A New Aortic Arch Inclusion Technique with Frozen Elephant Trunk for Aortic Arch Aneurysm Treatment

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Summary
Various surgical techniques have been proposed for treating aortic arch aneurysm (AAA); however, the optimal treatment has not been well defined. This study introduces a new aortic arch inclusion technique with frozen elephant trunk (FET) for AAA treatment.

A retrospective analysis was performed among 22 patients for AAA surgical treatment between March 2010 and March 2019. Patients were classified into Z1, Z2, and Z3 groups based on the origins of aneurysms. A stent graft with a 10 cm stented graft and 5-9 cm proximal vascular prosthesis was released into the descending thoracic aorta as FET through an incision in the aortic arch. The proximal vascular prosthesis was retracted into the aortic arch, trimmed to expose the orifices of the brachiocephalic vessels, and sutured inside the aortic arch using the inclusion technique. The proximal sealing location of the vascular graft was tailored to cover the origins of aneurysms.

There was no 30-day mortality. No patient had postoperative stroke or paraplegia. Complete aneurysm thrombosis was achieved in all patients. One patient died of severe respiratory tract stenosis 3 months postoperatively. All other 21 patients were alive during 53.3 ± 36.5-month follow-up. Computed tomography angiography was obtained in 15 patients during follow-up. Endoleak was observed in one patient, and the other 14 patients were free from aneurysm-related or graft-related complications during follow-up.

The aortic arch inclusion technique with FET provides an alternative technique in treating AAA with satisfactory mid-term follow-up results. A larger patient population with long-term follow-up results is warranted.

Key words: Surgery, Surgical procedure

The management of aortic arch aneurysms (AAAs) remains a clinical challenge. Several surgical strategies have been proposed; however, the optimal treatment has not been well defined. The conventional total arch replacement (TAR) method has become the standard surgical option for AAA treatment. Despite the improvements in surgical techniques, TAR is still reported with high mortality and high perioperative morbidities. Recently, with the advances of endovascular technology, total endovascular repair, or hybrid endovascular repair have emerged as a new option for AAA treatment in selected patients. They have been reported with promising short-term results; however, the long-term results of endovascular treatment for AAA require more investigations.

From October 2009, our center had adopted the aortic arch inclusion technique for type A aortic dissection (TAAD), which has shown satisfactory clinical results and aortic remodeling. After the initial experience and clinical results in TAAD patients, we proceeded to use this technique in AAA treatment. In this study, we introduce our experience and summarize the surgical results of the aortic arch inclusion technique in AAA treatment.

Methods
Patients: This retrospective study had full approval from the Research Ethics Committee of the Second Hospital of Jilin University. Consent forms were waived in all patients. Between March 2010 and March 2019, 22 patients with AAA were admitted to the Second Hospital of Jilin University for surgical treatment using the aortic arch inclusion technique. A retrospective analysis was performed among the 22 patients.

The preoperative characteristics of the patients are listed in Table I. Their mean age was 54.6 ± 11.2 (range 29-75), and 19 patients (86.3%) were males. Preoperative comorbidities included hypertension in 11 patients (50.0%), diabetes mellitus in six patients (26.3%), cerebral
Figure 1. Illustration of the group classification for Z1-Z3 groups. In the Z1 group were the aneurysms originating between the innominate artery (IA) and left common carotid artery (LCCA) (A). In the Z2 group were the aneurysms originating between LCCA and left subclavian artery (LSA) (B). In the Z3 group were the AAA originating distal to the LSA opening (C). IN indicates innominate artery; LCCA, left common carotid artery; and LSA, left subclavian artery.

