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ORIGINAL ARTICLE

STATE OF THE ART AND CURRENT TRENDS IN THE REPAIR OF THORACOABDOMINAL AORTIC ANEURYSMS AND DISSECTIONS

Open repair of thoracoabdominal aortic aneurysms under left heart bypass

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ABSTRACT

Background: Thoracoabdominal aortic aneurysm (TAAA) open surgical repair (OSR) is a highly complex procedure associated with significant mortality and morbidity. Despite advancements in surgical techniques and organ protection strategies, TAAA OSR remains a challenge. This study analyzes nearly 35 years of experience at a single center, with a focus on the evolution of surgical approaches and adjuncts, particularly the use of left heart bypass (LHBP) for organ perfusion maintenance.

Methods: This retrospective study was performed on all the patients who underwent elective TAAA OSR at our institution between 1989 and 2024. Patients were divided into two groups: Group 1 (1989-2009), where adjuncts were used selectively, and Group 2 (2010-2024), where a systematic multimodal approach was implemented. Preoperative, intraoperative, and postoperative data were analyzed to assess the impact of evolving surgical techniques, adjuncts, and patient outcomes. Key adjuncts included cerebrospinal fluid drainage (CSFD), motor and somatosensory evoked potentials (MEP&SSEP), LHBP, renal perfusion strategy, and rotational thromboelastometry.

Results: In total, 1211 patients underwent elective TAAA OSR, with 455 patients in Group 1 and 756 in Group 2. A modified surgical approach was employed in the two groups, with significant differences in terms of sites of aortic cross-clamping, techniques for vessel reconstruction, and approach in the management of intercostal artery. In addition, significant differences between the groups were observed for what concern the use of adjuncts. Regarding the outcomes, Group 2 demonstrated a significantly lower 30-day mortality rate (7.5% in Group 2 *vs.* 13.4% in Group 1; P=0.001), and a reduction in permanent spinal cord ischemia (SCI) (7.4% in Group 2 *vs.* 11.9% in Group 1; P=0.012). Additionally, Group 2 exhibited trends toward reduced respiratory failure and renal complications, but these differences were not statistically significant.

Conclusions: This single-center experience highlights the evolution of TAAA OSR over 35 years, demonstrating a significant reduction in mortality and SCI with the use of a comprehensive, multimodal approach. Although there were improvements in postoperative complications, further advancements are needed in this complex field to optimize outcomes. The ongoing refinement of surgical techniques and adjuncts continues to play a crucial role in improving patient care.

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Key words: Aorta; Aortic aneurysm, thoracoabdominal; Vascular surgical procedures.

Thoracoabdominal aortic aneurysm (TAAA) open surgical repair (OSR) is one of the most complex procedures in vascular surgery, posing a significant challenge for surgeons, anesthesiologists, and patients. The procedure is demanding due to both the technical complexity of aortic reconstruction and the physiological stress it places on patients, who are often elderly and have multiple comorbidities. Consequently, TAAA OSR carries notable risks of mortality and morbidity.[1-5]

Over the past decade, advancements in surgical techniques and organ protection strategies have led to significantly improved outcomes.[1, 4, 6] Among these strategies, the method used to maintain organ perfusion plays a critical role. Several approaches can be employed to sustain organ perfusion during TAAA OSR, while alternative techniques involving circulatory arrest may also be used to protect vital organs.[7-9]

In this study, an analysis of our center experience with TAAA OSR is reported, and the evolution of the therapeutic approach is described. The experience gained at our center over more than 30 years has shaped the treatment protocol, and contributed to better patient outcomes. In particular, we highlighted the technique used at our center to maintain organ perfusion during the procedure, namely the left heart bypass (LHBP).

Materials and Methods

Patients

Patients undergoing TAAA OSR at our institution between January 1989 and December 2024 were prospectively entered into a database and later analyzed retrospectively. Clinical data from these patients were examined for preoperative factors, comorbidities, surgical details, and outcomes. Patients with ruptured or contained ruptured TAAA were excluded from this analysis.

Over this 35-year period, the management of patients with TAAA undergoing OSR has evolved, with several improvements in both techniques and adjunctive strategies. These additions, referred to as “adjuncts,” were initially used selectively and later routinely in this reported experience. To assess the impact of these adjuncts on postoperative outcomes, the data were divided into two groups: Group 1 (January 1989 to December 2009) and Group 2 (January 2010 to December 2024). Group 1 includes patients from the early years with selective adjunct use, while Group 2 includes those treated with a systematic approach to adjuncts.

This research was carried out following the guidelines of the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) for reporting observational studies. Informed consent for data collection was obtained in accordance with our institution’s consent form and was approved by our Institutional Review Board under Italian law.

Preoperative patients’ assessment, and preoperative adjuncts

Routine preoperative evaluations included the assessment of carotid and peripheral arteries via duplex scan. The lung function was evaluated through chest X-rays, blood gas analysis, and respiratory function tests. In case of severe chronic obstructive pulmonary disease (COPD), respiratory therapy, physiotherapy, and smoking cessation were suggested to the patients, and bronchodilators and steroids were administrated if needed. Renal function was assessed using blood tests, with chronic renal failure defined as an estimated glomerular filtration rate (eGFR) <60 mL/min/1.73 m^2.

