Endovascular Aortic Arch Repair of Aortic Arch Lesions Using Hybrid Extra-Anatomic Reconstruction or Three-Vessel Branched Endografts

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Abstract: Significant developments and innovation have expanded the indications of endovascular aortic repair to include patients with aortic disease that involves the aortic arch. In these patients, open surgical repair continues to be the gold standard against which endovascular methods must be compared, providing durable reconstruction with excellent results in high-volume centers. However, open surgical repair is primarily reserved for good-risk patients who can tolerate median sternotomy, cardiopulmonary bypass, and deep hypothermic circulatory arrest. The older or high-risk patient is at higher risk of morbidity and mortality with open surgical repair. Techniques of endovascular repair of aortic arch lesions evolved from the extensive experience accumulated in the descending thoracic and abdominal aorta. Both hybrid repair and total endovascular arch repair allow for a minimally invasive option that expands the suitability of aortic repair to medically and anatomically unfavorable patient populations. The aim of this article is to review the technical aspects and outcomes of hybrid repair using extra-anatomic bypass and total endovascular repair with branched endografts.

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Introduction

Aortic arch diseases have been traditionally treated with open surgical repair, which remains the gold standard against which novel endovascular approaches must be compared.[1,2] Several adjuncts, including selective antegrade cerebral perfusion, shorter cardiac arrest times, optimized temperature control, and improved organ monitoring contribute to improved outcomes of open surgical total arch reconstructions.[3-5] Despite the favorable outcomes in lower-risk groups, however, mortality and neurological complications remain significant concerns with high variation between centers. In a meta-analysis, Takagi and colleagues reported 15 studies and 1,279 patients treated by frozen elephant trunk with an average operative mortality of 9% (ranging from 0% to 19%) and a stroke rate of 5% (ranging from 0% to 16%).[6] Urbanski and colleagues emphasized that institution and surgeon experience, patient age, and prior arch repair via median sternotomy are all independently associated with increased 30-day mortality.[7]

Endovascular aortic repair has evolved in the last 2 decades, becoming the first line of treatment in most patients with descending thoracic or abdominal aneurysms. Recent advances in fenestrated and branched stent-graft technology have expanded the indications of endovascular approaches to complex aneurysms involving the renal and mesenteric arteries.[8-10] The aortic arch poses a special challenge because of involvement of the supra-aortic trunks, proximity to the aortic valve and coronary arteries, and the inherent risk of cerebral emboli from catheter and stent manipulations. In these patients, hybrid reconstructions and total endovascular repair have been increasingly utilized to treat patients with dissections and degenerative aneurysms, offering a less invasive approach to patients previously considered unfit for open surgical repair, including older, higher-risk patients and those with hostile anatomy. The hybrid approach involves open surgical debranching based on cervical or aortic extra-anatomic reconstructions of one or more supra-aortic branches, followed by endovascular exclusion of the aneurysm. Total endovascular repair utilizes specially designed fenestrated and branched stent grafts with one to three vessel incorporation.[11] In the last decade, increasing experience has been gained using total endovascular approach with a patient-specific 3-vessel branched stent graft (Cook Medical).[12,13]

Anatomic Considerations

The aortic arch is a particularly challenging area to treat due to its angled nature, position and variations of the supra-aortic branch vessels, aortic pulsatility, respiratory motion, and proximity to the aortic valve and coronary arteries. Similar to other segments of the aorta, selection of the proximal sealing zone is the single most important determinant of long-term durability.[14,15]

Anatomic requirements for total endovascular arch repair using a 3-vessel arch branched stent graft include suitable supra-aortic branch vessels without involvement by dissection and with diameters of 8 mm to 20 mm. The proximal landing zone in the ascending aorta should be longer than 20 mm in length (ideally 40 mm), with a diameter less than 38 mm and without any thrombus or calcification. The distance from the sinotubular junction to the innominate artery should be at least 50 mm. The distal sealing requires a minimum length of 20 mm with a diameter of 18 mm to 38 mm.