Table 1. Preoperative Characteristics

| Variable                                | n = 22 |                      |
|-----------------------------------------|--------|----------------------|
| Age, years, mean ± SD                   | 54.6 ± 11.2 (range 29-75) |                      |
| Male gender, n (%)                      | 19 (86.3) |                      |
| Hypertension, n (%)                     | 11 (50.0) |                      |
| Diabetes mellitus, n (%)                | 6 (26.3) |                      |
| Cerebral vascular disease, n (%)        | 2 (9.1) |                      |
| Coronary artery disease, n (%)          | 4 (18.2) |                      |
| Ejection fraction of left ventricle, mean ± SD | 58.5 ± 5.4 |                      |
| Chronic obstructive pulmonary disease, n (%) | 3 (13.6) |                      |
| Chronic renal disease, n (%)            | 1 (4.54) |                      |
| Emergency/urgent, n (%)                 | 4 (18.2) |                      |
| Rupture, n (%)                          | 4 (18.2) |                      |
| Origin of aneurysms, n (%)              |        |                      |
| Zone 1                                  | 5 (22.7) |                      |
| Zone 2                                  | 9 (40.9) |                      |
| Zone 3                                  | 8 (36.4) |                      |
| Diameter of aneurysm (cm), mean ± SD   | 6.1 ± 0.9 (5.0-8.0) |                      |

vascular disease in two patients (9.1%), coronary artery disease in four patients (18.2%), chronic obstructive pulmonary disease in three patients (13.6%), and chronic renal failure in one patient (4.5%). No patient had previous cardiac operations.

All patients were divided into three groups based on the origins of AAA, adopting the Ishimaru aortic zone classifications. In the Zone 1 (Z1) group were the aneurysms originating between innominate artery (IA) and left common carotid artery (LCCA) (Figure 1A). In the Z2 group were the aneurysms originating between LCCA and left subclavian artery (LSA) (Figure 1B). In the Z3 group were the AAAs originating distal to the LSA opening (Figure 1C). In the study, five patients, nine patients, and eight patients were in the Z1, Z2, and Z3 groups, respectively. The size of the aneurysm was 6.1 ± 0.9 cm in diameter (range 5.0-8.0 cm).

Indications of the aortic arch inclusion technique: Indications for the aortic arch inclusion technique were that three brachiocephalic branch vessels were free from aneurysmal pathology and there had to be at least a 5 mm healthy tissue between aneurysms and the orifices of the brachiocephalic vessels.

Description of the stent graft for the aortic arch inclusion technique: The stent graft, Cronus (Microport Medical Co. Ltd, Shanghai, China) consisted of a 10 cm stented graft (available in 24-30 mm sizes) and a 5-9 cm proximal Dacron vascular prosthesis (Figure 2A, B). The proximal vascular portion would be trimmed and attached inside the aortic arch for completing the aortic arch inclusion technique (Figure 2C). The size of the graft was matched based on the preoperative computed tomography angiography (CTA) and intraoperative measurement.

Surgical technique: After general anesthesia, patients’ back surface cooling began. The right axillary artery and the femoral artery were exposed. Median sternotomy was performed in all patients. After systemic heparinization, cardiopulmonary bypass (CPB) was initiated via cannulation of the femoral artery, right axillary artery, inferior vena cava, and superior vena cava. The left side of the
In The Heart | November 2020 | INCLUSION TECHNIQUE FOR AORTIC ARCH ANEURYSM

**Figure 2.** Illustration of the stent graft for aortic arch inclusion technique. **A:** The compacted stent graft before implantation. **B:** After releasing, there is a 5-9 cm stent-free vascular graft on the proximal end for aortic arch anastomosis. **C:** An *in vivo* model of the trimmed vascular graft for aortic arch inclusion technique. The proximal vascular graft was trimmed to expose the orifices of the brachiocephalic vessels.

**Figure 3.** Illustration of the aneurysms of the Z1-Z3 groups after completion of the aortic arch inclusion technique. **A:** The proximal anastomosis site of vascular graft for the Z1 group is between IA and the LCCA openings. **B:** The proximal anastomosis site of the vascular graft for the Z2 group is between LCCA and the LSA openings. **C:** The proximal anastomosis site of the vascular graft for the Z3 group is just at the inferior margin of the LSA opening. IN indicates innominate artery; LCCA, left common carotid artery; and LSA, left subclavian artery.

heart was vented through the right superior pulmonary vein. Myocardial protection was achieved with antegrade cold blood cardioplegia, repeated every 30 minutes.

