Hybrid aortic arch repair (HAAR) consists of thoracic stent-graft repair and procedures to maintain cerebral blood flow. Several hybrid techniques have been used, including arch artery debranching, parallel graft technique, fenestration or branching of endograft, or a combination of these. We provided an overview of HAAR by presenting literature reviews as well as our clinical experience. The experience consisted of 172 patients who had undergone HAAR. The 30-day mortality was 3% (5/172). Persistent neurologic deficits occurred in 7 patients (4%), respiratory failure in 5 (3%), de novo aortic dissection in 3 and spinal cord injury in 2. 17% of the patients experienced type Ia endoleak. Seventeen patients required redo thoracic endovascular aortic repair. Fifty-six late deaths occurred during the follow-up period, including aortic-related death in 9 patients. In conclusion, hybrid arch debranching repair should be performed for elderly or high-surgical-risk patients. However, refining techniques and device technology is likely to reduce late endograft-related events. (This is a translation of Jpn J Vasc Surg 2018; 27: 385–391.)

Keywords: hybrid aortic arch repair, debranching, fenestration, parallel graft technique, branched endograft

Introduction

Thoracic endovascular aortic repair (TEVAR) has exhibited good results in the treatment of descending thoracic aneurysms; further, TEVAR has also been used for the treatment of aortic arch aneurysm and thoracoabdominal aortic aneurysm. The technical challenge involved in the treatment of these 2 conditions with stent graft is the maintenance of cerebral or visceral blood flow occluded by endovascular stent graft.

The following methods have been used to secure cerebral blood flow in aortic arch endovascular repair (AAER): 1. debranching, 2. fenestration, 3. parallel graft technique, and 4. branched stent graft which is under development. In this paper, we present the literature on these techniques and our institutional experience to describe the current status and future direction for AAER.

Techniques to Secure Cerebral Blood Flow

Debranching

A debranching is a method of maintaining cerebral blood flow by bypassing the supra-aortic vessels where stent grafting is expected to cause occlusion due to extending the proximal seal zone. It is the most feasible technique for surgeons because cerebral branch bypass has long been used for treating aortitis syndrome. After securing the cerebral blood flow with bypass, a stent graft is deployed in the aortic arch. This technique has been performed since endovascular treatment was first used for aortic arch aneurysm. However, with experience, it is understood that total debranching used for zone 0 landing requires a sternotomy; thus, it cannot always be minimally invasive. Based on their study targeting 104 patients, De Rango et al. reported that the zone 0 landing was the only multivariate independent predictor for perioperative mortality. Koulilas and Wheatley conducted a literature search and collected 139 patients of zone 0 landing. Early mortality rate was 10.2%, with 4.8% being attributable to stroke and 5.8% to spinal cord ischemia. Endoleak was confirmed in 12% of the patients. Although this technique was performed on patients who were at a high risk of open surgery, the result was unsatisfactory. Morishita et al. successfully performed zone 0 landing by using extrathoracic debranching that does not require a sternotomy to mitigate the invasiveness of total debranching. However, given the considerable length of the prosthesis for revascularization, there is a concern for late patency. Therefore, this technique is recommended for use only in select patients.
Going forward, successful zone 0 landing will require the development of a method to replace such an invasive total debranching. Fenestration, parallel graft technique, and branched stent graft methods described herein do not require sternotomy; therefore, it is likely that future treatment for patients with zone 0 landing will be based on these methods.

Fenestration

A fenestrated stent graft is provided by manufacturers preoperatively or is produced by a surgeon himself or herself intraoperatively. In the former case, a custom-made fenestrated stent graft eliminates the need for the surgeon to perform intraoperative fenestration tasks. However, because the manufacture of the custom-made graft requires time for preparation, it cannot be used in urgent settings. When performing intraoperative fenestration, physician-modified fenestration or in-situ fenestration is needed. However, because both the methods are technically challenging, a certain level of experience is required to smoothly perform these techniques. Once such techniques are learned, therapeutic options definitely increase.