The supra-aortic target vessels also need to provide proper sealing without dissection, stenosis, atherosclerotic disease, or excessive angulation. An innominate artery with at least 20 mm of sealing length and with less than 20 mm of diameter is recommended. The left subclavian artery (LSA) and left common carotid artery (LCCA) should be compatible with diameter requirements for commercially bridging stent grafts.[13,16]

Suitable access via the iliofemoral arteries is of paramount importance for both hybrid and total endovascular repair, which usually requires larger profile sheaths, ranging from 20 to 26 Fr. Analysis of computed tomography angiography (CTA) should identify access issues such as stenosis, tortuosity, and heavily calcified or narrow arteries. Anticipation of technical issues should prompt creation of an open surgical or endovascular conduit to prevent inadvertent disruption of the iliac arteries during the procedure, which leads to severe hypotension and high risk of neurological complications.[17] Similarly, involvement of the supra-aortic trunks by dissection may require staged procedures to replace the vessel and facilitate an adequate seal at the time of definitive endovascular repair.

Hybrid Repair

Hybrid arch repair combines open surgical revascularization of the supra-aortic trunk vessels with endovascular exclusion of the arch lesion using stent grafts. The fundamental principle of this approach is to create an adequate proximal landing zone by moving the arch vessels proximally in the aorta using either an aortic- or cervical-based reconstruction.

Aortic-based reconstructions require median sternotomy with reconstruction of innominate arteries, carotid arteries, and LSAs with or without concomitant repair of the ascending aorta.[18] A type 1 arch repair is described as aortoinnominate and left carotid bypass with endovascular repair of the aortic arch. In these patients, a suitable landing zone is present in the ascending aorta distal to the aortic graft. The reconstruction requires partial aortic clamping and avoids complete aortic cross-clamping and cardiopulmonary bypass.[19] Conversely, a type 2 repair requires open surgical reconstruction of the ascending aorta to provide a site for the aortic graft to the supra-aortic trunks, as well as the proximal landing zone for the stent graft. A type 3 repair is described as total arch replacement with an elephant trunk procedure combined with placement of a thoracic stent graft. This technique is useful in patients with extensive aortic lesions that involve the ascending, transverse arch, and segments of the descending thoracic or thoracoabdominal aorta. Because all these arch repairs require an intrathoracic approach, the revascularization of the great vessels is often performed in an anatomic fashion.

Extra-thoracic options imply the presence of a suitable segment of healthy aorta between zones 1 and 3. The LCCA and LSA are the most frequent vessels requiring revascularization, which is usually done using cervical incisions. The most frequent procedure is a left carotid-subclavian bypass or transposition. For Zone 1 landing, reconstruction of the LCCA and LSA based on the right CCA with either pretracheal or retropharyngeal tunnel is needed. Cervical debranching may also be used in conjunction with a single- or double-arch branch stent. The Valiant Mona LSA device (Medtronic) and TAG thoracic branch endoprosthesis (TBE) (Gore) thoracic stent grafts have a single branch, most often used for the LSA.[20] The TBE is also used for the innominate artery, which requires total cervical debranching. Use of these devices in zone 1 is infrequent because of the proximity between the innominate artery and LCCA. The Nexus aortic arch stent graft system (Endospan) has a single branch for the innominate artery, thereby requiring reconstruction of both the LCCA and LSA, akin to what is done with zone 0 TBE.[21] Other devices with 2 branches designed for the innominate and LCCA include the Zenith double inner-branched device (Cook Medical) and the Relay device with dual branches (Terumo Aortic).[22] In both cases, LSA revascularization is usually done using bypass or transposition. Other iterations of fenestrated and scalloped stent grafts have also been used but are less favored due to potential difficulty to orient the device in the aortic arch, which may require more manipulation and a higher risk of stroke.