When no specific contraindications were present, multidetector computed tomography angiography (CTA) was the preferred imaging modality to thoroughly analyze patients with TAAA, for both open and endovascular approach. Advanced post-processing software allows for comprehensive assessment of the aorta, collateral vessels, and spinal cord vasculature.[10] Since 2010, we have used ECG-gated Coronary CTA (CoroCTA) for patients with TAAA to simultaneously evaluate both the aorta and coronary arteries.[11] This enables us to identify coronary stenosis or blockages, improving patient risk stratification and the possibility of preoperative coronary interventions. In cases of significant coronary disease, a preoperative percutaneous coronary angioplasty with bare-metal stents is generally favored to minimize the need for dual antiplatelet therapy, thereby avoiding potentially dangerous delays in TAAA treatment.[12]

Over the past two decades, many Authors have emphasized the importance of patient selection, also in vascular surgery. Among the various tools to assess patient fitness, sarcopenia has emerged as a potential method for stratifying the risk of postoperative complications in patients with TAAA, in particular for what regard the endovascular management of this pathology. However, this tool has not been extensively studied for what concern OSR, with initial results showing no significant impact of sarcopenia analysis in patients with TAAA undergoing open surgical repair.[13]

Pre- and intraoperative adjuncts for spinal cord protection

Spinal cord ischemia (SCI) is a severe complication of TAAA OSR, impacting both short- and long-term outcomes and survival.[14-17] Despite the role of cerebrospinal fluid drainage (CSFD) has been widely discussed in endovascular TAAA repair, this tool has been shown to prevent SCI in TAAA OSR in randomized controlled trials, and its usage is recommended by recent guidelines.[18-20] In our practice, CSFD was placed by the anesthesiologist in the operating room before anesthesia induction, typically at the T7-T8 level using a loss-of-resistance technique. CSFD has been a standard practice at our center since 2003, initially using a dripping chamber-based system, later replaced in 2013 with an automated system (LiquoGuard - Möller Medical GmbH, Fulda, Germany).[21] CSFD is used routinely for patients with TAAA extension I to III, and selectively for extent IV cases, ad it is typically maintained for 48-72 hours after surgery, or longer in cases of neurological issues.[22] Since 2012, motor and somatosensory evoked potentials (MEP&SSEP) have also been routinely monitored to detect any impairment in spinal cord perfusion and function during surgery.[23]

Surgical procedure, LHBP, and other intraoperative adjuncts

When the preoperative maneuvers and the patient positioning have been completed, the surgical procedure begins with exposure of the thoracic and abdominal aorta. The surgical approach adopted for TAAA OSR at our institution has been outlined in previous descriptions from the same Authors.[24, 25]

The left superior (or inferior) pulmonary vein (LPV) and the left common femoral artery (CFA) are carefully exposed to establish left heart bypass (LHBP). The left CFA cannulation is generally performed through a surgical cut-down in the groin, with the exposure of the artery and with a purse-string suture; however, a percutaneous approach may also be employed. A cannula is inserted into the LPV, where oxygenated blood is drained and subsequently re-infused through a centrifugal pump into the left CFA. This process enables retrograde perfusion of critical vessels, including the intercostal, the visceral, and the renal arteries, while sequential cross-clamping is carried out. Additionally, two (or more) perfusion catheters are connected to the bypass circuit and are employed during visceral aortic replacement to selectively perfuse the celiac trunk (CT) and the superior mesenteric artery (SMA) (Figure 1). LHBP was first introduced into our practice in 1993, and since then, it has become a standard procedure at our institution for all patients with TAAA extension I-III; it is employed selectively for patients with TAAA extension IV. Furthermore, since 2013, the entire surgical procedure has been performed under continuous transesophageal echocardiography (TEE). This adjunctive intraoperative diagnostic tool allows to early detect any cardiac dysfunction, enabling prompt adjustments to be made to modulate the cardiac afterload and improve patient outcomes. In addition, an effective evaluation of the correct position of the cannula in the LPV is also offered to the surgeon and the perfusionist.

When the LHBP has been established and the circulatory assistance initiated, the clamps are positioned at the most suitable location. In case of extent I and II TAAA, the proximal clamp is typically placed between the left common carotid artery (LCCA) and the left subclavian artery (LSA), or just after the LSA. The distal clamp is placed a few centimeters below the proximal one, in this way, with this “sequential clamping approach”, the portion of aorta excluded from the blood-flow is limited, and the organ perfusion maintained (proximally from the heart, and distally from the LHBP). The descending thoracic aorta is then opened and carefully divided from the esophagus, with

