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Review Article

Surgical Approaches to Single-Stage Extended Aortic Repair from the Ascending to the Distal Descending Aorta

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Single-stage extended replacement from the ascending to the distal descending aorta or beyond is a formidable operation that should be preserved for those who have no other option or those who are physically fit, and should be performed in the experienced centers. Hybrid operations combining open surgical repair with thoracic endovascular aortic repair through a median sternotomy incision are preferable because these operations are less invasive than the extended open aortic repair and the risk of spinal cord ischemia is lower compared with the frozen elephant trunk operation. However, these operations are associated with the inherent demerits of endovascular aneurysm exclusion. When the underlying aortic pathology necessitates extended open aortic repair in a single stage, approaches such as the anterolateral partial sternotomy, straight incision with rib cross, and extended thoracotomy with sternal transection may be useful to provide sufficient exposure for both aortic reconstruction and organ protection, with less surgical stress to the patients.

Keywords: extended aortic repair, aneurysms, aortic dissection, sternotomy, thoracotomy

Introduction

Diffuse aneurysmal disease extending from the ascending to distal descending aorta or beyond is preferably managed by staged aortic repair. Introduction of the elephant trunk operation by Borst et al.[1] is a milestone in this field, facilitating second-stage downstream aortic repair after aortic arch replacement. When the distal aortic pathology has higher surgical priority than the proximal one, the reversed elephant trunk operation has also been employed.[2,3] However, such an approach may sometimes be undesirable or impossible. While staged repair reduces surgical stress of each operation, it is associated with the risk of rupture while awaiting the second-stage surgery. Diffuse dilatation of the aortic arch may preclude safe anastomosis of the prosthetic graft to the arch aorta during the first-stage operation. Therefore, the needs for single-stage extended repair are constantly present.

Since the introduction of thoracic endovascular aortic repair (TEVAR) and the frozen elephant trunk (FET) operation, various strategies have become selectable for both single-stage and two-stage extended repair, including hybrid operations combining open surgery with TEVAR. In addition, specific complications of TEVAR, such as stent-graft infection, may necessitate full extraction of the TEVAR device,[4] which may require

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single-stage extended repair when initial TEVAR involved the aortic arch. This is an emerging problem in thoracic aortic surgery that necessitates complex and prolonged operation. Therefore, not only full access to the affected aorta but also secure organ protection is mandatory. In this review, we outlined the various approaches for single-stage extended aortic repair in the endovascular era.

Combined Median Sternotomy and Lateral Thoracotomy

The proximal aorta from the aortic valve to the aortic arch is best exposed through a median sternotomy, while exposure of the descending thoracic aorta is optimal through a lateral thoracotomy. Therefore, combined median sternotomy and lateral thoracotomy through the fourth to the sixth intercostal space has long been used for extended repair. The patients are usually placed in the right semi-lateral position with the left arm elevated. Lateral thoracotomy incision may be either separate from or connected to the sternotomy incision.

In this approach, optimal exposure of the proximal aorta from the aortic valve to the supra-aortic vessels is provided, enabling the secure myocardial and brain protection. In addition, the descending thoracic aorta can be cross-clamped, which enables maintenance of distal aortic perfusion and obviates the need for deep hypothermia when selective cerebral perfusion is used. On the other hand, exposure of the descending thoracic aorta can be suboptimal when the thoracotomy incision is not connected to the sternotomy, depending on the patient positioning; while a more tilted positioning improves exposure of the descending thoracic aorta, it may compromise exposure of the proximal aorta. In addition, dense lung adhesion to the distal aortic arch may be difficult to dissect without extensive lung mobilization, which may result in alveolar hemorrhage and prolonged mechanical ventilation.

When the thoracotomy incision is connected to the sternotomy, exposure of the distal aortic arch is improved.[5,6] However, this approach, which we call the "door open" technique and had widely been used in the early 1990s in Japan,[6] is not preferably used in our country any more. One reason, in addition to the frequent postoperative respiratory problems as discussed later, is delayed wound healing at the junction between the sternotomy and thoracotomy incisions that is frequently seen postoperatively.

Combined median sternotomy and lateral thoracotomy incision, either separate or connected, frequently resulted in postoperative prolonged ventilator support. This may be due to its invasiveness to the bony thorax and suboptimal exposure of the descending thoracic aorta, which may necessitate extensive lung mobilization and result in alveolar hemorrhage. In addition, reconstruction of the intercostal arteries may be difficult through this approach. In the endovascular era, hybrid operations combining open aortic arch repair with TEVAR can be a potent alternative when resection of the descending thoracic aorta and reconstruction of the intercostal arteries are not mandatory. Therefore, such approaches became less frequently used.