In Japan, only the Kawasumi Najuta thoracic stent graft system (Kawasumi Laboratories, Inc., Tokyo, Japan) provides custom-made fenestrated stent grafts. As indicated above, it takes about 3 weeks to prepare such a stent graft; therefore, it cannot be used for urgent patients. Based on the preoperative computed tomography information of patients, compatible skeletons are selected from among the 64 types of skeletons. These skeletons are combined to build a stent graft that fits the three-dimensional structure of the deployment location. The advantage of this device is that when there is a sac-shaped aneurysm on the lesser curvature, blood flow in the brachiocephalic artery and left common carotid artery can be secured using the Najuta thoracic stent graft alone. It does not require any other auxiliary means such as debranching.

Kurimoto et al.6) reported on 37 patients treated using this system. All the patients required zone 0 landing. There was no patient of early death, and cerebral complication was observed in only 2 patients (5%). However, Type Ia endoleak was observed in 12 patients at the time of discharge (32%), and 50% of these patients presented late dilatation of ≥5 mm. Four patients required additional treatment in the late stage (11%). They suggested that the reason for the high number of Type Ia endoleaks was the average distance of only 10 mm between fenestration and aneurysm. Instruction for use (IFU) of this device recommends a distance of more or 20 mm between fenestration and aneurysm. The Kawasumi Najuta thoracic stent graft system has multiple fenestrations, and the area of the fenestrations is large; thus, if IFU is not followed, Type Ia endoleak can easily occur.

Physician-modified fenestration was developed for the treatment of emergency cases of juxtarenal aortic aneurysms.7) Therefore, this technique can be applied for the treatment of emergency ones of aortic arch aneurysms as well. This technique consists of the following 3 parts: unsheathing a part of the stent graft; creating fenestration of this part, as planned; and reloading this part into the stent sheath. The third step requires the highest experience. It requires the experience of about 10 cases for a surgeon to become skilled enough to smoothly perform the technique.

After reloading the fenestrated part into the sheath, the sheath is inserted into the femoral artery and elevated to the level of aortic arch aneurysm; the major issue here is that it is impossible to rotate the sheath within the aortic arch to make the micro-adjustment that the surgeon intends to make. If the fenestration site and the target arch branch are inconsistent, the anteroposterior discrepancy can be adjusted by moving the sheath; however, the lateral discrepancy cannot be adjusted by rotation of the sheath. In order to resolve this issue, we ensure that the lateral size of the fenestration is wider than the arch branch.8) In particular, in the case of tortuous aorta, the stent graft twists through the aorta, making it impossible to predict where the fenestrated part of the stent graft lands on the aortic arch. Therefore, in tortuous aorta, the width should be especially more so that the fenestration is one-third of the stent-graft circumference. On the other hand, if the fenestrated part is enlarged, there is a greater risk of an endoleak. Thus, this should be limited to cases wherein the fenestrated part and aneurysm are ≥20 mm apart.

An alternative type of intraoperative fenestration is in-situ fenestration that fenestrates through retrograde puncture from the supra-aortic trunk to the stent graft deployed in the aortic arch, eliminating the need for a large fenestration, as in physician-modified fenestration. Furthermore, when a covered stent is used as bridging stent graft; theoretically, an endoleak is unlikely.

On the contrary, this method involves several issues that need to be resolved. The biggest issue is an inaccurate puncture. The needle for puncture often glances off the graft fabric and pass parallel to the stent graft, resulting in an incomplete puncture. The tip of the needle may also dent the stent graft instead of puncturing it. Hong et al.9) used a snare to grasp a stent graft for achieving the safe and secure puncture of stent graft. Canaud et al.10) proposed the use of a stent graft with higher radial force to prevent the denting.

There is no consensus on the size of fenestration. As per a literature search, Crawford et al.11) have shown that in 76% of the facilities, final balloon dilatation is performed with a 6-mm balloon. Based on experimental results, some researchers have stated that if the stent graft dilates...
The atherosclerotic arch vessels must be considered more of atherosclerosis, the insertion of a covered stent into complications (29%). Considering that both patients were ture of the left subclavian artery. Although there was no except in 1 out of the 7 patients with unsuccessful puncture at the puncture site. Some authors revealed that the Zenith fabric had the greatest strength among Cook Zenith stent graft (Cook Medical, Bloomington, IN, USA), Medtronic Talent, and Medtronic Endurant (Medtronic, Santa Rosa, CA, USA), resulting in approximately 25% dilatation of nominal balloon diameter, while the Talent and Endurant grafts could be easily dilated with balloons. The strength of the materials should be considered while determining the balloon size.