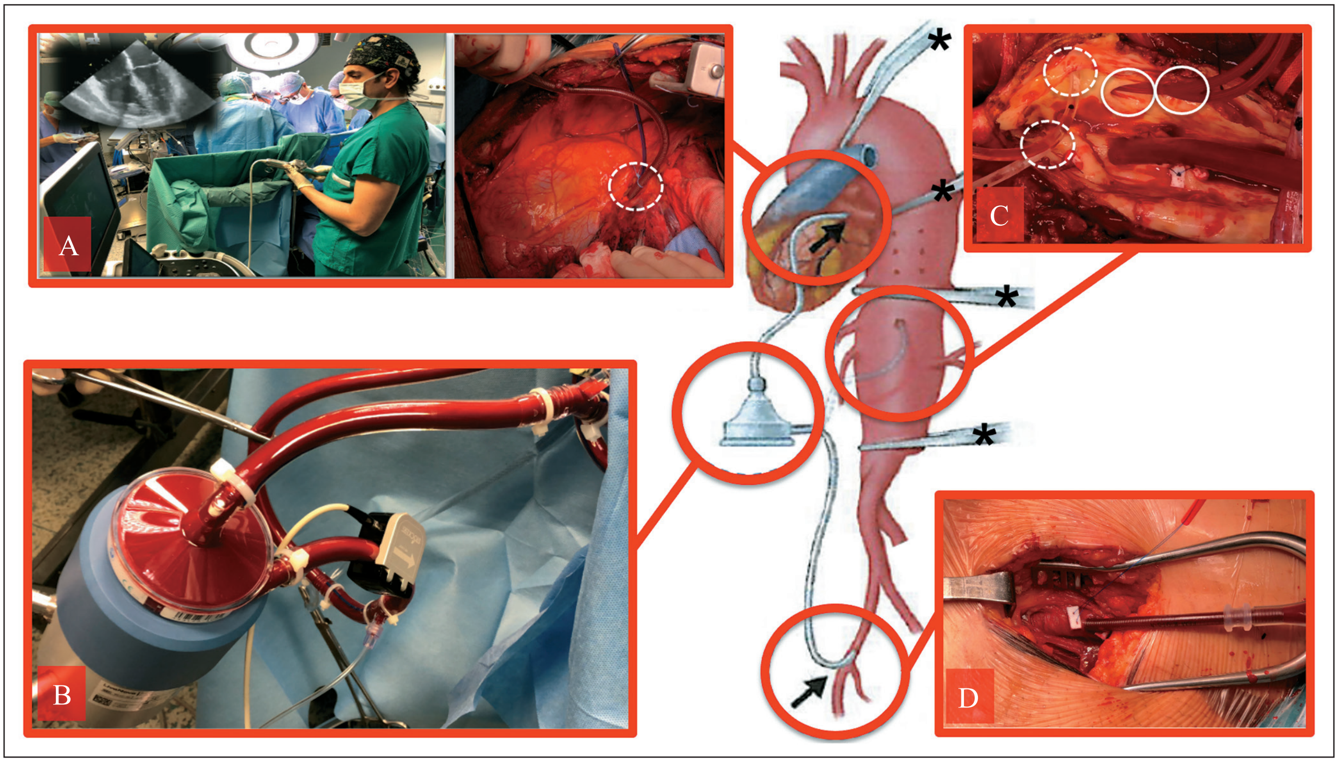

Figure 1.—A schematic overview of left heart bypass (LHBP). A) The left superior (or inferior) pulmonary vein (LPV) is carefully exposed, and a cannula is inserted into the LPV to drain oxygenated blood (dotted circle). Throughout the procedure, continuous transesophageal echocardiography (TEE) is used: this intraoperative diagnostic tool helps to detect cardiac dysfunction early, allowing for quick adjustments to manage cardiac afterload and improve patient outcomes. During this phase, it also provides the surgeon and perfusionist with a reliable assessment of the cannula's position in the LPV. The oxygenated blood is re-infused via a centrifugal pump (B) into the left CFA (D). Typically, left CFA cannulation is performed through a surgical incision in the groin, where the artery is exposed and a purse-string suture is placed; however, a percutaneous approach may also be used. Retrograde cannulation of the CFA allows retrograde perfusion of key vessels such as the intercostal, visceral, and renal arteries during sequential cross-clamping (*). C) Additionally, two or more perfusion catheters are connected to the LHBP circuit and used for selective perfusion of the celiac trunk and superior mesenteric artery with oxygenated blood during visceral aortic replacement (circles). During this phase, the renal arteries are cannulated and perfused with cold Custodiol (dotted circles).

non-essential intercostal arteries being ligated. The proximal end of a surgical graft is then sutured to the descending thoracic aorta using a continuous running suture with 2/0 or 3/0 Prolene, reinforced with pledgets. The proximal clamp is then removed to check the proximal anastomosis. Then, the distal clamp is removed, and it is repositioned on the distal thoracic aorta just above the CT. The aortic incision is then extended down to the diaphragm, with intercostal arteries being identified and temporarily occluded with occlusion Pruitt catheters. Reattaching the critical patent intercostal arteries, typically from T7 to L2, to the aortic graft is an important step that may help protect the spinal cord.[26] During this phase, MEP&SSEP are monitored to identify any potential issues with spinal cord perfusion. If any changes are detected in the SC function, the intercostal arteries are promptly reconnected to the aortic graft. The reattachment of the intercostal arteries can be performed through an island technique using a customized side-cut in the graft, or by selective bypasses.[26]