Combined median sternotomy and thoracoabdominal incision

When the aortic pathology extends into the abdominal aorta, median sternotomy combined with a separate thoracoabdominal incision[7,8] has been employed. We have previously used a full median sternotomy combined with a thoracoabdominal incision through the sixth intercostal space and an extraperitoneal exposure of the abdominal aorta, with the patient placed in a semi-lateral position.[8] Although this approach provided sufficient exposure for myocardial and brain protection and for reattaching the intercostal arteries, postoperative prolonged mechanical ventilation was also a major issue. We no longer use this approach, since the aorta can be exposed through a thoracoabdominal incision without a sternotomy[9–11] or through the straight incision with rib-cross (SIRC) approach.[12]

Hemi-clamshell approach

The hemi-clamshell approach that employs upper partial sternotomy connecting to the thoracotomy[13–15] has also been proposed for the aortic pathologies involving the distal aortic arch. Compared to the "door open" technique, this approach may not only reduce the surgical stress but also solve the issue of wound healing. However, since the exposure of the aortic root and the distal descending aorta becomes worse, it is not suitable for extended aortic repair. This approach, which was called the "trap door" approach or L-incision and had been used in some Japanese centers in the early 2010s,[13,14] was mostly abandoned in our country, because respiratory complications were prevalent,[14] and the distal aortic arch can be approached through a standard full median sternotomy alone.

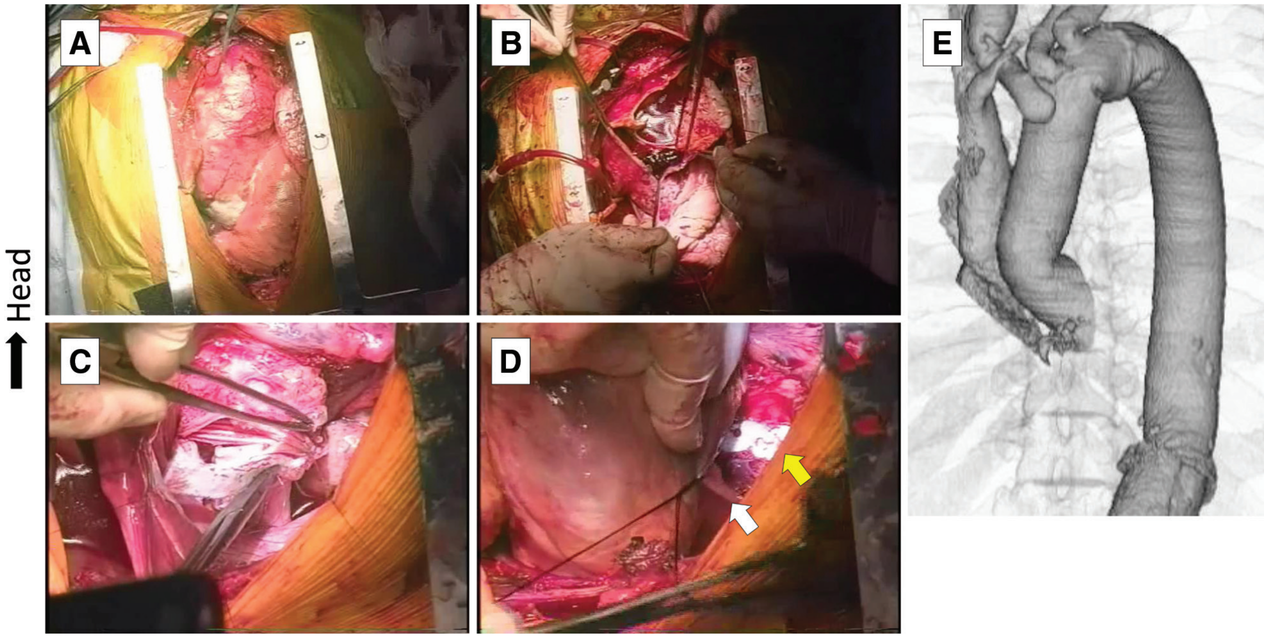

Fig. 1 Exposure of the distal descending thoracic aorta through a median sternotomy with left pleurotomy. (**A**) Ascending aorta after sternotomy. (**B**) After the ascending aorta was opened. (**C**) Distal anastomosis using the pull-through technique. The distal descending aorta was exposed through the left pleurotomy after the heart was displaced to the right along with the pericardium. (**D**) Distal anastomotic site (yellow arrow) and the pericardium (white arrow) while the heart was being returned to the original position. (**E**) Postoperative 3-dimensional computed tomography.