With the in-situ fenestration method, cerebral blood flow temporarily stops owing to coverage of the supra-aortic vessels by the deployed stent graft. Therefore, it is necessary to use auxiliary means to maintain the cerebral blood flow. Especially in zone 0 and 1 patients, endovascular stent deployment can lead to severe cerebral complications; thus, cerebral blood flow maintenance must always be considered. Previously, extracorporeal circulation or external shunt was used; however, they were time-consuming. In contrast, recently, a method to maintain blood flow with an endovascular shunt was developed and was being used in clinical settings. This method allows blood flow maintenance via retrograde insertion from the arch arteries using the Seldinger technique; therefore, it can be easily applied to clinical cases of zone 0 and 1 landing. Practically, however, most cases remain in zone 2 disease. It is likely that the use of extracorporeal circulation to maintain cerebral blood flow is creating a barrier in cases of zone 0 and 1. Therefore, clinical application in such cases remains limited to case reports. Katada et al. reported 7 patients requiring zone 0 landing with the use of in-situ fenestration under extracorporeal circulation. All punctures of the triple arch arteries were successful, except in 1 out of the 7 patients with unsuccessful puncture of the left subclavian artery. Although there was no early death or endoleak, there were 2 patients of cerebral complications (29%). Considering that both patients were of atherosclerosis, the insertion of a covered stent into the atherosclerotic arch vessels must be considered more carefully.

Parallel graft technique
The parallel graft technique features the retrograde insertion of a covered stent (or bare stent) in the aorta from the arch branch vessels and the position of the stent in the aorta parallel to the stent graft to secure the cerebral blood flow. The advantage of this method is that technical achievement can be easily obtained by combination of the existing techniques. Thus, it is technically feasible and is less invasive than debranching. It can also be used in urgent cases. However, it carries the risk of endoleak (gutter endoleak) caused by the gap between the chimney graft and stent graft.

Pecoraro et al. reported the results of parallel graft techniques in 41 patients. About 50% (20) of the patients required zone 0 landing; however, there was no patient of Type Ia endoleak. Bosiers et al. reported the results of 95 patients, including 13 patients of zone 0 landing treated at multiple facilities in Europe. Type Ia endoleak was confirmed in 6 patients (6.3%); however, these were resolved within a month. In zone 0 patients, only 1 out of 13 patients experienced Type Ia endoleak, and this was resolved within 3 months using coil embolization. They used a covered stent to prevent gutter endoleak and proposed that it be placed parallel to stent graft at a distance of at least 2 cm.

Considering the low incidence of gutter endoleak that was initially a concern, the opportunities to use the parallel graft technique will increase in the future. However, in Japan, the reimbursement for coils used for gutter endoleak treatment, covered stents, and bare stents is strictly limited; therefore, it poses an issue with respect to hospital management.

Originally, this method was reported as a bail-out treatment for left common carotid artery inadvertently covered by an endovascular stent graft. Despite enough surgical experience, there is always a risk of occlusion of the arch branch vessels during AAER. Therefore, it is essential to learn the parallel graft technique as a rescue technique.

Branched stent graft
Branched stent grafts are currently under development and are not yet being used widespread in clinical settings. Theoretically, it is less invasive than debranching, involves a lower risk of endoleak than fenestration and chimney techniques, and has better reproducibility than in-situ fenestration. However, if there is tortuous aorta, the procedure becomes difficult. Moreover, the side branch is directly inserted into the arch branch, posing a risk of cerebral embolism.