The distal clamp is then repositioned below the renal arteries, and the aneurysm is opened. Both the CT and the SMA are catheterized and selectively perfused with isothermic blood from the LHBP, while the renal arteries are catheterized and perfused with a cold solution. While different kind of perfusion has been adopted to protect the kidneys during vascular procedures, since 2009 a selective renal perfusion using histidine-tryptophan-ketoglutarate (HTK) solution (Bretschneider's) at 4 °C has been implemented during TAAA OSR to provide renal protection.[27-29] The visceral and renal arteries are reattached to the aortic graft using a tailored side cut in the graft (Carrel patch) or through selective bypasses. In patients with genetically triggered aortic diseases, such as Marfan syndrome, the reattachment of large sections of native aorta is typically

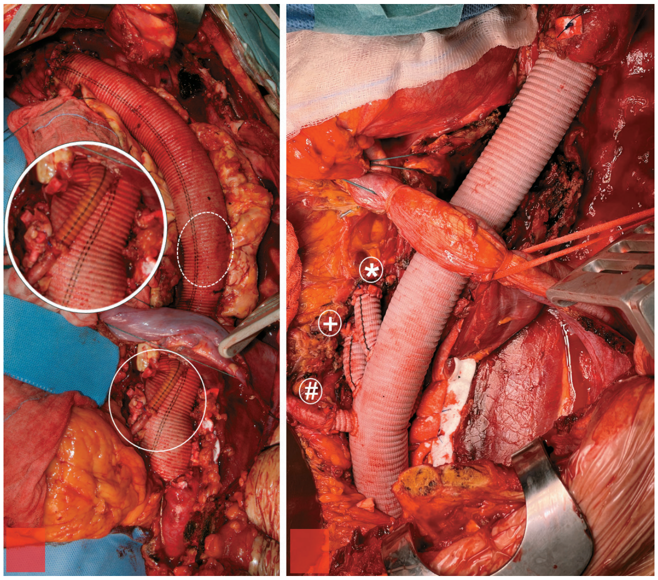

Figure 2.—Two intraoperative images of patients treated with OSR in Group 2. (A) Final repair after OSR of an Extent II TAAA with a tube graft. The proximal anastomosis was performed below the left subclavian artery (LSA), using a proximal clamping between the left common carotid artery and the LSA. A distal beveled anastomosis included the celiac trunk, superior mesenteric artery, right renal artery, and the distal infrarenal aorta. In order to avoid the reattachment of a large island of aortic tissue, the left renal artery was divided from the aortic wall and reattached using a selective bypass (circled image, also magnified). Two pairs of critical intercostal arteries were reattached to the tube graft directly, using an aortic island (dotted circle). (B) Final reconstruction after Extent III TAAA OSR with a branched graft. Visceral and renal vessels were reattached using selective bypasses, namely the left renal artery (#), the superior mesenteric artery (+), and the celiac trunk (*). The selective bypass for the right renal artery arises posteriorly.

avoided to prevent the risk of late dilation of the remaining aortic tissue.[30] In these cases, aortic replacement is more often performed with multi-branched surgical grafts. An end-to-end anastomosis is then performed with the distal aorta, and the final clamp is removed (Figure 2). A specific surgical approach is used to avoid sequential aortic cross-clamping in cases of extensive aortic wall thrombosis to minimize the risk of thrombus mobilization and embolization.[31]

Despite extensive surgical expertise, TAAA OSR remains associated with a high risk of significant intraoperative and perioperative bleeding, often necessitating blood product transfusions. The loss of large volumes of blood, if not rapidly replaced, can lead to hypotension, increasing the risk of spinal cord injury (SCI) and overall organ hypoperfusion. However, blood transfusions also carry well-documented risks, including complications such as lung injury. As a result, effective bleeding management is a critical component of TAAA OSR.

To address coagulation abnormalities, rotational thromboelastometry (ROTEM) was integrated into our practice in 2016. This technology enables the early detection of specific disruptions in the coagulation cascade, identifying abnormalities in both the intrinsic and extrinsic pathways. By utilizing ROTEM, intraoperative bleeding can be better controlled, potentially reducing the need for blood transfusions.[32, 33]

Postoperative adjuncts

Selective non-invasive ventilation (NIV) during the postoperative period has demonstrated positive outcomes in preventing respiratory insufficiency in patients undergoing TAAA OSR. Based on this experience, early prophylactic NIV has been routinely implemented since 2014 for all patients without contraindications, such as emphysematous bullae, to optimize postoperative recovery.[34]

Outcomes

Primary endpoints include perioperative outcomes occurring within 30 days of surgery or during the hospital stay if longer. These outcomes include 30-day mortality, respiratory failure (requiring prolonged intubation, reintubation, or tracheostomy), permanent SCI, renal failure (stage 4 or 5 according to the RIFLE classification), myocardial ischemia, major stroke, mesenteric ischemia (requiring intervention), and the need for any re-intervention.[35] Due to its prophylactic usage, NIV was not considered as an indicator of respiratory failure in the current analysis.