Anterolateral thoracotomy with partial sternotomy

The anterolateral thoracotomy with partial sternotomy (ALPS),[16–19] first described by Yunoki and Oba in the 32nd annual meeting of the Japanese Society for Vascular Surgery in 2004, provides sufficient exposure from the aortic valve to the distal descending aorta. In its original form, the lower partial median sternotomy is continued to the anterolateral thoracotomy through the fourth intercostal space.[18] This approach provides full access to the aortic root.[17,19] To better expose the innominate artery, several authors prefer to enter the third intercostal space.[16,17,19] However, exposure of the distal descending aorta may become suboptimal when the third intercostal thoracotomy is selected. The incidence of respiratory complications is reportedly low; prolonged mechanical ventilation was required in 6%–17%,[18,19] which was comparable to that after median sternotomy.[19] This approach seems to be the best option when replacement from the aortic root to the distal descending aorta is mandatory.

Median Sternotomy

Median sternotomy incision provides optimal exposure of the heart, ascending aorta, aortic arch, and supra-aortic vessels, enabling secure myocardial and cerebral protection. We can optimize the exposure of the left subclavian artery by dividing the left anterior cervical muscles. The distal aortic arch is accessible without entering the pleural cavity, and the proximal descending aorta can be reached down to the carina level through the pleural cavity.[20]

To expose the distal descending aorta, the left mediastinal pleura is totally opened, and the heart is displaced to the right along with the pericardium during circulatory arrest (**Fig. 1**). This technique, first reported by Minale et al.[21] and subsequently used by many others,[17] can provide access to the descending thoracic aorta between the pulmonary hilus and the diaphragm. However, reattachment of the intercostal arteries may be difficult, and suture closure of the proximal intercostal arteries, especially those behind the carina, is impossible. Therefore, retrograde pull-through operation[22] is frequently selected through this approach.

Alternatively, the distal descending aorta can be exposed through the posterior pericardial approach.[23] In this method, the pericardium behind the heart is longitudinally opened without entering the pleural cavity, after the heart is displaced. This technique is advantageous when dense lung adhesion is present. It can provide access to the supraceliac abdominal aorta through a

