

# Hybrid repair of aortic arch aneurysms: a comprehensive review

Steve Xydas<sup>1</sup>, Christos G. Mihos<sup>2</sup>, Roy F. Williams<sup>1</sup>, Angelo LaPietra<sup>1</sup>, Maurice Mawad<sup>1</sup>, S. Howard Wittels<sup>3</sup>, Orlando Santana<sup>4</sup>

<sup>1</sup>The Columbia University Division of Cardiac Surgery, Mount Sinai Medical Center, Miami Beach, FL, USA; <sup>2</sup>Cardiac Ultrasound Laboratory, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA; <sup>3</sup>The Department of Anesthesia, Mount Sinai Medical Center, Miami Beach, FL, USA; <sup>4</sup>The Columbia University Division of Cardiology, The Mount Sinai Heart Institute, Miami Beach, FL, USA

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*Correspondence to:* Steve Xydas, MD. Chief of Cardiac Surgery, The Columbia University Division of Cardiac Surgery, Mount Sinai Medical Center, 4300 Alton Road, Suite 2110, Miami Beach, Florida 33140, USA. Email: stevexydas@gmail.com.

**Abstract:** Open total arch replacement (TAR) has become safer with refinements in cerebral protection techniques. The frequent extension of aortic arch aneurysms into the descending thoracic aorta customarily requires a two-staged conventional elephant trunk procedure, carrying relatively high mortality and morbidity risks and high rates of rupture in the interval between the two open surgeries. The technical demands and invasive nature of TAR has therefore precluded many high-risk patients from being surgical candidates for aneurysm repair. As a result, hybrid techniques and approaches to the aortic arch have become common since the adoption of thoracic endovascular aortic repair (TEVAR) and advancement in the commercial grafts that are available. The results of hybrid aortic arch repairs have been encouraging, though with higher rates of re-interventions than TAR and variable reported rates of stroke and spinal cord ischemia. The aim of this publication is to review the current literature on hybrid repair of aortic arch aneurysms.

**Keywords:** Aortic arch aneurysms; hybrid aortic arch repair; total aortic arch replacement (TAR); frozen elephant trunk (FET)

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## Introduction

Aortic arch aneurysms frequently also involve the ascending and/or the descending thoracic aorta, making aneurysm repairs complex. Open total aortic arch replacement (TAR) typically requires a long period of hypothermic circulatory arrest and a 2 staged operation for repair. An elephant trunk repair was first described by Borst and colleagues in 1983 for extensive aneurysms involving both the aortic arch and the descending thoracic area (1). These complex, staged operations carry substantial perioperative mortality risk, as well as significant risks of interval aneurysmal rupture between the staged operative interventions (2,3). Neuroprotection techniques have evolved and been refined, improving the mortality and stroke risk associated with

total TAR. Advances have included selective antegrade and retrograde cerebral perfusion techniques for maintaining cerebral perfusion during periods of circulatory arrest, as well as the use of deep hypothermia.

Since the introduction of thoracic endovascular aortic repair (TEVAR) in the early 1990's (4), the less invasive endovascular approach to descending and thoracoabdominal aneurysms have been advanced with the commercial availability of different types of thoracic stent grafts. Related to the morbid invasiveness and complexity of open arch surgical techniques, hybrid aortic arch repairs have been developed incorporating the use of TEVAR with a conventional elephant trunk repair, or combined with an open debranching of the cerebral vessels, frequently in combination with a left carotid subclavian bypass (5,6). This

has simplified aortic arch reconstruction and made aortic arch repair feasible in high-risk individuals with comorbid conditions. No randomized control trial has been performed comparing TAR and hybrid aortic arch repair, though hybrid aortic arch repair has become commonplace. This study reviews the current literature on hybrid approaches to aortic arch aneurysm repair.

### Selective antegrade cerebral perfusion (SACP)

The use of SACP requires either direct cannulation or cannulation of a constructed side graft on the right axillary or innominate artery, but has also been described with use of both axillary arteries in cases entailing extensive circulatory arrest periods. In its most common form, an 8 or 10 mm Dacron graft is sewn end-to-side to the right axillary artery. Cardiopulmonary bypass flow through an arterial cannula placed within this axillary artery graft provides a peripheral site of cannulation and unencumbered access to the ascending aorta and aortic arch during aneurysm repair. The added advantage is that during the circulatory arrest period, a vascular clamp placed through the median sternotomy approach on the proximal innominate artery allows for selective flow via the axillary artery cannula in an antegrade fashion into the right carotid artery and typically perfuses the entire cerebral circulation if there is an intact circle of Willis.