After the CPB was started, the patients were cooled to a rectal temperature of 25°C or 28°C (25°C before 2014 and 28°C after 2014). Circulatory arrest was started, and a transverse incision was made in the normal tissue of the aortic arch. Antegrade selective cerebral perfusion was initiated via the LCCA and right axillary artery cannulation. The stent graft was inserted into the descending aorta and positioned to ensure that the proximal side of the stent graft was just at the inferior margin of the LSA orifice. After that, the stent graft was released into the descending aorta as FET and the proximal stent-free vascular graft was retracted back into the aortic arch for next anastomosis. Different trimming and suturing methods were used for the Z1 and Z3 groups.

For the Z1 group, the vascular graft was trimmed into an elliptical shape around the orifices of the LCCA and LSA openings and to expose the orifices of LCCA and LSA openings. Then, one or two pledgeted mattress sutures were placed at the inferior margin of the LSA orifice using a 4-0 polypropylene 17 mm 1/2C double-armed mattress suture, which would attach the vascular graft with the healthy tissue of the aortic arch. Then the vascular graft was attached to the posterior wall of the aortic arch with a continuous running suture, and the suture should be passing through the vascular graft and aortic arch as deep as possible. Next, the vascular graft was anastomosed onto the anterior aortic arch wall with penetrating sutures. After that, a circumferential running suture was performed to anastomose the vascular graft and proximal aortic arch between IA and LCCA. In this way, the aortic arch was covered with vascular graft except for the orifices of the LCCA and LSA. In this way, the AAA was excluded with vascular graft inclusion. (Figure 3A)

For the Z2 group, the vascular graft was trimmed to expose the orifice of the LSA opening. After releasing the stent graft into the descending aorta, the aortic arch anastomosis method was the same as the Z1 group using the aortic arch inclusion technique. However, the difference was that the proximal anastomosis site of the vascular graft was between the LSA and LCCA openings (Figure 3B). In this group, there was a patient with extensive AAA, which both involved the aortic arch and the descending thoracic aorta (DTA). For this patient, after the application of the aortic arch inclusion technique for aortic arch repair, one-stage hybrid thoracic endovascular repair (TEVAR) was performed via the femoral artery.

For the Z3 group, after releasing the stent graft into
the descending aorta, we pruned away the redundant vascular graft, and a circumferential running suture was directly done at the inferior margin of the LSA opening to attach the vascular graft and distal aortic arch (Figure 3C).

After the aortic arch repair, the incision in the aortic arch was closed. Then, CPB was gradually resumed to normal flow, and systemic rewarming was started. After air was eliminated from the heart with the patient in the Trendelenburg position, the chest was closed after careful inspection of bleeding. Concomitant procedures were performed if necessary.

Results

Intraoperative and postoperative results: There was no operative or 30-day mortality. No uncontrollable bleeding from the anastomosis sites occurred in our study. The circulatory arrest time, aortic cross clamp time, and the mean CPB time were 28.3 ± 3.4 minutes, 33.0 ± 4.5 minutes and 121.2 ± 25.4 minutes, respectively. Concomitant procedures were ascending aorta-right carotid artery bypass in one patient, as the patient had severe preoperative carotid artery stenosis. One patient had aorta-LSA bypass as the patient had preoperative LSA stenosis. Coronary artery bypass graft was performed in two patients. One patient with extensive AAA and descending thoracic aneurysm had aorta-LSA bypass and one-stage TEVAR after the aortic arch inclusion technique treatment (Table II).