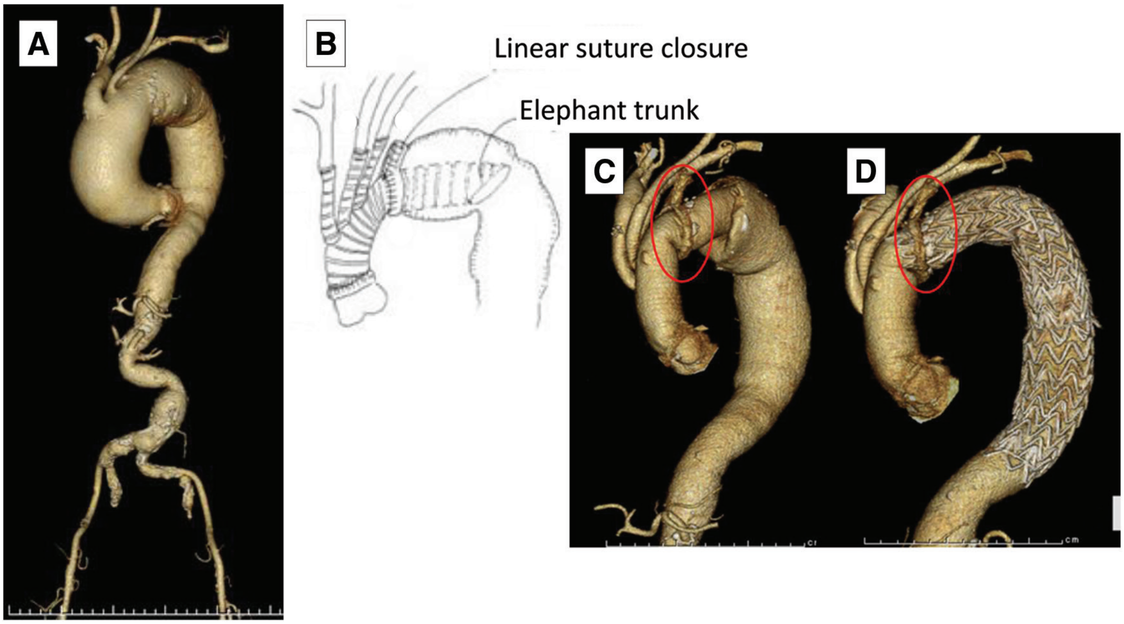

Fig. 2 Plication of the dilated aortic arch for the distal anastomosis of aortic arch replacement. The aorta was linearly suture closed on the cranial side to accommodate its size to the prosthetic graft. Although this patient underwent 2-stage hybrid operation, such a technique may more safely be applied in a single-stage hybrid operation. (**A**) Preoperative 3-dimensional computed tomography. (**B**) Schematic drawing of the elephant trunk operation. (**C**) 3-dimensional computed tomography after the elephant trunk operation. (**D**) 3-dimensional computed tomography after completion of TEVAR. TEVAR: thoracic endovascular aortic repair

median laparotomy with mid-line division of the diaphragm. On the other hand, access to the proximal side is limited, compared to the transpleural approach. Therefore, reconstruction or suture closure of the intercostal arteries is also difficult through this approach. We have used it in a patient with a history of descending aortic replacement who underwent concomitant replacement of an aortic arch aneurysm and a localized thoracoabdominal aortic aneurysm,[23] or in a patient with diffuse aneurysmal disease and poor pulmonary function who underwent aortic arch replacement and exclusion of the descending thoracic aorta for rupture.[24]

In the TEVAR era, such an approach has become less frequently used. Both the pull-through operation and the aneurysm exclusion have a problem of sac growth that is similar to the type-2 endoleak after TEVAR, while these operations are much more invasive than the single-stage hybrid repair combining open surgery with TEVAR. On the other hand, access to the distal descending thoracic aorta through a median sternotomy may be a valuable option in the FET operation for chronic aortic dissection because it provides the possibility of descending aortic procedures to block the retrograde blood flow in the false lumen.

Single-stage hybrid operation

The hybrid aortic repair combining TEVAR with total debranching bypass, which is sometimes called type-1 hybrid arch,[25] is not suitable for extensive aortic disease, since the presence of healthy ascending aorta is mandatory. On the other hand, type-2 or -3 hybrid arch operation combining TEVAR with graft replacement of the ascending aorta to the aortic arch can be applied to the extensive aortic pathology in a single stage.[26] When diffuse aortic dilatation is present, these operations may not be a good option because the aortic graft needs to be sutured to the dilated aorta. However, since the distal anastomotic site is excluded by TEVAR, dilated aorta can be selected as an anastomotic site either by adding aortic plication (**Fig. 2**) or by using a collared graft.[27] Unlike the FET operation, single-stage hybrid operations are not associated with high incidence of spinal cord ischemia.[26] Such operations seem useful for patients with poor pulmonary function but is associated with the problem of sac growth in the long term.

Frozen elephant trunk (FET) operation

The FET operation was first described by Kato et al. for the surgical treatment of aortic dissection[28] and