Statistical analysis

Descriptive statistics were used for discrete variables (numbers and percentages), continuous variables (mean±standard deviation), and variables with non-normal distribution (median and interquartile range). Continuous variables were compared using the Student's *t*-test, and categorical data were analyzed using the Chi-square Test with Yates correction. A P value of <0.05 was considered statistically significant. All analyses were performed using SPSS version 29.0.1.1 for MacOS.

Results

Between 1989 and 2024, a total of 1211 patients underwent elective TAAA OSR at our institution. Of these, 455 patients were classified into Group 1, while 756 were included in Group 2. The procedure was performed for TAAA I-III extensions in 81.0% of cases, primarily due to degenerative causes. The two groups shared most preoperative characteristics, with the exception of smoking history and prior aortic surgery. Group 1 had a significantly higher proportion of smokers (P=.034), but there was no notable difference in preoperative COPD rates (P=0.773). Conversely, patients in Group 2 had a significantly higher incidence of prior aortic surgery (P<0.001). A summary of demographic and baseline characteristics for both groups is presented in Table I.

Significant differences were observed between the two groups regarding the use of intra-procedural adjuncts and various aspects of the surgical technique. Specifically, CSFD, TEE, MEP&SSEP, LHBP, renal perfusion with HTK solution, and ROTEM were routinely utilized in Group 2, showing statistically significant differences compared to Group 1. Additionally, surgical techniques differed between the groups in terms of aortic clamping location, aortic replacement approach, visceral vessel reconstruction, and intercostal artery reattachment rates. A higher frequency of “more proximal” aortic cross-clamping, specifically between the LCCA and the LSA, was observed in Group 2, with a concomitant significant reduction of proximal aortic cross-clamping below the LSA. Furthermore, the approach to visceral and renal vessel reconstruction varied significantly: in Group 1, a Carrel patch (or beveled) method including the CT, SMA, and both renal arteries was predominantly used (57.4%). In Group 2, the reattachment of large aortic islands of tissue was significantly reduced to 20.9%; smaller patches associated with selective bypass were favored in 56.9%, and reattachment of visceral and renal vessels with selective bypass (multi-branched grafts) was preferred in 22.2% of cases. Group 2 also showed a more aggressive approach to intercostal artery reattachment (p =.020), utilizing techniques such as aortic island, selective bypass, or loop bypass. Details of intra-procedural techniques and adjunct usage are summarized in Table II.

The overall 30-day mortality rate was 9.7% (118/1211). Causes of death included multiple organ failure (MOF) in 45 cases, cardiac complications such as myocardial ischemia and arrhythmia in 38 cases, bleeding in 12 cases, systemic embolization in 14 cases, and stroke in 9 cases. Compared to Group 1, Group 2 showed a significant reduction in mortality (P=0.001). Similarly, the incidence of permanent SCI was lower in Group 2 than in Group 1 (P=0.012), with rates of 7.4% and 11.9%, respectively, and an overall incidence of 9.1% (110/1211).

The total incidence of respiratory failure was 28.6% (346/1211), with Group 1 exhibiting a rate of 31.9% and Group 2 showing a lower rate of 26.6% (P=0.056). Renal failure occurred in 5.6% of patients, with rates of 7.2% in Group 1 and 4.6% in Group 2 (P=0.073). Although reductions in respiratory and renal failure were observed in Group 2, these differences did not reach statistical significance. A slight positive trend was also noted in the incidence of postoperative myocardial ischemia, stroke, mesenteric ischemia, and the necessity for re-intervention,

Table I.—*Demographics and baseline characteristics.*

	Group 1 (455 pts)	Group 2 (756 pts)	P	Total (1211 pts)
Preoperative characteristics				
Age, years	71.3 (±6.5)	71.6 (±8.2)	0.742	71.5 (±7.2)
Male sex	337 (74.1)	559 (73.9)	0.984	896 (74.0)
Hypertension	286 (62.8)	511 (67.6)	0.105	797 (65.8)
History of smoking	223 (49.0)	322 (42.6)	0.034	545 (45.0)
Diabetes	72 (15.8)	128 (16.9)	0.672	200 (16.5)
Dyslipidemia	191 (42.0)	314 (41.5)	0.927	505 (41.7)
History of coronary artery disease	114 (25.1)	213 (28.2)	0.263	327 (27.0)
Cerebrovascular disease	34 (7.5)	51 (6.7)	0.716	85 (7.0)
Chronic obstructive pulmonary disease	55 (12.1)	97 (12.8)	0.773	152 (12.6)
Chronic renal failure	167 (36.7)	298 (39.4)	0.379	465 (38.4)
Aneurysms diameter, mm	64 (±7)	69 (+9)	0.198	67 (+9)
Previous aortic surgery	37 (8.1)	114 (15.1)	<0.001	151 (12.5)
Extension				
TAAA extent I	93 (20.4)	158 (20.9)	0.906	251 (20.7)
TAAA extent II	127 (27.9)	219 (29.0)	0.742	346 (28.6)
TAAA extent III	141 (31.0)	243 (32.1)	0.723	384 (31.7)
TAAA extent IV	94 (20.7)	136 (18.0)	0.284	230 (19.0)
Etiology				
Degenerative	328 (72.1)	525 (69.4)	0.362	853 (70.4)
Dissection	96 (21.1)	188 (24.9)	0.153	284 (23.5)
Other	31 (6.8)	43 (5.7)	0.504	74 (6.1)

TAAA: thoracoabdominal aortic aneurysm.

