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# Spinal cord protection by normothermic artery bypass and visceral-anastomosis-first strategy in thoracoabdominal aortic aneurysm repair

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## Abstract

**Background** Spinal Cord Injury is a disastrous complication of thoracoabdominal aortic aneurysm surgery. This study is to assess the effectiveness and safety normothermic artery bypass and visceral-anastomosis-first strategy for thoracoabdominal aortic aneurysm repair.

**Methods** Normothermic artery bypass and visceral-anastomosis-first strategy prioritizes the reconstruction of visceral and other distal vessels, with intercostal arteries serving as the physiological blood supply at high pressure during this period. Reconstruction of intercostal arteries and proximal anastomosis is then performed, ensuring the longest possible physiological blood supply to the spinal cord. From July 2019 to December 2023, we retrospectively analyzed early postoperative complications in two groups of patients undergoing thoracoabdominal aortic aneurysm repair using the new strategy compared to normothermic iliac artery perfusion, clarifying the protective effects of the new strategy on visceral organs, especially the spinal cord.

**Results** The incidence of paraplegia was significantly lower in the NABP group than in the normothermic iliac perfusion (NIP) group (0.00% vs. 9.72%, $p = 0.047$), and the duration of postoperative mechanical ventilation was significantly lower in the NABP group than in the NIP group ($p = 0.004$). In addition, we found that the incidence of gastrointestinal adverse events was significantly lower in the NABP group than in the NIP group (7.32% vs. 45.83%, $p < 0.001$). Typically, patients' lactate levels returned to normal within approximately 48 h postoperatively. Although not statistically significant, lactate fell to normal more quickly in the NABP group after surgery.

**Conclusions** The treatment of thoracoabdominal aortic aneurysm through open surgery is still an important method and remains difficult. The data we have suggests that our approach of normothermic artery bypass and visceral-anastomosis-first strategy can lower the risk of spinal cord injury complications.

**Keywords** Thoracoabdominal aortic aneurysm, Open repair, Spinal cord protection, Paraplegia

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## Background

Thoracoabdominal aortic aneurysm (TAAA) makes up about 5% of all aneurysms, occurring at a rate of 1 per 10,000 new cases each year. TAAA with a diameter greater than 6 cm poses a yearly rupture risk of 7%, leading to rupture in 80% of patients eventually [1]. The surgical repair comes with significant dangers, including the possibility of surgical death and severe postoperative issues like permanent stroke, paraplegia, and renal failure necessitating dialysis [2]. TAAA typically involves multiple thoracic and abdominal organs, making it a complex surgical procedure associated with high mortality rates and complications. Consequently, the surgical management of TAAA presents a significant area of complexity within the field of vascular surgery.

TAAA surgery can lead to a serious Spinal Cord Injury (SCI), with a frequency of 2–15% [3–4], depending on factors such as the aneurysm size, underlying etiology, patient comorbidities, procedural urgency, and surgical experience. To mitigate the risk of SCI, cardiovascular surgeons have implemented various neuroprotective strategies in clinical practice, including cerebrospinal fluid drainage, motor and sensory evoked potentials monitoring, distal perfusion, intercostal artery reconstruction, and hypothermia induction [5–8]. Despite the use of these neuroprotective measures, the current incidence of SCI following type II TAAA surgery at the Baylor College of Medicine Aortic Centre remains alarmingly high at 13.6% [9].

Over the past two decades at our institution, the primary treatment approach for extensive TAAA has involved deep hypothermic circulatory arrest and normothermic iliac perfusion [10]. However, this approach has been linked to high mortality and morbidity rates, largely due to inadequate protection of the viscera and spinal cord, as well as issues related to blood damage and bleeding. To address these risk factors, we have optimized the technique by focusing on normothermic iliac perfusion. The main goal is to guarantee adequate safeguarding of the internal organs and spinal cord, as well as minimizing bleeding and the reliance on blood products. This enhanced approach, known as the normothermic artery bypass and visceral-anastomosis-first strategy, will be further elucidated in the detailed introduction that ensues.