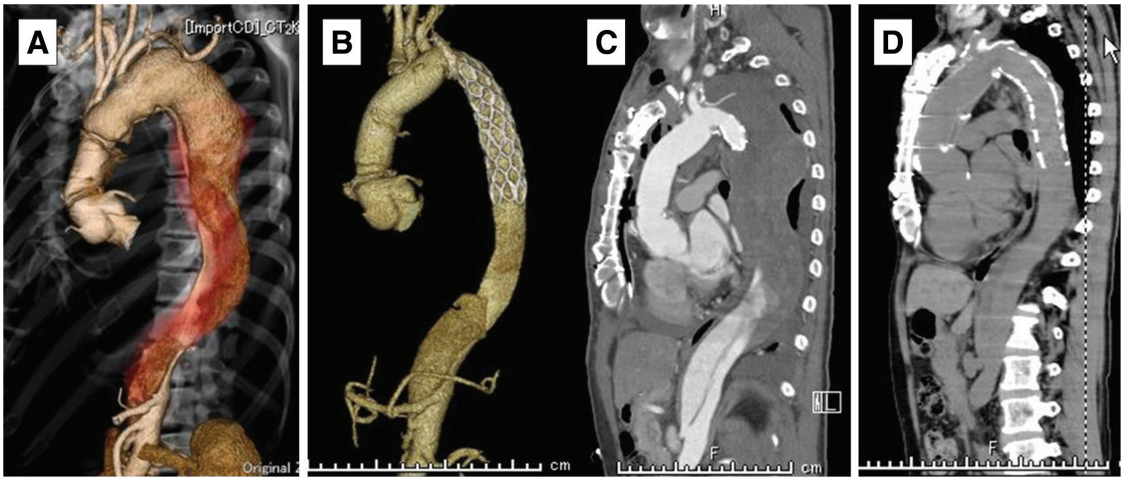

Fig. 3 Complete remodeling of the thoracic aorta after the FET operation. (**A**) Preoperative 3-dimensional computed tomography of a patient after hemiarch replacement for acute type A aortic dissection performed elsewhere. (**B**) Postoperative 3-dimensional computed tomography after the FET operation. (**C**) Multiplanar reconstruction of the postoperative computed tomography showing the dilated false lumen. (**D**) Multiplanar reconstruction of the computed tomography 2 years postoperatively showing complete remodeling of the thoracic aorta. FET: frozen elephant trunk

subsequently for the aneurysms involving the distal aortic arch.[29] This operation has also been used for extensive aortic aneurysms.[30–32] In our initial experience with the FET operation for an extensive aortic aneurysm, we tried to preserve the important intercostal artery using an angioscopy.[30] However, the FET operation is associated with an elevated risk of ischemic spinal cord injury.[31,33–36] Risk factors for spinal cord ischemia include the distal landing zone lower than the 7–10th thoracic vertebral level, a history of abdominal aortic aneurysm repair, atherosclerotic aneurysms, fusiform aneurysms, non-elective operations, postoperative hypotension, and diabetes mellitus.[31,33–36] Although selective antegrade cerebral perfusion to all the 3 supra-aortic vessels and distal aortic perfusion during deployment have been reported protective, these procedures do not completely prevent spinal cord ischemia. Therefore, we no longer use the FET operation for the atherosclerotic aneurysms because the descending thoracic aorta down to the carina level is accessible through a standard median sternotomy, and considering the extra length required for secure distal landing, the FET operation carries an elevated risk of spinal cord ischemia for the aneurysms with distal extension beyond the carina level.

If the FET device is not “frozen,” either intentionally to facilitate subsequent TEVAR completion or unintentionally due to insufficient distal landing, the flapping motion of the device may result in aortic wall injury. In the 1990s, we experienced a case of aneurysm rupture early after the FET operation that was caused by this mechanism. The insertion of FET device may be too deep or too shallow, since the transesophageal echo is not precise enough to control the distal landing zone. Therefore, we believe that hybrid operations consisting of the conventional elephant trunk and TEVAR are preferable for extensive aneurysms.

For chronic aortic dissection with diffuse dilatation of the thoracic aorta, the FET operation is increasingly used because the device can be inserted into the narrow true lumen with low risk of kinking or obstruction. It is usually the first-stage operation of the staged treatment, since insertion of the FET below the 7–10th thoracic vertebral level is generally avoided to prevent spinal cord ischemia. Eliminating antegrade blood flow to the false lumen by the FET frequently results in remodeling of the portion of aorta covered by the stent graft.[37–39] Therefore, although the distal false lumen may continue to expand due to the retrograde flow,[37] early second-stage surgery is not mandatory in most cases. This is in clear contrast to the fate of descending aorta after the non-FET operation; since the conventional elephant trunk is usually inserted into the common channel after the flap is resected, rapid expansion of the residual false lumen is anticipated, necessitating early second-stage surgery. Furthermore, complete aortic remodeling may be expected in some cases after the FET operation,[38] obviating the need for second-stage surgery (**Fig. 3**). Therefore, the FET operation may be worth considered as an