Flow rates of 10 cc/kg/min are instituted during the SACP period, and in our institutional experience, can be safely increased to 12–15 cc/kg/min (particularly with a bovine arch anatomy) to maintain a mean arterial pressure of 65 mmHg in the right radial arterial line. Axillary artery cannulation has been shown to improve survival and neurologic outcome with complex atherosclerotic aneurysm repairs, as well as with acute type A dissection repairs (7,8). Adoption of SACP with TAR allows for cerebral flow during the extensive circulatory arrest period often necessary to perform the distal aortic anastomosis and separate end-to-end anastomoses to each of the head vessels. SACP has also been adapted as part of hybrid aortic repairs to reduce, or eliminate the total circulatory arrest period (6).

### Retrograde cerebral perfusion

Retrograde cerebral perfusion was first described by Lemole and colleagues in 1982 (9), and later espoused and refined by Ueda and colleagues (10). With a separate arterial line into the superior vena cava, retrograde flow can be continuously run through the cerebral circulation during periods of

circulatory arrest with a superior vena cava snare placed at the junction of the right atrium. Central venous pressure is monitored and kept less than 20 mmHg during periods of retrograde cerebral perfusion. This technique has been shown to decrease stroke risk and improve mortality, likely by reducing air and debris from embolizing to the brain during TAR, and is a valuable adjunct for neuroprotection during aortic arch surgery (11,12).

### Hybrid aortic arch replacement

Hybrid aortic arch repairs have been developed incorporating the use of TEVAR with a conventional elephant trunk repair (5), in lieu of an open left thoracotomy to complete the distal aneurysm repair. Since TEVAR is generally well-tolerated, patients can undergo the second stage of the elephant trunk procedure earlier in their convalescence period, reducing the risk of rupture during this interval. TEVAR can also be combined with an open debranching of the cerebral vessels, frequently in combination with a left carotid subclavian bypass, in a hybrid approach to the aortic arch (6). The benefit of a left carotid subclavian bypass procedure is that only two cerebral vessels (the innominate and left common carotid artery) need to be addressed at the time of the aortic arch repair, decreasing cerebral ischemia. During TAR, the left subclavian artery is often the deepest and most difficult anastomosis to perform; given it is a quite posterior structure. The left carotid subclavian bypass can be done immediately before the debranching procedure (as part of a combined procedure) or 1–2 days prior to the arch reconstruction.

Several iterations and variations of a hybrid aortic arch repair have been proposed, depending on the aneurysm extent and location of the proximal landing zone. Criado and colleagues created definitions for the proximal landing zone, defined as zone 0 (proximal to the innominate artery), zone 1 (between the innominate and left common carotid artery), zone 2 (between the left common carotid and subclavian arteries), and zone 3 (distal of the left subclavian artery) (13). Zone 1 through 3 procedures frequently can be performed with extra-anatomic bypasses to the head vessels with subsequent TEVAR, without sternotomy and open debranching. We will focus our discussion to zone 0 procedures in which the entire aortic arch requires reconstruction and how this compares to TAR.

### Frozen elephant trunk (FET)

The combination of a proximal aortic arch reconstruction

with an antegrade TEVAR deployment was first described by Kato and colleagues in 1996 (14), and the technique was subsequently termed a “FET” (15). This hybrid aortic arch repair technique has been refined to utilize a short TEVAR device which anchors in the native distal aortic arch. This creates a proximal landing zone should further extension be required at a later time related to more distal aneurysmal degeneration of the descending thoracic aorta. The staged extension and distal aortic coverage with subsequent TEVAR devices may also reduce the incidence of spinal ischemia and paralysis by allowing time for a collateral network of the spinal circulation to develop (16).

In a case series of 51 patients undergoing a FET between 2006 and 2013, the 30-day mortality rate was 7.8% (17). Stroke occurred, however, in 11.8% (n=6) and paraplegia in 19.6% (n=10). The estimated 1- and 5-year survival rate was  $80.2\% \pm 5.5\%$  and  $59.7\% \pm 10.2\%$ , respectively. The authors cautioned concerning the high rates of neurologic complications associated with FET, and found a prolonged circulatory arrest time (>45 min) in combination with core body temperature  $\geq 28^\circ\text{C}$  to be an independent predictor of paraplegia (OR =4.8, P=0.04). Based on these findings, the authors recommended deep hypothermic arrest in patients who were expected to have prolonged circulatory arrest times.