## Methods

### Participants

Between July 2019 and December 2023, 113 patients with TAAA of Crawford types II and III were included in the research conducted at the Vascular Centre of Fuwai Hospital. Criteria for repairing TAAA consisted of an aortic size over 55 mm, an aneurysm expansion rate of more than 5 mm annually, or signs of organ malperfusion like kidney issues from renal artery blockage or significant compression by the false lumen as shown on CT scans. The surgeons in our center are proficient in both normothermic repair techniques for TAAA and repair techniques involving deep hypothermic circulatory arrest. Operative mortality was characterized as death occurring within 30 days of the surgical procedure, encompassing deaths that occurred during the surgery itself. Upon admission, aortic lesions were confirmed through echocardiography and CT scans of the aorta. In addition, the radiologists in our team all clarify the location of the Adamkiewicz artery (AKA) by aortic CTA and measure the distance between the left renal artery and the critical intercostal artery (ICA - AKA, i.e., intercostal artery branch of the AKA), before the surgery, and inform the surgeon about this result through the preoperative discussion, which will provide an important reference for the surgery.

Every patient who was released received follow-up care, either at the outpatient clinic or through phone consultations. Approval for the study was granted by the Ethics Committee of Fuwai Hospital, Chinese Academy of Medical Sciences (Grant No. 2023–2085, following the guidelines of the Declaration of Helsinki. Furthermore, all patients provided informed consent by signing a consent form.

### Surgical procedures

We previously reported the surgical technique and clinical outcomes of normothermic iliac perfusion (NIP) in a study [10]. In this paper, our focus will be on the novel strategy:

All patients received general anaesthesia, with nasal temperature > 35℃, and warming blankets were used to keep body temperature normal. The patient was placed in a right lateral decubitus position, with the upper body inclined at a 60-degree angle to the operating table and the hips at a 30-degree angle to the horizontal plane. A left posterolateral thoracoabdominal incision was made, starting just posterior to the inferior aspect of the left scapula, curving along the costal margin and extending to just above the pubic symphysis. Based on the extent of the thoracoabdominal aortic aneurysm (TAAA), the surgical entry point was selected from the 4th -7th intercostal space. For extent - II TAAA repairs, a double intercostal entry point could be used. The abdominal aorta was exposed through a retroperitoneal approach. It's crucial to distinguish three aortic segments: the TAAA's proximal aorta, the aorta at the celiac axis (CA) proximal location, and the aorta at the renal arteries (RA) distal location. This distinction aids in aortic segment clamping during TAAA repair.

Once it was confirmed that the proximal aorta could be occluded without deep hypothermic circulatory arrest, 200 U/Kg heparin was given to keep the Activated Clotting Time of Whole Blood (ACT) above 300 s. The left iliac vein was cannulated for blood transfusion, and intraoperative bleeding was filtered and re - circulated. For autogenous arterial diversion, the key is choosing the right site for proximal arterial cannulation. Common sites are the descending aorta and the left axillary artery. The best insertion point is proximal to the proximal end of the proximal anastomosis. Since exposing and cannulating the left axillary artery is tough and the tube can easily twist during surgery, we seldom use this method now (Fig. 1). The ideal cannulation site is the proximal aorta of the proximal anastomosis. But due to the aneurysm's extent, not all thoracoabdominal aortic aneurysms (TAAAs) can be cannulated here, especially type II TAAAs. In such cases, a tube can be inserted at the distal aneurysm of the proximal anastomosis. However, this approach causes transient distal organ ischemia during proximal anastomosis.

After the completion of arterial cannulation, the arterial diversion tube was connected to a four-branched artificial blood vessel (multi-branched artificial vessels may also be applied in some cases), with each opening of the artificial blood vessel serving as a blood outflow point, enabling sequential restoration of blood supply to each organ as necessary (Fig. 2).