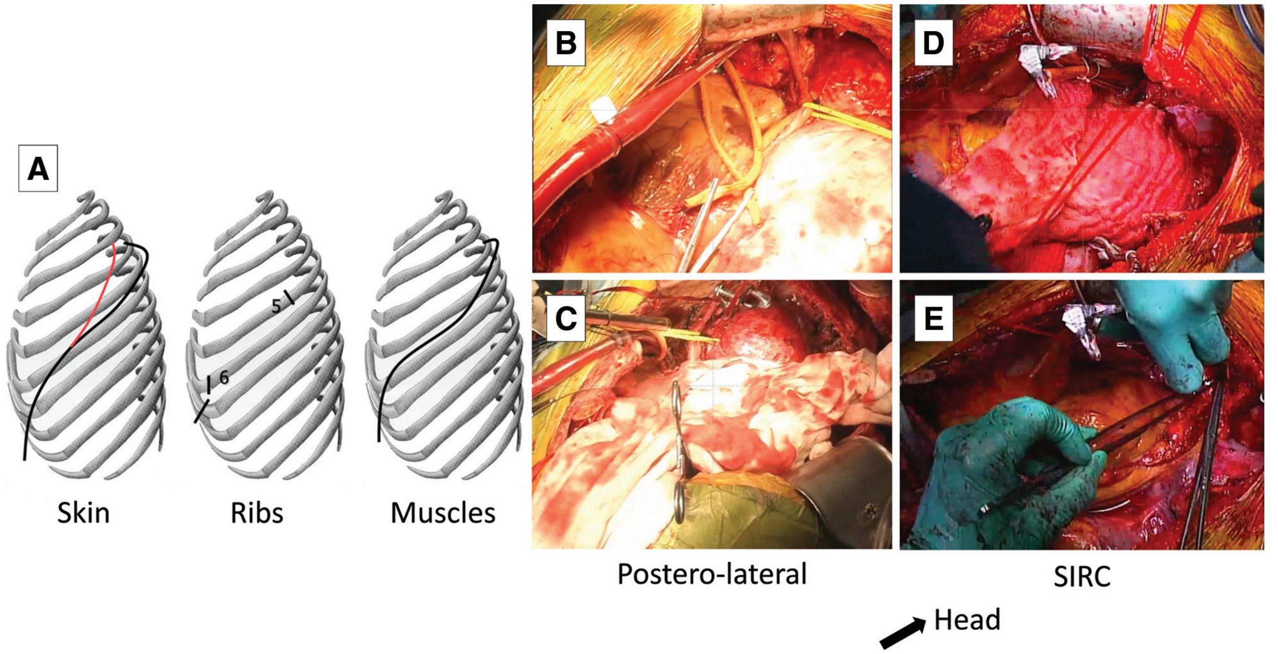

Fig. 4 Comparison of the posterolateral thoracotomy and the SIRC approach. (**A**) Incision of the skin, ribs, and intercostal muscles. Black lines indicate the posterolateral thoracotomy incision, while the red line indicates skin incision of the SIRC approach. Rib and muscle incision of the SIRC approach is the same as that of posterolateral thoracotomy. (**B** and **C**) Ascending aortic cannulation (**B**) and cross-clamping the supra-aortic vessels (**C**) before circulatory arrest through the posterolateral thoracotomy. (**D** and **E**) Ascending aortic cannulation (**D**) and encircling the innominate artery (**E**) before circulatory arrest through the SIRC approach. SIRC: straight incision with rib cross

alternative to single-stage extended repair for chronic expanding aortic dissection, including that after hemiarch replacement for type A aortic dissection.[38]

When applying the FET operation for chronic aortic dissection, care should be taken to prevent distal stent graft-induced new entry (SINE) because chronic dissection is a risk factor for SINE.[40,41] Other risk factors for distal SINE include excessive oversizing, aortic angulation, device length, a small false lumen, and the spring back force of the device.[40,42,43] Therefore, the distal end of the device should be placed in the straight portion of descending aorta with minimum oversizing. Since distal SINE is easy to fix by TEVAR if it is recognized before the catastrophic event and the incidence is high irrespective of the device used,[40,41,43] appropriate follow-up protocol is warranted after the FET operation for aortic dissection.

Lateral Thoracotomy

Lateral thoracotomy incision provides optimal exposure of the aorta from the left subclavian artery to the diaphragm. It can be continued to the abdomen when the thoracoabdominal aorta is involved. To expose the entire descending thoracic aorta, the fourth and seventh intercostal spaces are opened classically through a single or 2 skin incisions. More recently, the sixth (or fifth) posterolateral intercostal thoracotomy has been used with division of the costal margin.[44,45] However, exposure of the proximal aorta is difficult through this approach.