Haulon et al. treated 38 zone 0 patients using a double-branched thoracic stent graft as a multicenter study. The results showed 5 patients of early death (13%), 6 of cerebral complications (16%), 32 of technical successes (84%), and 11 of endoleak (29%). However, 4 out of the 6 patients of cerebral complications were of a transient ischemic attack. In 1 patient, cannulation to the arch branch was unsuccessful. Four patients required early secondary procedures. The types of the endoleak were Type I in 5 patients, Type II in 5, and Type III in 1. There was a learning curve for the technique and results improved in the later experience group compared with the early one. Riam-bau reported 26 patients with a different double-branch device. With respect to intraoperative complications, there
was 1 patient each of subclavian artery occlusion and left common carotid artery dissection. In another patient, he or she died because of intraoperative multiple strokes. Type I endoleak was observed in 2 patients. Thus, there was a considerable prevalence of complications.

Dake and Pate12 obtained good results in a multiinstitutional study on zone 2 patients using a single branched device; they plan to conduct a clinical trial on zone 0, zone 1, and zone 2 patients including dissection and trauma cases. They will have registered 435 patients and aim to observe the course over a period of 5 years. These study results will present an accurate clinical picture of the outcome using branched stent grafts; therefore, these findings will be crucial and are much awaited.

**Institutional Experience with Hybrid Aortic Arch Repair**

From January 2009 to December 2017, 172 AAER were performed at our department. The patients consisted of 130 men and 42 women, with a mean age of 73 ± 10 years. The etiology was atherosclerosis in 119 patients, dissection in 31, post-TEVAR complications in 16, Kommerell’s diverticulum in 5, and trauma in 1. There were 13 patients of ruptures. The mortality of open treatment that was predicted preoperatively with Japan score was 18% ± 19%. There were 67 patients of total aortic arch replacement performed at this facility during the same study period.

To maintain cerebral blood flow, debranching was performed in 138 patients, physician-modified fenestration + debranching in 23, physician-modified fenestration in 4, in-situ fenestration in 4, and chimney technique in 3. The breakdown of debranching was as follows: 73 patients of the left subclavian artery reconstruction, 31 of the left common carotid artery and left subclavian artery reconstruction, 29 of total debranching, 3 patients of the left common carotid artery reconstruction, and 2 of extrathoracic total debranching. Among these, 41 patients underwent TEVAR in a staged fashion, including 10 patients with physician-modified fenestration + debranching. The stent graft landing location was zone 0 for 57 patients, zone 1 for 37, and zone 2 for 78.

Early death was confirmed in 5 patients (3%). The causes of deaths were septic shock, retrograde type A aortic dissection, hemorrhage due to access-related problems, hemorrhage due to injury to the descending aorta, and intestinal necrosis due to acute type B aortic dissection. Four out of 5 deaths were related to procedure or devices. The last 2 patients had strong tortuosity from the abdomen to the thoracic aorta. The following perioperative complications were observed: stroke (4%) in 7 patients, respiratory failure (3%) in 5, retrograde type A aortic dissection in 2, paraparesis in 2, and acute type B aortic dissection in 1. Eight patients experienced access-related problems (5%), and 2 patients suffered an injury to the aorta.

Type I endoleak was confirmed in 29 patients (17%). Comparing the earlier and later 86 patients, we found that the frequency of occurrence reduced; however, the reduction was not statistically significant [19 (22%) and 10 (12%); p = 0.06]. Type II endoleak was confirmed in 10 patients (6%). There were 17 patients requiring secondary TEVAR in the late stage (mean follow-up period: 317 ± 288 days) (10%). The reasons for the second interventions were Type I endoleak in 9 patients, dilatation of independent thoracic descending aorta aneurysm on the distal side in 5, aneurysm dilatation due to continued blood flow into the false lumen in 2, and migration of the stent graft in 1. Coil embolization of the left subclavian artery was insufficient in the 10 patients; therefore, 3 patients who developed aneurysm dilatation due to type II endoleak underwent secondary coil embolization.

In 4 patients, the occlusion of the vascular graft used for debranching was confirmed, and infection was confirmed in 3 patients during the same follow-up period (317 ± 288 days). In the 4 patients who developed occlusion, 1 patient experienced a stroke. Late death occurred in 56 patients. Nine of these deaths (5%) were related to aneurysms. Seven patients died due to rupture caused by Type I endoleak. Additional treatment was not recommended for 3 of these patients because of frailty or old age. In 2 patients, death was caused by rupture because the patients refused additional treatment. A patient died from acute heart failure due to delayed diagnosis of aorticopulmonary fistula, missing the treatment opportunity. The remaining patient with Type I endoleak was hospitalized for treatment; however, the rupture occurred before treatment, and the patient died. With respect to the 2 patients without Type I endoleak, 1 died due to rupture of the supra-renal abdominal aortic aneurysm. Treatment for the aneurysm was not indicated for this patient owing to frailty. The other patient died of sudden rupture of acute type B aortic dissection that developed in the distal end of the endovascular stent graft during antihypertensive treatment.