First, the aorta above the celiac trunk and away from the renal artery was clamped to perform visceral blood flow reconstruction. The clamped abdominal aorta section was dissected to locate the celiac trunk, superior

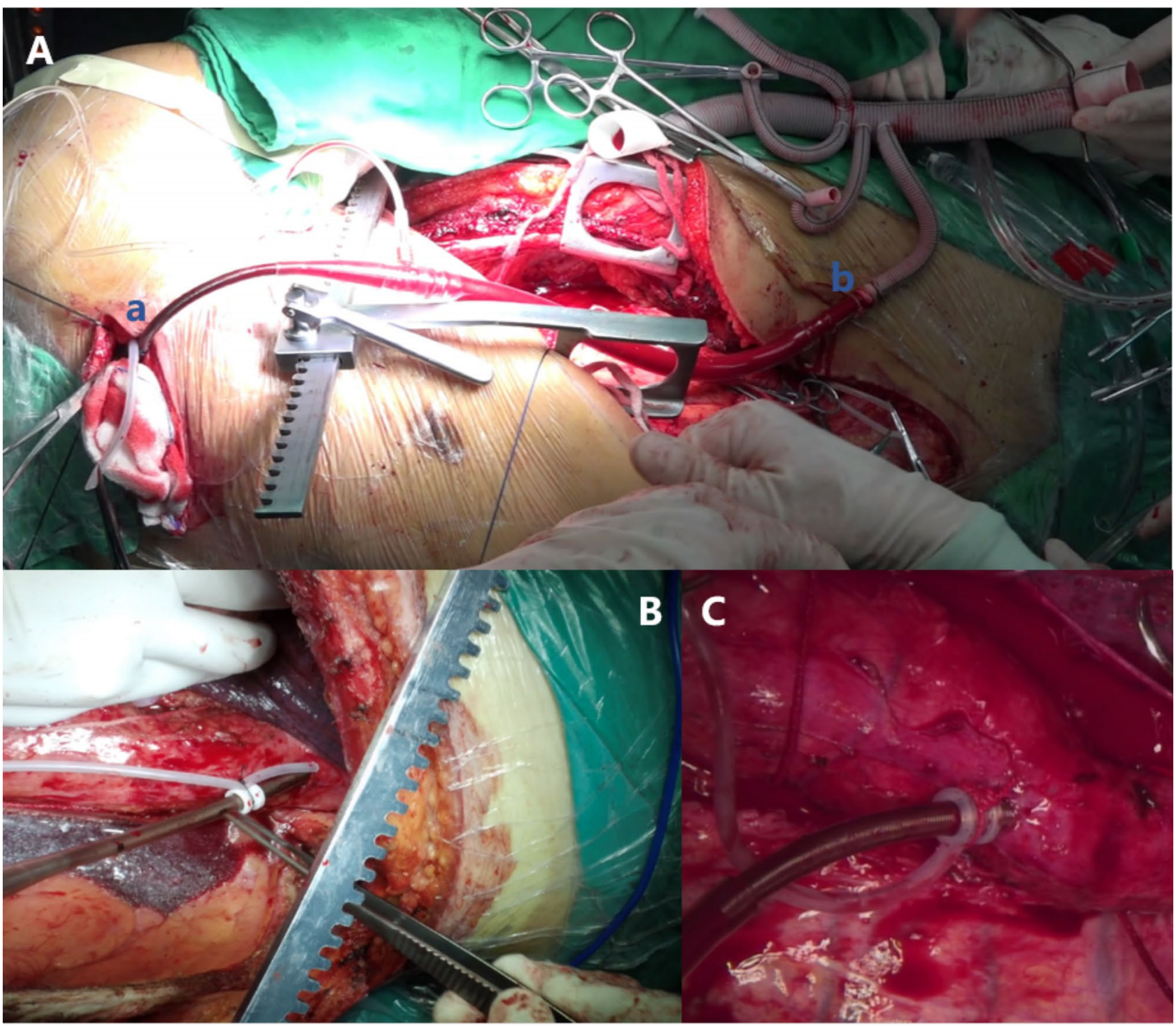


**Fig. 1** Three types of proximal arterial cannulation. (**A**) Visualization and cannulation of the left axillary artery. (**a**) cannulation of the left axillary artery. (**b**) a 4-branched graft is used to connect the left axillary artery cannula. (**B**) Cannulation at the proximal end of the proximal anastomosis. (**C**) Cannulation at the distal end of the proximal anastomosis