To better expose the ascending aorta and the entire aortic arch through a posterolateral thoracotomy, we enter the pleural cavity through the fifth intercostal space and extend the incision into the fourth interspace dorsally and sixth ventrally with rib cross.[46,47] Through this approach, we cannulate the ascending aorta for arterial inflow in deep hypothermic operations and selectively perfuse the brain unilaterally (left subclavian and left carotid perfusion with a clamp on the innominate artery) (**Fig. 4**). We could perform simultaneous total aortic replacement from the sinotubular junction to bifurcation through this approach.[9] Several authors have reported simultaneous replacement of the total aortic arch and the descending aorta down to or below the diaphragm using a similar approach.[10,11,17] However, reconstruction of the innominate artery is difficult, and protection of the heart

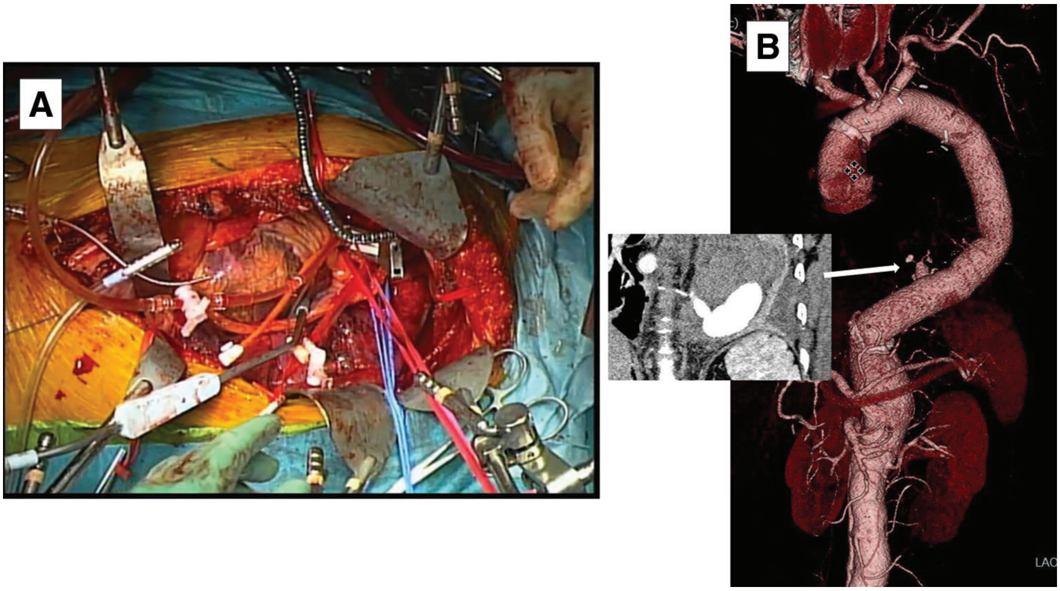

Fig. 5 Single-stage aortic replacement from the ascending aorta to the diaphragm through the SIRC approach. (**A**) Operative view. The ascending aorta was cross-clamped and a cardioplegic solution was delivered through the aortic root. (**B**) Postoperative 3-dimensional computed tomography showing the patency of the reconstructed intercostal artery. SIRC: straight incision with rib cross

and brain is suboptimal. Therefore, we switched from the posterolateral incision to the SIRC,[47] which will be discussed in the next section.

Straight incision with rib cross (SIRC)

The SIRC approach, first described by Minatoya et al. in 2016,[12] was developed to preserve the thoracodorsal artery as a potential collateral source to the spinal cord. In its original form, a straight incision is made from the axilla to the umbilical region, the fourth to sixth ribs are transected beneath the skin incision, and the latissimus dorsi muscle and thoracodorsal artery are preserved. We transect the fifth rib at the posterior axillary line and the sixth rib at the costal angle, and divide the fourth intercostal muscles dorsally up to the erector spinae muscles, preserving the latissimus dorsi muscle. The way we open the rib cage is exactly the same as the one we use for posterolateral thoracotomy (**Fig. 4**). We found that the SIRC approach improves exposure of the innominate artery and the ascending aorta, enabling the ascending aortic cross-clamping for secure myocardial protection and facilitating innominate artery reconstruction (**Figs. 4** and **5**).

Clamshell approach

Bilateral anterior thoracotomy, usually through the fourth interspace, with transverse sternotomy, which is also called the clamshell incision, has been used for single-stage extended aortic replacement.[17,21,48] This incision provides sufficient exposure of the entire thoracic aorta; however, respiratory complications are frequent. In the largest experience by Kouchoukos (n = 95), in-hospital mortality was 8.4% and prolonged (>72 hours) mechanical ventilation was required in 48%.[49] Therefore, it has not been widely used for aortic surgery.