Table II.—*Intraprocedural details and intraoperative adjuncts.*

	Group 1 (455 pts)	Group 2 (756 pts)	P
Intraoperative details			
CSFD	204 (44.8%)	654 (86.5%)	<0.001
TEE	12 (2.6%)	721 (95.4%)	<0.001
MEP&SSEP	7 (1.5)	648 (85.7%)	<0.001
Procedural time, minutes	258 (201-390)	229 (198-377)	0.058
LHBP	371 (81.5%)	670 (88.6%)	<0.001
Renal arteries perfusion with HTK solution	73 (16.0%)	661 (87.4%)	<0.001
Use of ROTEM	0	298 (39.4%)	<0.001
Proximal clamping			
Between LCCA and LSA	26 (5.7%)	135 (17.9%)	<0.001
Distally to the origin of the LSA	277 (60.9%)	366 (48.4%)	<0.001
DTA mid/distal portion	152 (33.4%)	255 (33.7%)	0.958
Intercostal artery reattachment	217 (47.7%)	414 (54.8%)	0.020
Visceral artery reattachment			
Carrell patch 4-vessels (or beveled)	261 (57.4%)	158 (20.9%)	<0.001
Carrell patch (or beveled) + selective bypass	133 (29.2%)	430 (56.9%)	<0.001
Selective bypasses	61 (13.4%)	168 (22.2%)	<0.001

CSFD: cerebrospinal fluid drainage; TEE: trans-esophageal echocardiography; MEP&SSEP: motor and somatosensory evoked potentials; LHBP: left heart bypass; LCCA: left common carotid artery; LSA: left subclavian artery; DTA: descending thoracic aorta; HTK solution: histidine-tryptophan-ketoglutarate solution; ROTEM: rotational thromboelastometry.

Table III.—*Postoperative outcomes.*

	Group 1 (455 pts) N. (%)	Group 2 (756 pts) N. (%)	P	Total (1211 pts) N. (%)
Perioperative results				
30-day mortality	61 (13.4)	57 (7.5)	0.001	118 (9.7)
Respiratory failure	145 (31.9)	201 (26.6)	0.056	346 (28.6)
Permanent SCI	54 (11.9)	56 (7.4)	0.012	110 (9.1)
Renal failure	33 (7.2)	35 (4.6)	0.073	68 (5.6)
Myocardial ischemia	12 (2.6)	11 (1.5)	0.214	23 (1.9)
Stroke	5 (1.1)	9 (1.2)	0.894	14 (1.2)
Mesenteric ischemia	13 (2.9)	15 (2.0)	0.434	28 (2.3)
Need of re-intervention	35 (7.7)	42 (5.6)	0.176	77 (6.4)

SCI: spinal cord ischemia.

though these differences were not statistically significant. A summary of overall postoperative outcomes and the specific results for each group can be found in Table III.

Discussion

Thoraco-abdominal aneurysms is one of the most challenging and intricate clinical condition encountered in vascular surgery. Patients who suffer from this aortic pathology face a significant risk of life-threatening rupture if left untreated. However, the surgical repair itself carries a considerable risk of postoperative complications, including paraplegia, renal failure, cardiac issues, and even death.[1-6] Given the involvement of multiple vital organs, the surgical and anesthesiological management of patients undergoing TAAA repair must be centered around the organ protection.

In recent decades, several new intraoperative and perioperative adjunctive techniques and maneuvers for organ protection, the "adjuncts," have been introduced at high-volume centers performing TAAA OSR. Thus, a multimodal approach, which incorporates various adjuncts, has progressively evolved in an effort to maximize organ protection and minimize surgical trauma. The introduction of this multimodal approach carried several advantages, with significant reduction in term of mortality and morbidity rates.[25] The aim of this paper was to provide an updated perspective on the results of TAAA OSR in a center with extensive experience in treating aortic diseases, focusing the analysis of the results on the role of the adjuncts, and the influence of the increased surgical experience.

Two consecutive patient groups were established for the purpose of this analysis: Group 1 (comprising 455 patients treated from January 1989 to December 2009) and Group

2 (comprising 756 patients treated from January 2010 to December 2024). Group 2 was chosen to include the routine use of most adjuncts that were introduced during the second period, and the most updated results. The two groups were largely comparable in terms of preoperative characteristics, with the exception of smoking history and prior aortic surgery (Table I). In Group 2, a greater number of procedures were performed on patients who had undergone previous open or endovascular repairs. This trend may be associated with the growing frequency of endovascular procedures in both the thoracic and abdominal aortic segments.[36, 37] Notably, the progressive introduction of various adjuncts in Group 2, alongside the concurrent use of multiple adjuncts, made it difficult to isolate and define the specific role of any individual adjunct. Therefore, we focused our analysis on the broader multimodal approach adopted in Group 2, which involved the cumulative application of various adjuncts, rather than evaluating each adjunct independently. The same rationale was applied to the surgical strategy, with the introduction of variations in surgical techniques.