**Discussion**

Although the operative risk was predicted to be high, early outcomes for patients with AAER were favorable. In contrast, the late results were unsatisfactory because several patients required reinterventions or had aneurysm-related deaths during follow-up periods. This phenomenon is observed in the TEVAR for thoracic descending aorta aneurysm, indicating the limitation of the present stent graft treatment. Therefore, the indication of AAER should be limited to elderly patients or patients at a high risk of
open surgery.

The device anatomical requirements cannot be simply applied to AAER because the anatomic structure of the aortic arch is complex. For example, if the curvature of the aortic arch is high, commonly, the proximal seal length on the greater and lesser curvatures differs by ≥20 mm. Therefore, if the proximal neck length is determined using central flow measurement, Type Ia endoleak may easily occur at the lesser curvature. In our experience, the proximal seal length was 20 ± 3 mm for patients who presented with Type Ia endoleak; this was significantly different from that in patients without an endoleak (35 ± 11 mm: p < 0.05). This suggests that the same strategy cannot prevent Type Ia endoleak when performing endovascular stent graft repair on highly curved arch cases. It is important to establish a tailored plan for AAER for each patient.

Even in the absence of a statistically significant difference in the prevalence of Type Ia endoleak during the study period, there was a trend in the reduction of Type Ia endoleak between the first 86 patients and the last 86 patients. We believe that this was attributable to the following reasons. When determining the proximal seal length, we made sure to set a value of at least 2-cm neck length on the lesser curvature. As a result, the proximal seal length was longer than before. The elongation affected the determination of the proximal landing zones. In the earlier patients, the landing zone was 0 for 25 patients, 1 for 12, and 2 for 49. In contrast, in the later patients, the landing zone was 0 for 32 patients, 1 for 24, and 2 for 30. It reflects a shift to the proximal site (p < 0.01). In order to extend the proximal seal length, the stent was inserted closer to the proximal location, leading to a reduced prevalence of Type Ia endoleak.

It is clear that Type Ia endoleak is the major factor in reinterventions or aneurysm-related deaths at a later stage. In order to prevent this, increasing the length of proximal landing, as discussed above, is promising. However, with the aortic arch, the elongation of the proximal seal length means that the arch branch is occluded with a stent graft. Especially when the occluded supra-aortic vessel includes the brachiocephalic artery or the left common carotid artery, we have to secure the cerebral blood flow. Normally, debranching, fenestration, and parallel graft techniques must be considered. Debranching is a familiar procedure for vascular surgeons; however, it is more invasive than other methods. In particular, total debranching is not commonly used at present because it is highly associated with respiratory failure or retrograde type A aortic dissection. Another disadvantage of debranching is the infection and occlusion of the bypass graft. Vascular graft infection has a low prevalence; however, it is a challenging complication and requires considerable effort for treatment. Use of debranching should be considered carefully in patients who are at a high risk of infections, such as those who are obese or have uncontrolled diabetes.

In order to resolve the above-described problems, we have recently started using the fenestration technique. For zone 0 landing patients, instead of total debranching, physician-modified fenestration + debranching is used (Fig. 1). With this technique, the cerebral blood flow of the left subclavian artery and left common carotid artery is secured via a bypass. The cerebral blood flow of the brachiocephalic artery is maintained using the fenestration technique. Because this technique does not require sternotomy and partial clamping of the ascending aorta, severe complications of total debranching such as respiratory failure or retrograde type A aortic dissection can be avoided. For patients at a high risk for vascular graft infection, instead of the debranching technique, in-situ fenestration or parallel graft technique is chosen as the first choice. These methods do not require a prosthetic vascular graft, making it effective in reducing the graft infection risk. Furthermore, the Najuta thoracic stent graft system does not require additional skin incision with the above-described procedures; therefore, it is the simplest procedure for preventing bypass graft infection. It should be considered in patients at an anatomically low risk of endoleak.