No new postoperative onset of paraplegia or stroke occurred. Temporary delirium occurred in one patient (4.5%), and acute kidney dysfunction requiring dialysis occurred in two patients (9.1%). The patient with temporary delirium and the patient with kidney dysfunction both recovered before discharge. The postoperative mechanical ventilation support period was 17.6 ± 7.2 hours. The mean duration of intensive care unit stay and hospital stay were 2.6 ± 3.1 days and 14.8 ± 5.3 days, respectively.

Postoperative CTA was performed in all patients before discharge, showing that complete aneurysmal thrombosis was achieved in all patients. No stent graft endoleak or migration was detected.

Follow-up: The follow-ups were obtained from clinical interviews with the latest follow-up in July 2019. One patient with syphilis died of severe respiratory tract stenosis 3 months postoperatively. The other 21 patients were followed up at a mean of 53.3 ± 36.5 months (range 4-114 months) by telephone or clinical interview, with a survival rate of 100% (21/21) during follow-up. CTA was obtained in 15 patients (71.4%) during the follow-up, while the remaining six patients did not undergo follow-up CTA. The mean size of the aneurysm was reduced to 3.9 ± 0.3 cm in diameter (Figure 4).

Postoperative endoleak was observed in one patient (6.67%, 1/15). The patient with original Z1 aneurysm underwent the aortic arch inclusion technique with FET (Figure 5A). He had sudden chest pain 10 months postoperatively, and CTA showed a huge pseudoaneurysm of about 10 cm in diameter (Figure 5B). He had emergency surgery, and a 5 mm tear was found under the orifice of the LCCA between the vascular graft and the anterior wall of the aortic arch. The repair of the tear was completed using 4-0 polypropylene pledgeted sutures (Figure 5C). He was closely followed up ever since. The 53 months postoperative CTA showed no more endoleaks, and his aortic arch has returned to a normal size (Figure 5D). All the other 19 patients were free from complications such as stent displacement and aneurysm enlargement, and resumed a normal life after hospital discharge.

| Variables | Values |
|-----------|--------|
| Concomitant procedures | Ascending aorta-right carotid artery bypass 1 (4.5%) |
| Ascending aorta-LSA bypass | 1 (4.5%) |
| Coronary artery bypass graft | 2 (9.1%) |
| Ascending aorta-LSA bypass + TEVAR | 1 (4.5%) |
| CPB time (minutes) | 121.2 ± 25.4 |
| Aortic cross clamp time (minutes) | 33.0 ± 4.5 |
| Circulatory arrest time (minutes) | 28.3 ± 3.4 |
| Reoperation for bleeding | 0 |
| Hospital mortality | 0 |
| Postoperative morbidity | Paraplegia 0 |
| Stroke | 0 |
| Temporary neurological dysfunction | 1 (4.5%) |
| Acute kidney injury | 2 (9.1%) |
| Mechanical ventilation period (hours) | 17.6 ± 7.2 |
| ICU stay (days) | 2.6 ± 3.1 |
| Length of hospital stay (days) | 14.8 ± 5.3 |

TEVAR indicates thoracic endovascular aortic repair; CPB, cardiopulmonary bypass; and ICU, intensive care unit.

Figure 4. CTA of a patient with Z2 aortic arch aneurysm. A: Preoperative CTA of this patient showing a 6.5 cm aneurysm. B: CTA performed at discharge, showing complete thrombosis of the aneurysm 2 weeks after surgery. C: CTA performed 12 months postoperatively showing that the size of the aneurysm was reduce, compared with CTA at discharge. D: The latest CTA was taken 25 months postoperatively, showing that the size of the aneurysm was further reduced. CTA indicates computed tomography angiography.
Discussion