LSA Revascularization

Revascularization of the LSA can be performed with either a left carotid-subclavian bypass or subclavian-to-carotid transposition. Both procedures are approached via a supraclavicular incision with division of the clavicular head of sternocleidomastoid muscle. The anterior scalene fat pad is retracted cephalad to uncover the anterior scalene muscle, which is transected. The phrenic nerve is identified and protected. The distal subclavian artery is dissected free distal to the vertebral and internal mammary arteries. Transposition requires a more extensive dissection of the LSA at least 1 or 2 cm proximal to the origin of the left vertebral artery. The bypass is done using an 8-mm polyester graft (less often 7 mm), which does not need to be externally supported. After systemic heparinization, proximal and distal control is obtained in the LSA. A small longitudinal arteriotomy is made, and the 8-mm polyester graft is spatulated and anastomosed end-to-side with 6-0 Prolene sutures. The anastomosis is initiated at the heel with a running suture and worked toward the middle. Three interrupted sutures are used at the toe of the anastomosis to avoid stenosis. These sutures are run toward the middle to complete the anastomosis, which is tested by flushing the graft with heparinized saline. The flow is then restored to the left upper extremity. The clamp is applied into the graft, adjacent to the anastomosis. The polyester graft is then routed behind the internal jugular vein and in front of the vagus nerve. The left common carotid artery is clamped proximally and distally. A lateral longitudinal arteriotomy is made. The graft is cut to length and anastomosed end-to-side using running 5-0 Prolene sutures, starting in the middle of the posterior wall and running toward the corners. Each corner is interrupted to avoid a purse-string effect in the anastomosis. The anastomosis is then de-aired, and the flow is restored first toward the LSA, and then into the LCCA. The proximal subclavian artery is occluded using an Amplatzer vascular plug (Abbott), which is typically introduced via a small incision and puncture in the distal left brachial artery. Although LSA transposition is a durable alternative in young patients, it is less favored due to more extensive dissection and the need to clamp the LSA proximal to the vertebral and left internal mammary artery. This avoids the need for a prosthetic conduit and uses a single anastomosis.[22] The LSA stump is closed in 2 layers of running 4-0 Prolene sutures. The LCCA is test clamped, and the anastomosis of the LSA to the LCCA is performed in running and interrupted 5-0 or 6-0 polypropylene sutures in the posterior wall. Interrupted sutures are preferred in the anterior wall to avoid narrowing. The anastomosis is then de-aired and interrogated for patency.

LCCA Revascularization

Revascularization of the LCCA may be achieved using several configurations that avoid the thoracotomy, but our preference is for a right carotid to left subclavian bypass with reimplantation of the LCCA using retropharyngeal tunnel. The RCCA is surgically exposed via a right oblique cervical incision. The LCCA and LSA are exposed as detailed previously, using a left supraclavicular incision. The graft can be routed anterior to the trachea or behind the esophagus. We avoid using pretracheal tunnel due to the risk of tracheostomy. To decrease this risk of dysphagia and esophageal injury, the graft should be tension-free and the tunnel needs to be created close to the vertebral ligaments and away from the esophagus. First, the 8-mm polyester graft is anastomosed to the LSA. Flow is then restored into the left arm. Then the graft is tunneled behind the left internal jugular vein and behind the esophagus. The LCCA is tested, transected, and oversewn proximally with running 4-0 Prolene sutures. A small graftotomy is made in the upper portion of the graft, and the LCCA is anastomosed end-to-side using running 5-0 Prolene sutures for the posterior layer and interrupted 5-0 Prolene sutures for the anterior layer. Flow is then restored to the LCCA, and the clamp is transferred to the graft just beyond the carotid anastomosis. Finally, the last anastomosis is performed end-to-side to the right common carotid artery using running 5-0 Prolene sutures. Once flow is restored, the proximal LSA is occluded using an Amplatzer vascular plug.

Three-Vessel Endovascular Repair

The procedure is performed in a hybrid operating room with fixed imaging, onlay fusion of preoperative computed tomography angiography, and high-definition cone beam computed tomography. Bilateral percutaneous femoral access is obtained whenever possible using preclosure technique. Small bilateral cervical incisions for exposure and sequential clamping of the common carotid arteries are usually done, although recently total percutaneous femoral or axillary access has also been used to avoid the cervical incisions.[23] The patient is systemically heparinized to achieve an activated clotting time >300 seconds. The stent graft is flushed with carbon dioxide, which is then flushed with heparinized saline to minimize risk of cerebral air embolism.[24] A 300-cm Lunderquist wire (Cook Medical) is carefully advanced across the aortic valve and positioned in the left ventricle. The device is introduced via the Lunderquist wire across the aortic valve. It is crucial to accurately align the device in the aortic arch to avoid disastrous complications such as coronary artery occlusion, coverage or misalignment of supra-aortic branch vessels, or injury to the aortic valve and ventricle. To facilitate precise deployment, cardiac output is decreased using rapid ventricular pacing (less often, inferior vena cava occlusion), Valsalva maneuver or pharmacologic cardiac arrest may be used during stent graft deployment. Cardiac function is resumed immediately following stent graft deployment and removal of the diameter-reducing ties. The delivery system and the Lunderquist wire are removed from the left ventricle and partially withdrawn to the thoracic aorta.