A meta-analysis by Tian and colleagues examined 17 observational reports of the FET technique in hybrid aortic arch repairs (18). The pooled mortality was 8.3%, strokes occurred in 4.9% and spinal cord injury in 5.1%. The cardiopulmonary bypass, myocardial ischemia and circulatory arrest times all correlated with perioperative mortality in a linear relationship. The 5-year mortality ranged from 63% to 88%, suggesting that the FET procedure can be done safely with acceptable mortality and morbidity.

The advantages of the use of a novel Thoraflex hybrid graft (Vascutek, Scotland) consisting of a four-branch arch graft with a stent graft at its distal end has been demonstrated (19). It allows for a FET hybrid repair in a single stage operation to complete total arch reconstruction. In the “first in man” study of 34 patients, the hybrid arch repair was completed in all patients. The patients comprised 18 with acute type A dissection and 16 with elective indications for surgery. There were 3 deaths (8.8%), though all were in the setting of emergent type A dissection repairs. This allowed for total hybrid arch reconstruction in one stage, with an average of  $48 \pm 22$  minutes of circulatory arrest time. However, the follow-up was short in these patients. This hybrid graft is now under formal clinical investigation in the United States (20).

### Comparisons with TAR

No randomized control trials have been performed comparing TAR with hybrid aortic arch repairs. In addition, most case series of hybrid aortic arch repairs have comprised high-risk patients, making comparison with historical TAR control groups challenging due to selection bias. In a propensity score-matched analysis, the results of 143 TAR were compared with 50 patients undergoing hybrid aortic arch repair, with a mean follow-up of 25 months (21). Of these hybrid repairs, only 14 were zone 0 repairs, with the remainder comprising zone 1 and zone 2 repairs without need for open debranching. The 30-day mortality was similar between the open and hybrid patients (3% vs. 2%, P=0.76), though the hybrid arch patients had significantly shorter intensive care unit (P<0.001) and hospital (P=0.015) lengths of stay. The hybrid arch patients did have a higher rate of re-intervention at 3 years (20% vs. 1%, P<0.001,) mostly related to endoleaks. Based on this study, hybrid aortic repair patients did appear to recover sooner than TAR; however, this was at the cost of higher re-intervention rates.

In a meta-analysis of four observational studies comparing TAR with hybrid aortic arch repair in a total of 378 patients, the operative mortality was not improved with hybrid aortic arch repair (OR =0.67, P=0.92) (22). There were non-significant increases in permanent neurologic deficit with hybrid repairs vs. TAR (OR =1.93, P=0.10) and late mortality (OR =1.73, P=0.10).

In another propensity score-matched analysis, Tokuda and colleagues examined 124 patients undergoing TAR and compared them to 58 high-risk patients who underwent hybrid aortic arch repair (23). The hybrid aortic arch group was older ( $77 \pm 6$  vs.  $69 \pm 9$  years, P<0.0001) and had a higher logistic EuroSCORE ( $31 \pm 18$  vs.  $20 \pm 15$ , P<0.0001). There were 38 matched pairs utilized in the propensity score matching. The hybrid group had significantly shorter cardiopulmonary and circulatory arrest times, but no difference in operative mortality. At a mean follow-up of 52.5 months, the hybrid arch patients had a higher rate of re-intervention (21% vs. 1% at 24 months, P<0.0001). This study concluded that hybrid aortic arch repairs should be considered predominantly in high-risk individuals.

Other published cases series have been limited by the lack of a control group for comparison. However, experience with hybrid aortic repair has become more extensive. One recent large case series by Bavaria et al, reported on the results of 47 patients who underwent extensive hybrid arch repairs with either antegrade or retrograde TEVAR of the

aortic arch (24). The mean age of the group was  $71\pm 8$  years, and 14% of the group had a prior history of a sternotomy. The mean circulatory arrest time was  $19\pm 10$  minutes. The in-hospital mortality was 8%, with a stroke and paraplegia rate of 8% and 5.5%, respectively. There were no endoleaks noted, and the aortic re-intervention rate was 3% over a median follow-up of  $30\pm 21$  months. This series demonstrates that hybrid aortic arch can be done safely with favorable short-term and mid-term outcomes with careful selection of patients in an experienced center.

### *Acute type A dissections*

Historically, patients with a type A dissection undergo an emergent surgical repair with replacement of the ascending aorta and resection of the patient's primary tear site, with a hemiarch replacement and obliteration of the false lumen in the aortic arch. Unfortunately, the long-term prognosis of these patients is largely dependent on the patency of the false lumen, which predisposes to aneurysmal degeneration of the distal aortic arch and descending thoracic aorta and risks of aortic rupture (25). In a study of the long-term survival of 189 patients after type A dissection repair, the 10-year survival was 90% for patients with an occluded false lumen *vs.* 60% for patients with a patent false lumen ( $P=0.001$ ) (25).