Since 1989, when the first TAAA OSR was performed at our institution using the "clamp and go" technique, many aspects of the surgical approach have evolved, but most of the major changes occurred during the last 15 years. When comparing the surgical strategies between Group 1 and Group 2, significant differences were observed in the site of aortic clamping, the techniques used for visceral vessel reconstruction, and the frequency of intercostal artery reattachment (Table II). Although TAAA extensions were similar between both groups, a significantly higher number of "high" proximal clamping procedures (namely between LCCA and LSA) was reported in Group 2 ($P<0.001$). Over time, the proximal aortic segment between the LCCA and the LSA became regarded as a "safer zone" for cross-clamping compared to the aortic segment distal to the LSA, and it was frequently preferred in order to obtain an extended aortic region for the proximal anastomosis, with an apparently healthier aortic wall. As a result, it was more frequently chosen for proximal clamping during extent I-II TAAA OSR; this approach was adopted in 17.9% of cases in Group 2. Additionally, a trend toward using smaller aortic patches was observed in Group 2, with a significant reduction in the use of Carrel patches that included four vessels. Instead, there was an increase in the use of three-vessel Carrel patches combined with selective bypass ($P<0.001$), and in the use of multi-branched graft with selective reattachment of visceral and renal vessels ($P<0.001$). This shift in the surgical technique was driven by the observation of visceral aortic patch aneurysms during follow-up, leading to efforts to reduce the risk of subsequent dilation.[38, 39] Furthermore, Group 2 demonstrated a more aggressive approach to intercostal artery reattachment ($P=0.020$), a change likely influenced by increased surgical experience, updated evidence regarding the protective role of this procedure, and the routine use of MEP and SSEP intraoperatively.[7, 23, 26, 40, 41]

Regarding the different adjuncts used in the multimodal approach, in 2010 CoroCTA has been introduced as a routine part of the preoperative evaluation. Significant coronary artery stenosis that could limit blood flow was addressed prior to TAAA OSR with percutaneous interventions, such as the use of bare-metal stents or bypass surgery, when appropriate.[12] Since 2013, TEE has been routinely used during surgery for continuous cardiac monitoring, allowing the application of maneuvers to address changes in cardiac function, such as volume loading or vasoactive medications, in an effort to prevent hypotension.

One of the most significant adjuncts employed in the field of spinal cord protection is the CSFD; its protective role during TAAA OSR was initially reported by a randomized clinical trial in the early 1990s, and it is now widely recognized and recommended by current guidelines.[18-20] At our center, a drip-chamber-based system was introduced as a routinely employed tool for spinal cord protection during TAAA OSR in 2003, and a transition toward an automated pressure-controlled system was completed in 2013 to obtain a safer and more controlled drainage, with fewer complications from over-drainage compared to the previous system.[21] CSFD was used significantly more in Group 2 ($P<0.001$), and it was routinely placed in patients with Extent I-III TAAA, provided there were no specific contraindications. It was used selectively in patients with Extent IV TAAA who were considered at high risk for SCI. However, as with any adjunct, it is important to consider potential complications related to CSFD, as recent evidence cautions against its universal application in all cases.[42]

The LHBP is another essential tool used during TAAA OSR, with a protective role well established since the early 1990s.[43] The benefits provided by the LHBP are several: it requires low levels of heparinization, it protects both the spinal cord and visceral organs during the clamping time using a sequential clamping technique, and it also offers cardiac protection by reducing the afterload during the aortic cross-clamping.

Intraoperative neuro-monitoring using MEP and SSEP is another crucial component of spinal cord protection.

This technique provides real-time monitoring of spinal cord function, allowing for the detection of any impairment in spinal cord blood supply and the immediate application of corrective measures, such as adjusting arterial pressure, early reattachment of hypogastric arteries, or selective reattachment of critical intercostal arteries.[23] The use of MEP and SSEP during TAAA OSR was first reported by Jacobs *et al.* in 1997, and it was routinely introduced into our practice in 2012.[44]

Renal failure remains one of the most concerning complications associated with TAAA OSR and is closely linked to perioperative mortality; therefore, strategies aimed at protecting renal function are critical during the procedure.[27, 28] The perfusion of the kidneys with cold solutions is essential, and while ringers lactated has been commonly used for kidney perfusion during renal ischemia, HTK solution, typically used for cardioplegia during cardiac surgery, has emerged as an alternative and has also shown its efficacy in preserving renal function.[29] We began using HTK solution for renal perfusion during TAAA OSR in 2009, and its role in preserving renal function has been confirmed through a randomized, double-blind clinical trial.[41, 45]