Sequential stenting of the supra-aortic trunks is performed starting with the innominate artery. To minimize the risk of distal embolization, the RCCA is clamped, followed by catheterization of the antegrade inner branch. Confirmation of successful catheterization can be done using intravascular ultrasound, balloon, or a curved catheter. A patient-specific stent graft is deployed in the innominate artery, followed by balloon angioplasty of the attachment areas, completion angiography, flushing of the carotid artery, and repair of the arteriotomy with interrupted 5-0 Prolene sutures. The same steps are followed for the LCCA. A Lunderquist wire is advanced via the preloaded catheter, which allows access into the left subclavian retrograde inner branch. The stent graft delivery system is removed and exchanged for a 22 Fr DrySeal Flex sheath (Gore). A 10 Fr 80-cm long Flexor sheath (Cook Medical) is introduced into the LSA inner branch, followed by catheterization of the LSA with a soft-angled Glidewire (Terumo Interventional Systems) and a 5 Fr catheter. After the guidewire is exchanged for a Amplatz wire, the repair is extended to the LSA using a self-expandable stent graft, which is deployed just proximal to the origin of the left vertebral artery. Completion LSA angiography is performed to exclude dissection, distal embolization, stent kink, or endoleak. A distal thoracic stent graft extension may be needed in patients with extensive thoracic or thoracoabdominal disease. A completion cone-beam CT with rotational subtraction angiography with and without contrast is performed to evaluate structural defects of the stent graft and the bridging stents, dissection, stenosis, and endoleaks.

Outcomes

Hybrid vs Total Open Repair

The Society of Thoracic Surgeons (STS) Adult Cardiac Surgery Database was queried for elective total open arch repair and hybrid arch procedures in a study that included a total of 1,011 patients treated by open surgical repair in 884 patients and hybrid repair in 127.[25] Open surgical repair patients were younger (63 vs 67 years-old; *P*=.001) and had less peripheral vascular disease (34% vs 50%; *P*=.001) and preoperative dialysis (1.7 vs 4.7%; *P*=.026). Composite mortality and stroke were significantly lower with open repair (11.4% vs 23.6%; *P*<.001), even after risk adjustment, advocating for careful adoption of hybrid strategies. A meta-analysis of comparative studies of open arch replacement versus hybrid repair revealed no significant difference in operative mortality (6 % vs 9 %, odds ratio [OR] 0.67; *P*=.66) and neurological events (12 % vs 6 %, OR 1.93; *P*=.99) between the two approaches in 378 patients.[26] The major limitations of these results are that they likely involve relevant selection bias, reflecting the absence of prospective randomized data and the great heterogeneity among the types of procedures considered as hybrid repair.

Hybrid Arch Repair

For elective endovascular repair of thoracic or thoracoabdominal aortic aneurysm, where coverage of the LSA is necessary for adequate stent graft seal, the guidelines of the Society for Vascular Surgery[27] suggest preoperative or concomitant LSA revascularization (Recommendation Grade 1; Quality of Evidence B). For patients in whom the anatomy to be treated compromises perfusion to vital structures, the guidelines also recommend LSA revascularization (Recommendation Grade 1; Quality of Evidence B). These circumstances include the following: (a) presence of a patent left internal mammary artery to coronary artery bypass graft; (b) termination of the left vertebral artery into the posterior inferior cerebellar artery; (c) absent, atretic, or occluded right vertebral artery; (d) patent left arm arteriovenous shunt for dialysis; (e) prior infrarenal aortic operation or endovascular aneurysm repair (EVAR) with previously ligated or covered lumbar and middle sacral arteries; (f) planned extensive coverage (>15 cm) of the distal thoracic aorta; (g) hypogastric artery occlusion or significant occlusive disease; (h) presence of aneurysm disease in the young patient, for whom future therapy involving the distal thoracic aorta may be necessary.

Brusa and colleagues[28] reported on 48 patients treated by 25 (52%) carotid-subclavian bypass and 23 (48%) carotid-subclavian transposition with thoracic EVAR (TEVAR) performed simultaneously in 39 (81%) patients (11 of them in an emergent setting). Reintervention rate at 30 days was 15%. After a median follow-up of 38 months, there were no further reinterventions or occlusions, and no graft infections. Primary patency was 90% and primary assisted patency 98%.