Despite significant improvements in the fields of surgical techniques and perioperative care, conventional open aortic arch replacement is still associated with substantial morbidity and mortality even at centers of excellence.\(^8,9\) The traditional aortic arch replacement needs resection of the aortic arch and replacement with a vascular graft prosthesis. This procedure is invasive and technically demanding. For aortic arch reconstruction techniques in open surgery, the most commonly used techniques were the en bloc technique (EBT) and branched graft technique (BGT).\(^10\) In the EBT, the three brachiocephalic vessels are resected together from the aortic arch as “an island,” and after distal anastomosis, the vessel island is anastomosed en bloc to the graft.\(^11\) In the BGT, a four-branch vascular graft was used to replace the aortic arch and the three brachiocephalic vessels. EBT has only one anastomosed site in the aortic arch, which is easier to perform; however, bleeding from the posterior wall of the aortic arch and from the distal anastomosis site are difficult to control.\(^12\) In the BGT, it requires more anastomosis sites, and the branched graft may be twisted and occluded.\(^13\) Moreover, the distal anastomosis is deep in the surgical field, which is difficult to manipulate and makes bleeding from the distal anastomosis site difficult to control.\(^14\)

Comparing our aortic arch inclusion technique with the EBT, we completed the aortic arch reconstruction from inside the aortic arch in an island fashion, thus eliminating the possibility of bleeding from the posterior aortic arch wall anastomosis. As for the BGT, our technique does not require distal anastomosis, which avoids the potential risks of bleeding from the distal anastomosis and difficulty in controlling the bleeding. The potential rates of branched graft-related complications will be avoided. Furthermore, the extension of the aortic arch repair is tailored specifically to the individual’s pathology, which avoids unnecessary replacement and is less invasive. In our series, the mean circulatory arrest time, aortic cross clamp time, and CPB time were 28.3 ± 3.4 minutes, 33.0 ± 4.5 minutes, and 121.2 ± 25.4 minutes, respectively, which is satisfactory compared with other reported series.\(^15,16\)

For AAAs, the management of the distal aortic arch remains a difficult issue because of its deep surgical field. The anastomosis of the distal aortic arch is technically challenging, and bleeding from the anastomosis site is difficult to stop. Furthermore, chances of phrenic nerve and recurrent laryngeal nerve injury will be increased, especially for patients who present with hoarseness and difficulty in swallowing.\(^17\) Therefore, how to deal with these tasks remains a challenge for cardiac surgeons. In our technique, after the deployment of the stent graft into the descending aorta, distal anastomosis was avoided. Extensive dissection and resection of the aortic arch and brachiocephalic vessels can also be avoided. This will be less invasive, and the chances of anastomosis site bleeding and nerve injury will be reduced.

Since endovascular repair has emerged as a less invasive alternative treatment for patients with AAA, various modifications to the endovascular technique have been proposed, including the chimney technique, fenestrated technique, and hybrid technique. The chimney technique has been reported with lower mortality than totally open or hybrid technique; however, it is also associated with a high incidence of endoleak and long-term occlusions of branched grafts.\(^18,19\) Hybrid arch repair, which includes supra-aortic vessel transposition and endovascular therapy, has emerged as an alternative treatment option for AAA.\(^20\) But serious risks of stroke and paraplegia remain. Retrograde type A dissection is reported to be one of the most catastrophic complications, which requires reoperations.
and the reoperation still carries a high mortality rate.\textsuperscript{21} Endoleak is also reported to be another serious complication, which may require reoperation.\textsuperscript{21,22} Currently, no strong evidence supports hybrid arch repair is superior to TAR, although it is less invasive. Further studies with large numbers of participants and long-term follow-ups are necessary to confirm the effectiveness of hybrid arch repair.\textsuperscript{20}

Our aortic arch inclusion technique with FET in treating AAA can also be called “hybrid technique,” which combines the aortic arch reconstruction technique and stent graft implantation. Comparing our technique with the other hybrid techniques for aortic arch treatment, our technique does not require interventions of the three brachiocephalic vessels, and the sutures were done under direct surgical vision. Complications of the hybrid technique, such as endoleak and retrograde dissection, will also be avoided.