Another adjunct introduced in Group 2 was the ROTEM, a rapid diagnostic tool that provides real-time information about fibrinogen levels and fibrinolysis. In our experience, ROTEM has led to a significant reduction in intraoperative blood transfusions, which has the added benefit of reducing complications such as transfusion-associated circulatory overload and respiratory issues.[32, 33]

Lastly, to address postoperative respiratory failure, which remains the most frequent complication following TAAA OSR, we began using early prophylactic NIV in 2014. NIV has proven to be effective in improving lung volumes, enhancing gas exchange, reopening atelectasis, increasing ventilation, and lowering the risk of pneumonia. This approach has contributed to a reduction in both postoperative respiratory complications and mortality rates.[34]

All the adjuncts employed during TAAA OSR, and a timeline with the progressive introduction as a routine part of the multimodal approach performed at our center, are reported in Figure 3. As outlined in Table II, the use of CSFD, TEE, MEP&SSEP, LHBP, renal perfusion with HTK solution, and ROTEM was significantly higher in Group 2. Although it is challenging to define the impact of each individual adjunct in isolation, the overall multimodal approach adopted in Group 2 resulted in significantly better outcomes in terms of mortality (P=0.001) and prevention of permanent SCI (P=0.012) in our more recent experience. This approach also led to reductions in respiratory failure, renal failure, and other postoperative complications, although these improvements did not reach statistical significance.

Moreover, the approach implemented at our center can be considered not only multimodal but also multisystem, as many of the adjuncts serve multiple protective functions. For instance, LHBP offers both spinal cord protection and visceral organ protection, while also reducing cardiac afterload. Similarly, preoperative CoroCTA helps prevent cardiac complications, which could potentially lead to hemodynamic instability and impair perfusion to both the spinal cord and visceral vessels. These considerations apply to most of the adjuncts used during TAAA OSR at our institution.

Limitations of the study

The study has some limitations, such as its retrospective design and the use of data from a single center. This design

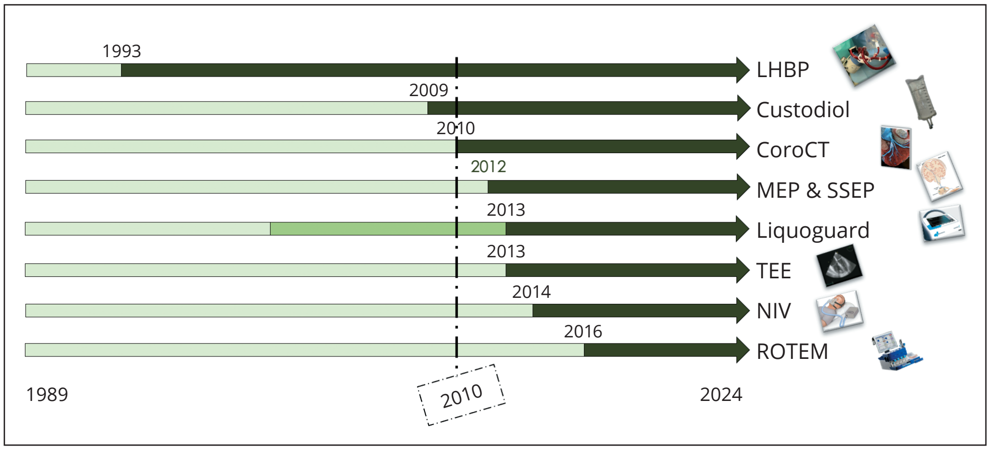

Figure 3.—A visual overview of the various adjuncts incorporated into our clinical practice, and the timeline of their introduction.

somewhat restricted the ability to explore various potential negative factors that might have influenced the outcomes, which could introduce a degree of bias.

Conclusions

In this 35-year single-center experience, a progressively modifying approach for TAAA OSR has been reported. The use of various adjuncts - within a comprehensive, multimodal, and multisystem approach - has led to a significant reduction in mortality and SCI rates and. In addition, although not statistically significant, an improvement in the incidence of other postoperative complications after 2010 has been also reported. Over time, surgical techniques and strategies for organ protection have been continuously refined to reduce early mortality and prevent life-altering complications; however, despite these advancements, further improvements are still needed in this complex field of aortic surgery.

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Conflicts of interest

The authors certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

Authors' contributions

Conceptualization: Enrico Rinaldi, Andrea Kahlberg and Roberto Chiesa; methodology: Enrico Rinaldi, Andrea Kahlberg, Daniele Mascia and Germano Melissano; validation: Enrico Rinaldi, Andrea Kahlberg, Daniele Mascia, Nicola Favia, Germano Melissano, Roberto Chiesa; formal analysis: Enrico Rinaldi, Andrea Kahlberg, Daniele Mascia and Nicola Favia; investigation: Enrico Rinaldi, Andrea Kahlberg and Nicola Favia; data curation, writing—original draft preparation:: Enrico Rinaldi, Andrea Kahlberg, Daniele Mascia and Nicola Favia; writing—review and editing: Enrico Rinaldi, Andrea Kahlberg, Daniele Mascia, Nicola Favia, Germano Melissano, Roberto Chiesa; supervision: Roberto Chiesa. All authors read and approved the final version of the manuscript.

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