A recent retrospective cohort study reviewed LSA revascularization methods,[29] including direct coverage without revascularization in 28 patients (16%), carotid-subclavian bypass in 100 (58%), and fenestrated TEVAR in 43 (25%). Vessel incorporation by endovascular repair, such as in fenestrated TEVAR (F-TEVAR), means focusing on branch vessel preservation instead of debranching. The incidence of postoperative spinal cord ischemia was significantly higher in patients who had no LSA revascularization compared with those who had revascularization (10.7% vs 1.4%; *P*=.032). During a mean follow-up of 25 months, there was no difference in 30-day and mid-term rates of mortality, stroke, and left upper extremity ischemia between carotid-subclavian bypass and F-TEVAR, with F-TEVAR offering a less time-consuming and minimally invasive alternative.

A definitive comparison of hybrid vs other types of arch repair is limited by several factors. Most studies available are of unicentric retrospective nature. There is also considerable heterogeneity among the types of repairs that are combined.[18] Despite great variations in the surgical approach (proximal debranching and elephant trunk procedures require thoracotomy and intrathoracic ascending aorta-based debranching, while distal debranching can be performed by cervical extra-anatomical bypasses), these procedures should not be used for the same indications. Hybrid procedures with distal debranching can also be performed with several combinations of endografts and extra-anatomic revascularizations, contributing to high heterogeneity. A meta-analysis concerning hybrid aortic arch debranching procedures included 122 patients with type 1 and 40 patients with type 2 hybrid approach.[30] For type 1, the pooled endoleak rate was 11%, 30-day or in-hospital mortality was 4%, stroke rate was 4%, and weighted permanent paraplegia rate was 2.4%. For type 2, the endoleak rate was 12.5%, 30-day or in-hospital mortality rate was 5%, stroke rate was 2.5%, no permanent paraplegia was noticed, and late mortality rate was 12.5%. A former meta-analysis by Moulakakis et al[18] included 46 studies including 2,272 patients treated by hybrid aortic arch reconstruction. The study included patients who had arch debranching, elephant trunk with endovascular completion, and frozen elephant trunk. Of these, 26 studies reported a total of 956 patients who had arch debranching done in Zone 0 in 42%, Zone 1 in 29%, and Zone 2 in 29%. Overall technical success was 93%, and pooled perioperative mortality was 12%. Retrograde dissections were noted in 4.5%. Perioperative cerebrovascular event and irreversible paraplegia occurred in 7.6% and 3.6%, respectively. After a mean follow-up of 22 months, 17% of the patients had endoleaks (106 type 1, 51 type 2, and 8 type 3). Another review of the literature up to 2012 by Rana MA et al[31] of 255 patients undergoing hybrid aortic arch reconstructions revealed technical success of 97% and 30-day mortality of 6%. Stroke and spinal cord injury were reported in 2% and 1.5% of the patients, respectively. The total endoleak frequency was 6%. These outcomes were comparable with contemporary results from total open and total endovascular reconstructions in spite of the fact that the hybrid approach is generally taken in patients with high surgical risk for open repair and with prohibitive anatomy for total endovascular repair.

Increasing experience and refinements in stent graft design and delivery system have lowered morbidity and mortality, rivaling the outcomes of open surgical repair in lower-risk patients.[32,33] The largest experience, with 70 patients treated with double-arch branch stent grafts and left LSA debranching, showed 30-day mortality and stroke rate of 3% each.[34] Although LSA reconstruction is associated with low mortality, phrenic nerve injury occurs in up to 25% of patients and local bleeding complications in up to 11%.[35,36]

Total Endovascular Arch Repair

Endovascular arch repair using 3-vessel inner branch stent grafts is a recent technique with few reported patients and short-term follow-up. Tenorio et al reported in a multicenter early feasibility study 39 patients treated with the 3-vessel arch stent graft for 14 degenerative aneurysms and 25 chronic post-dissection arch aneurysms. Technical success was 100%, 30-day or in-hospital mortality, and stroke rate was 5%. The combined mortality and stroke rate was 8%, and the reintervention rate was 32% in a mean follow-up to 3.2 months. These were promising outcomes when compared with open surgical repair in high-risk patients; however, the high reintervention rates reveal that a larger experience with this approach is required.[13]

Conclusion

Arch debranching with endovascular exclusion and total endovascular repair are alternatives to open arch reconstruction in high-risk patients. Despite the operative advantages, debranching carries a persistent high risk of perioperative mortality and neurological complications. The preliminary results of the total endovascular repair are promising, but this technology is still taking its first steps and larger series are needed. ■

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