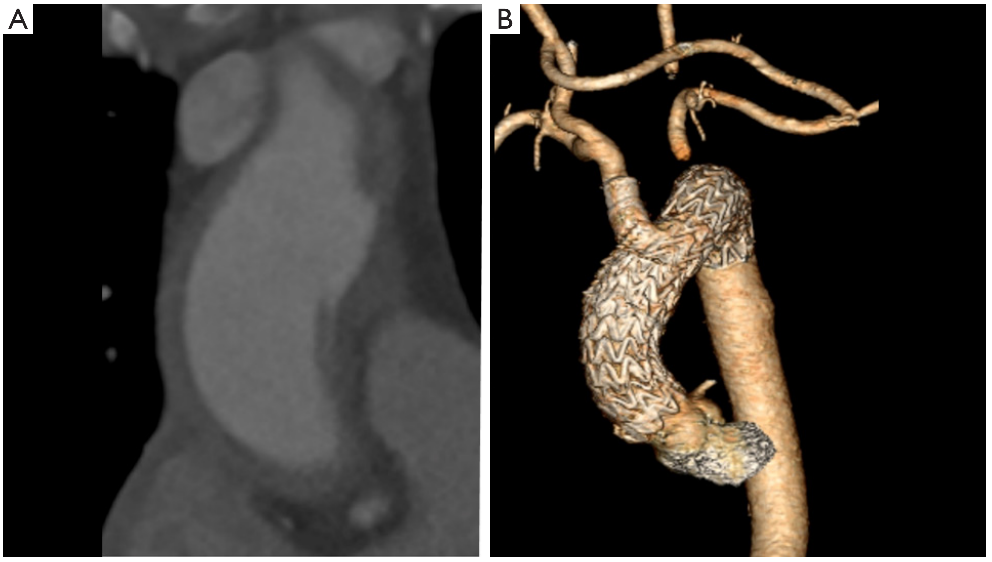

Figure 5 Pre- and post-operative 3D CTA-reconstruction of a patient with local acute type A aortic dissection (A) managed with cervical debranching (carotid-carotid-subclavian bypass) followed by implantation of a GORE TBE in zone 0, completed with a GORE CTAG to the sinotubular junction (B). 3D, three-dimensional; CTA, computed tomography angiography.

shorter length, enhanced conformability, and specialized branch configurations, is required before this approach can be widely adopted. In this context, advances in device design, imaging, and procedural planning have facilitated the development of dedicated ascending stent-graft systems. Recent prospective investigations with such devices, most notably the ARISE trial, have demonstrated the feasibility and early safety of TEVAR in carefully selected patients with ascending aortic pathology, including type A dissection and focal aneurysms (55). These findings build upon prior observational studies and registries reporting promising technical success rates and encouraging short-term outcomes, but only in highly selected cohorts (52).

Despite these advances, significant challenges remain, including device fixation, hemodynamic forces in the ascending aorta, and the risk of stroke or coronary compromise. Current evidence is therefore limited to early feasibility trials and small series, with a lack of long-term durability data. Nevertheless, TEVAR in the ascending aorta holds promise as a complementary or alternative strategy in inoperable or high-risk patients, reflecting a broader shift toward endovascular solutions across the entire thoracic aorta. Ongoing device innovation and clinical trials will be essential to define its role in routine practice.

Neurological complications

Neurological injury remains a major concern in endovascular aortic arch interventions. Stroke is the most feared complication of both hybrid and total endovascular strategies and may result from the embolization of atherosclerotic debris during arch manipulation, thrombosis at branch fenestrations or seal zones, or cerebral hypoperfusion related to supra-aortic branch coverage (56). Embolization may occur during wire or catheter manipulation, deployment of bridging stents, or interaction of the delivery system with a diseased, atheromatous arch. Patient-related risk factors include advanced age, prior cerebrovascular disease, and severe arch atheroma or calcification. Studies suggest that meticulous procedural technique, minimization of arch manipulation, the use of low-profile delivery systems, and the selective use of embolic protection devices may reduce stroke risk (56).

Spinal cord ischemia is another devastating complication of TEVAR. It presents particularly in cases involving extensive thoracic aortic coverage or in patients with prior thoracoabdominal aortic repair. Key risk factors include compromise of the collateral network, especially with coverage or occlusion of the LSA and hypogastric arteries, as well as perioperative hypotension and prolonged procedural time (57). Preventive strategies include staged aortic repair, maintenance of adequate mean arterial pressure, and preservation or revascularization of critical collateral pathways. When indicated, cerebrospinal fluid drainage should be considered as part of spinal cord protection protocols.

Impact of TEVAR on cardiovascular physiology

Beyond the anatomical and technical challenges, TEVAR appears to have an important impact on cardiovascular physiology. The proximal aorta functions as an elastic Windkessel reservoir, buffering left ventricular pulsatile output and supporting diastolic flow. By contrast, currently used thoracic stent-grafts are markedly less compliant than the native aorta, creating a compliance mismatch that increases aortic stiffness after implantation. Clinical and experimental studies have shown that TEVAR is associated with higher pulse wave velocity and adverse changes in cardiac loading conditions, with potential implications for left ventricular remodeling and long-term cardiovascular risk, particularly in patients with pre-existing cardiac dysfunction (16,58). These findings support strict blood pressure control and continued cardiac surveillance after TEVAR, especially when the proximal thoracic aorta is treated.