Thoracotomy with sternal transection (extended thoracotomy)

Sternal transection with minimum extension into the contralateral intercostal space has been used as a method to improve exposure of the ascending aorta and the entire aortic arch.[10,50,51] This approach is sometimes called an extended thoracotomy. We enter the pleural cavity through the fourth interspace, extend the incision into the third interspace ventrally and fifth interspace dorsally with rib cross, according to the extent of distal extension. The sternum is transected obliquely into the right second interspace to facilitate exposure of the innominate artery, with division of the left internal thoracic artery (**Fig. 6**). The right internal thoracic artery is preserved, and the right pleural cavity is not entered as far as possible. We found that this approach is particularly useful for those who had a history of ascending to aortic arch replacement and required full access to the

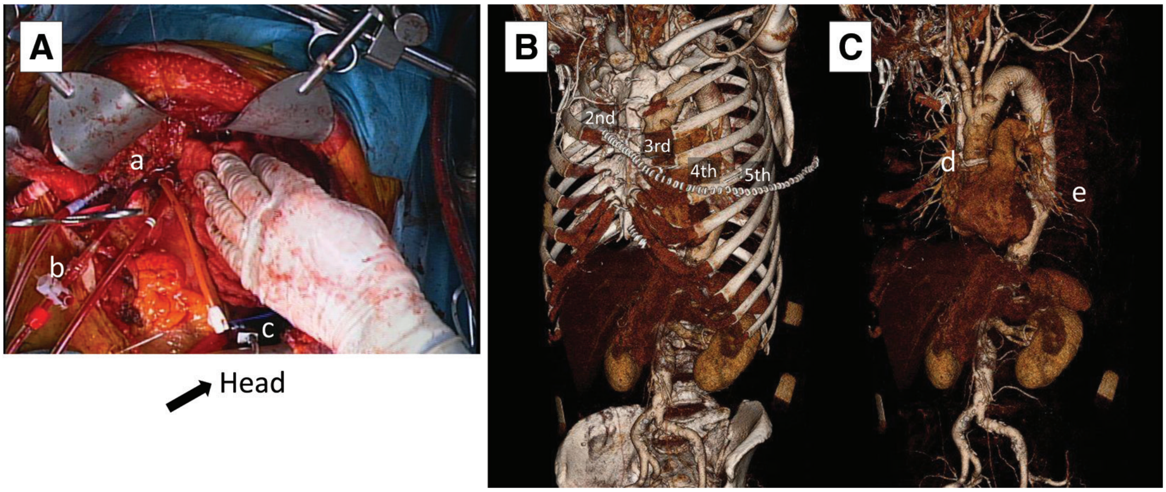

Fig. 6 Single-stage aortic replacement from the ascending aorta to the distal descending thoracic aorta through an extended thoracotomy in a patient with a history of ascending to aortic arch replacement. (**A**) Operative view. (a) A clamp on the ascending aortic graft. (b) A cardioplegic needle. (c) A clamp on the descending thoracic aorta. (**B** and **C**) Postoperative 3-dimensional computed tomography showing the incision (**B**) and the reconstructed aorta (**C**). (d) Proximal anastomotic site. (e) Distal anastomotic site.

previous graft and the entire descending aorta.[52] On the other hand, this approach does not provide sufficient exposure for aortic root replacement. In our limited experience with 5 cases, there were no in-hospital deaths and no patients required prolonged (>72 hours) mechanical ventilation, including 2 patients with secondary aortoesophageal fistula[52] and 1 patient with rupture.

Conclusion

Single-stage extended replacement from the ascending to the distal descending aorta is a formidable operation that should be preserved for those who have no other option or those who are physically fit and should be performed in the experienced centers. Hybrid operations combining open surgical repair with TEVAR through a median sternotomy incision are preferable because these operations are less invasive than the extended open aortic repair and the risk of spinal cord ischemia is lower compared with the FET operation. However, these operations are associated with the inherent demerits of endovascular aneurysm exclusion. When the underlying aortic pathology necessitates extended open aortic repair in a single stage, approaches such as the ALPS, SIRC, and extended thoracotomy may be useful to provide sufficient exposure for both aortic reconstruction and organ protection with less surgical stress to the patients.

Disclosure Statement

All authors including spouses and other immediate family members have no financial relationships with commercial manufacturers, pharmaceutical companies, or other commercial entities that have an interest in the subject matter or materials discussed in this manuscript.

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