The parallel graft technique can be also used as a salvage procedure for the unintentional occlusion of the supra-aortic trunk. Because there was a risk of gutter endoleak, we had limited our use of this technique. However, the number of endoleak cases was fewer than expected. We could prevent gutter endoleak by placing a covered stent parallel to a stent graft at a distance of at least 2 cm. Despite the disadvantage that reimbursement does not cover the cost of materials in Japan, this technique features technical feasibility and off-the-shelf availabil-
The parallel graft technique should be mastered for troubleshooting situations.

In-situ fenestration does not involve the risk of gutter endoleak, making it more advantageous than the parallel graft technique. However, it is technically challenging. Thus, the unsuccessful rate is significant. We attempted to use in-situ fenestration in 7 patients but it was successful in only 4 patients. Consequently, we used the parallel graft technique to rescue the unsuccessful cases. The in-situ fenestration is more challenging when the angle between the stent graft and arch branch is acute or when there is a short distance between the planned puncture site and proximal edge of the stent graft. Therefore, appropriate patient selection becomes critical to maximizing success rates.

We believe that in-situ fenestration benefits a patient with Kommerell’s diverticulum. Previously, open graft replacement was used as the first line of treatment. When the operative risk was high, debranching + TEVAR was performed. However, the operative procedure can be simplified using in-situ fenestration. The subclavian artery arises from the top of a saccular aneurysm in patients with Kommerell’s diverticulum; therefore, after TEVAR, from the subclavian artery retrogradely, an opening can be simply created on the stent graft body with in-situ fenestration to maintain cerebral blood flow. Our patient was an 83-year-old woman with a history of left thoracotomy for lung cancer operation; she was considered at high risk for open graft replacement (Fig. 2). The procedure took 2 h; however, it could have been shorter. Initially, we created a fenestration at the center of the stent graft, and when advancing the introducer sheath into the stent graft, the force caused the sheath itself to bend inside the aneurysm because of the fabric resistance of the stent graft, preventing it from advancing. Therefore, we changed the fenestration location to the distal edge of the Kommerell’s diverticulum. Consequently, the sheath went along the aneurysmal wall, which supported the introducer sheath to puncture the stent graft by transmitting the pushing force perpendicularly to it. If we had used this approach in the first place, the operation time could have been reduced by 30 min.

As mentioned, AAERs are still under development. In particular, the long-term results are unsatisfactory because several patients required reinterventions and there were considerable aneurysm-related deaths. However, AAER has only been conducted for the past 15 years, compared with the long history of >60 years for open graft replacement. Therefore, there is a considerable scope of improvement for the technology of endovascular repairs, and there may be improvement in the long-term results in the future. Patients undergoing AAER include those with frailty or the elderly; therefore, in cases of subsequent complications, additional treatments are often refused. Thus, the development of an endovascular repair that eliminates the need for reintervention is important from the above-mentioned point of view.

We expect that the most promising method is in-situ fenestration using an endovascular shunt because of the following 3 reasons: (1) The use of an endovascular shunt to secure cerebral blood flow during the procedure is less invasive than the extracorporeal circulation technique; (2) Fenestration is performed for the stent graft that has already been deployed; thus, even in cases with a tortuous aorta, matching the positions of the fenestration and arch branch is easy; and (3) There is no gap between the stent graft fenestration and the covered stent that is inserted; thus, an endoleak is unlikely. The only concern is that if this method is used in a lesion with severe atherosclerosis, the frequency of cerebral embolism increases. It may be necessary to use filter devices as distal embolic protection devices.

**Conclusion**

Considering the poor long-term results of AAERs, the indication should be limited to elderly patients or patients at high risk for open graft replacement. However, with more experience, improved technology, and advanced techniques, the number of long-term postoperative complications is likely to decrease. Therefore, indications for the use of AAER may increase in the future.

**Disclosure Statement**

There is no conflict of interest to disclose.
Additional Note

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