Extensive AAA in which aneurysms also involve the DTA is more surgically challenging. Different surgical approaches have been proposed; however, they all have advantages and disadvantages. In median sternotomy, distal anastomosis will have to be done on the aneurysmal tissue, and this would increase the difficulty in anastomosis. Chances of bleeding and long-term complications from the anastomosis site will also be increased. Besides, bleeding from the distal anastomosis site will be difficult to control because of the deep field. Using our technique, distal anastomosis was done on normal aortic tissue, which is solid and secure. After application of the aortic arch inclusion technique and FET implantation, TEVAR was inserted into FET during a one-stage surgery, thus providing complete coverage of the aneurysm. Furthermore, the TEVAR stent was inserted inside the FET, so the proximal expandable zone of TEVAR stent would not directly touch the intima of the aorta. In this way, our technique would cause no damage to the wall of the aorta and avoid the possibility of endoleak and pseudoaneurysm formation of other hybrid techniques. In our study, the aneurysm of this patient extended to the level of the 10th intercostal space, which is very surgically challenging (Figure 6). Our technique was effective in treating this patient, and the circulatory arrest time and postoperative recovery course of this patient were short. There was only one case with extensive AAAs in our study, and the effectiveness of our technique needs to be further validated.

Our follow-up results are satisfactory, with a mean follow-up period of 53.3 months. The initial results of AAA exclusion were 100% successful. One patient presented with aortic arch pseudoaneurysm formation at postoperative 10 months, and all other 14 patients who underwent follow-up CTA had no long-term complications. For this patient, we think that the most possible reason was suture dehiscence in which sutures were not penetrating through all layers of the aortic arch. Therefore, the blood flow caused consistent stress on the aortic arch wall, leading to the formation of false aneurysm. His aorta was repaired with artificial vascular patches by penetrating 4-0 polypropylene sutures. He developed no further aneurysm or endoleak after reoperation. Moreover, the patient was closely followed up ever since, and the CTA performed at postoperative 53 months showed no more endoleak, and his aortic arch has returned to a normal size. In our series, the average sizes of aneurysms during follow-up reduced from 6.1 ± 0.9 cm to 3.9 ± 0.3 cm, while some patients regained a normal size of the aorta. These results demonstrate that the aortic arch inclusion technique with FET shows good results in aortic remodeling.

The aortic arch inclusion technique is easy to perform and can be successfully applied in different medical conditions.\textsuperscript{6,23} There are two technical points to our technique. First, sutures must be performed on the healthy tissue of the aortic arch wall. The inclusion technique can be safely applied as long as there is a 5 mm healthy tissue between the aneurysms and orifices of the brachiocephalic vessels. Even though there is calcification in other parts of the aorta, it will not affect the application of the technique. Second, the sutures should be “all layers,” totally through the vascular graft and all layers of the aortic arch wall to achieve secure anastomosis. As for the only case with postoperative pseudoaneurysm formation, the most suspected reason was that the sutures did not penetrate through all layers of the aortic arch. Therefore, in our experience, penetrating sutures through all layers of the aortic arch is critical in achieving satisfactory aortic remodeling. This case was done in the early phase of the study, and after the complication of this patient, we have gained more experience in the following years. After that, no more patients developed postoperative endoleak or false aneurysm.

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**Figure 6.** CTA of the patient with extensive AAA. A, B: Preoperative extensive AAA. C: Postoperative AAA. AAA indicates aortic arch aneurysm.
This study has the following limitations. First, the application of this technique in AAA treatment has several indications and needs to be carefully selected. The choice of treatment should be based on the patients’ conditions as well as anatomical features. Second, this single-center observational, retrospective study on a specific cohort of patients was limited by its small size. A larger population with long-term follow-ups was needed to confirm the results.

Conclusion

The application of the aortic arch inclusion technique is an alternative technique for AAA treatment with satisfactory clinical and mid-term follow-up results in selected patients. A larger sample size with long-term follow-up results needs to be investigated.

Disclosure

Conflicts of interest: None.

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