In small patient cohorts and experimental models, stent-graft implantation has also been shown to alter aortic deformation significantly. TEVAR reduces strain within the stented segment while increasing longitudinal and circumferential strain in adjacent unstented segments, suggesting a local strain mismatch and increased wall stress near the ends of the device (59). This biomechanical mismatch may contribute to stent graft-related complications, including retrograde dissection, stent graft-induced new entry tears, and aneurysmal degeneration in adjacent aortic segments.

Moreover, awareness should be raised regarding the hemodynamic impact of branched TEVAR. Computational studies of double-branched arch stent-grafts suggest that inner branch configuration and branch diameter can influence local flow patterns and supra-aortic branch perfusion (60,61). Such studies offer the possibility to study a large variety of side branch configurations. Significant effects have been reported of the number of side branches, as well as antegrade versus retrograde inner branch designs, on cerebral flow and potential stroke risk (61). Finally, multiple inner branches protruding into the aortic lumen may reduce the effective luminal area and could create a pseudocoarctation-like physiology, especially in patients with a narrow true lumen. Recently, we have encountered increased pressure gradients (>20 mmHg) in two patients treated with a single branched stent-graft in zone 2. Both patients had narrow true lumens, which seemed to be an important predisposing factor leading to a pseudocoarctation. After post-dilatation the gradient decreased successfully. Continuous awareness of the effects of TEVAR on normal cardiovascular physiology is vital to reduce early- and long-term complications and improve stent-graft design.

Aorta team

Management of complex aortic arch pathology requires a dedicated multidisciplinary aortic team to optimize outcomes, particularly in an era of evolving endovascular and hybrid approaches. To date, several treatment techniques are available to treat the aortic arch, arising from different medical fields (e.g., cardiothoracic surgery, vascular surgery, interventional radiology, interventional cardiology, and anesthesiology). Endovascular repair of the aortic arch is particularly complex due to anatomical variability, supra-aortic branch involvement, and the need for precise cerebral protection strategies. Combined expertise from different fields may strengthen each other to optimize patient safety. As an example, experiences from transcatheter aortic valve implantation are of great value for safe passage of the aortic valve during TEVAR in the ascending aorta, but also for controlling cardiac output using rapid pacing. Moreover, advanced wire skills in the aortic arch reduce the risk of stroke and aortic dissection. Detailed preoperative planning together with a radiologist, including analysis of the supra-aortic vessels and cerebral vascularization (such as an isolated vertebral artery or the circle of Willis), are also of vital importance to reduce complication rates. A multidisciplinary aortic team is able to combine all such experiences and techniques within one team. By weighing the benefits and risks per treatment option, a shared decision should be made together with the patient. As also stated in recent guidelines, outcomes improve in specialized centers where multidisciplinary teams can tailor therapy, ensure procedural safety, and provide longitudinal surveillance (9,62). This highlights that successful aortic arch repair is not solely a technical achievement but a coordinated team effort. If a medical center is limited regarding open- and endovascular aortic arch repairs, close collaboration with a specialized aortic center is recommended. Finally, emerging data suggest improvements in outcomes when complex care, such as aortic arch repair, is performed in high-volume centers. Therefore, an individualized strategy performed in high-volume aortic centers that master multiple treatment techniques is favorable.

Future perspectives

The field of endovascular arch repair continues to evolve rapidly. Next-generation devices include off-the-shelf multibranched stent-grafts, modular delivery platforms, and adaptive sealing technologies designed to simplify planning and broaden anatomical applicability. Dedicated ascending and aortic arch devices with improved conformability and fixation are also under development.

Future developments regarding optimized pre- and perioperative imaging include intraprocedural fusion imaging and computational fluid dynamics, leading to optimized stent-graft orientation and reduced contrast and radiation exposure.

Finally, emerging innovations such as bioresorbable scaffolds, shape-adaptive sealing zones, and robotic delivery systems may further improve the safety and durability of endovascular arch repair. Prospective clinical trials, long-term registry data, and standardized outcome reporting are critical for defining device performance, neurological risk, reintervention rates, and patient selection criteria.

Conclusions

Endovascular technologies have significantly expanded therapeutic options for patients with aortic arch pathology. Hybrid strategies, branched- and fenestrated stent-grafts, and emerging stent-graft designs now enable treatment of increasingly complex lesions, while potentially reducing morbidity and mortality associated with open surgery. Although open arch replacement remains the gold standard for many patients, endovascular approaches play an increasingly important role in carefully selected individuals. Continued technological innovation, rigorous imaging and procedural planning, and accumulation of long-term clinical data will further define the role of endovascular therapy in contemporary aortic practice.

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Footnote

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