This has led proponents to argue for a more extensive arch procedure in the form of a hybrid aortic arch repair at the time of the initial type A dissection repair. As pioneered by Roselli and colleagues, a simplified approach to a frozen elephant trunk has been proposed in the setting of acute type A dissections (26). This involves a modified frozen elephant trunk repair, with an open, antegrade deployment of a TEVAR device into the true lumen of the distal aortic arch under direct visualization. The TEVAR device is scalloped to allow for the ostium of the left common carotid and subclavian arteries, with incorporation of the TEVAR device and native aortic arch tissue in the distal aortic graft anastomosis. In a group of 17 patients, this hybrid repair was performed with no perioperative deaths, with 2 strokes without residual deficit, and 2 with temporary paraparesis. Importantly, 87.5% had thrombosis of the false lumen evident on surveillance imaging over a mean follow-up of  $154\pm 144$  days, implying a durable repair that will likely decrease the risks of late aneurysmal degeneration that occur with traditional, more limited type A dissection repairs.

Subtotal arch replacements in the setting of a type A

dissection has also been advocated, with debranching of the cerebral head vessels to the ascending aorta (27). This allows for interval TEVAR to complete the hybrid aortic arch reconstruction in cases of an "unstable" false lumen on subsequent radiologic imaging. In a case series of 89 patients, 65 patients (73%) required subsequent TEVAR to complete the aortic arch repair. Complete thrombosis of the false lumen was achieved in 94% of patients over 46 months of follow-up and in-hospital mortality was 9%. The late reoperation rate was 1%. There were no patients with permanent stroke or paraparesis. The 8-year survival rate was 92% in patients requiring subsequent TEVAR. Although there was no control group in this study, the early results compare favorably with contemporary reports of type A dissection repair.

### *Chronic arch and type B dissections*

Chronic type B dissections frequently lead to aneurysmal degeneration that requires surgical treatment. Many patients who survive a type A dissection repair similarly may have aneurysmal degeneration of their distal aortic arch and proximal descending thoracic aorta if there is a large re-entry tear feeding the false lumen. Depending on the extent of their first repair, these patients frequently require a redo sternotomy and TAR. Hybrid aortic arch repairs have become commonplace for this pathology, though staged TEVAR is complex, particularly if some of the visceral perfusion is fed by the false lumen. Endovascular approaches have been shown to be feasible in experienced centers. In a comparison of open TAR ( $n=23$ ) *vs.* hybrid arch repairs ( $n=27$ ), 1- and 5-year survival rates were similar, but 24% of hybrid repairs required re-intervention over a mean follow-up of 34 months (*vs.* 0%,  $P=0.001$ ) (28).

### **Future directions**

Branched aortic arch endografts have been developed and are undergoing clinical investigation in the United States and Europe. These devices may supplant hybrid aortic arch repairs, at least for zone 1 and 2 repairs. The feasibility results of a novel branched device designed for zone 2 repairs have been reported (29). There were a total 22 patients who underwent total endovascular repair of distal arch aneurysms, with a single side branch designed to facilitate aortic coverage proximal to the left subclavian artery. The procedural success rate was 100%, with no strokes, no permanent paraplegia, nor deaths at 30 days,



with a Kaplan-Meier survival rate at 6 months of 94.7%. Investigational devices designed with dual arch branches appropriate for zone 0 and 1 repairs may soon be available and may supplant TAR and hybrid aortic arch repairs in the future.

## Conclusions

In summary, aortic arch aneurysms pose a formidable surgical challenge. TAR requires deep hypothermic circulatory arrest, but is safe and represents the gold standard for surgical repair. Adjuncts such as SACP and retrograde cerebral perfusion with advancements in perfusion strategies have made TAR safer. Hybrid aortic arch repairs, utilizing TEVAR devices within conventional or frozen elephant trunks, show promise in shortening circulatory arrest times, intensive care unit and hospital lengths of stay, with acceptable morbidity and mortality rates. They have variable reports rates of neurologic events and carry higher rates of re-interventions that may make them best suited for high-risk patients. Institutional experience with this approach has been variable, emphasizing that appropriate patient selection may lead to favorable short-term and mid-term results in experienced centers. Novel branched aortic arch endografts may supplant TAR and hybrid aortic arch repairs in the future, though they are in the early stages of development and investigation.

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## Footnote

*Conflicts of Interest:* The authors have no conflicts of interest to declare.

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