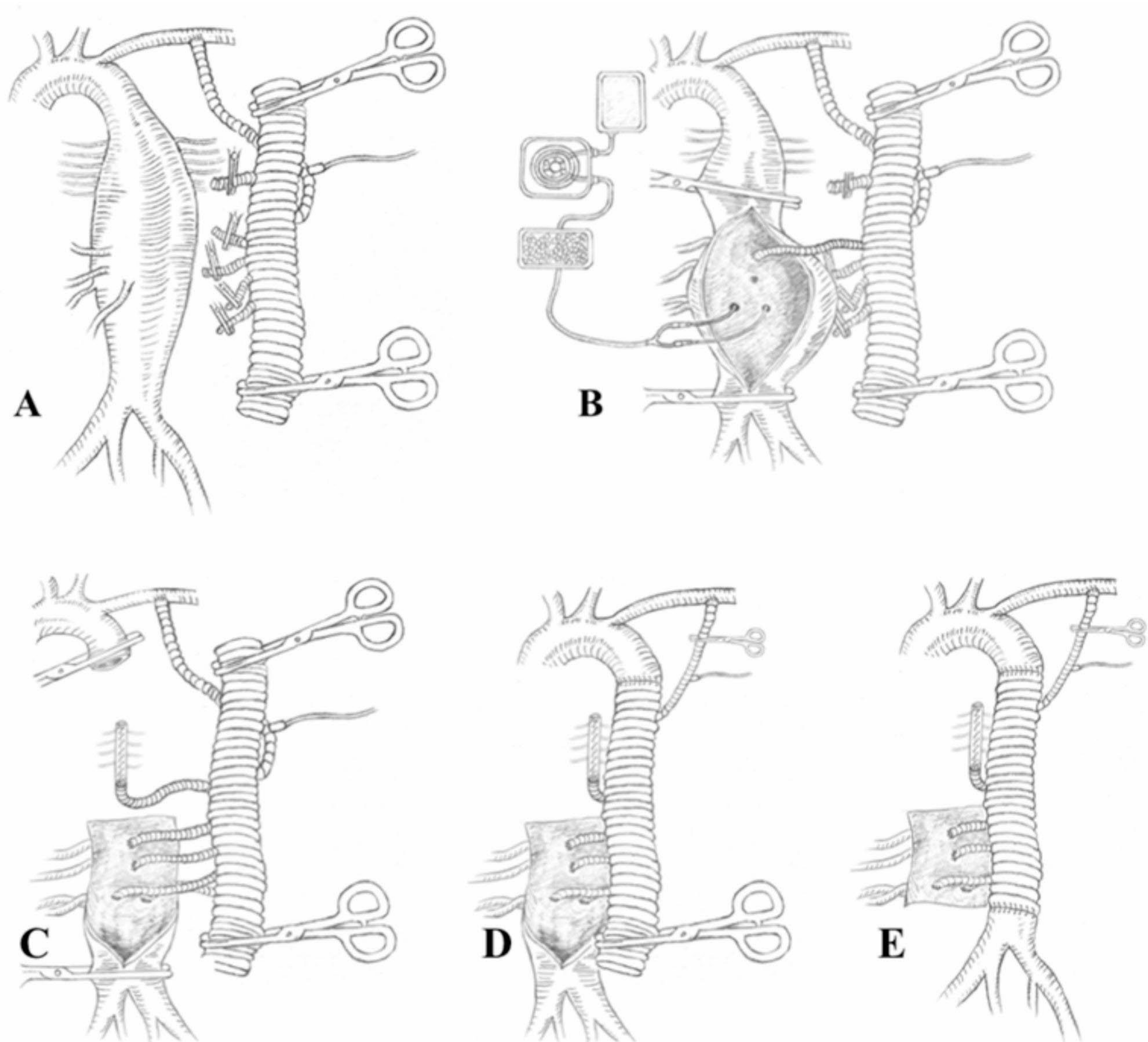


**Fig. 2** (**A**) End to side anastomosis was performed between a 10-mm Dacron graft and the axillary artery; (**B**) Reconstructed the CA with a 10-mm branch; (**C**) The T8–L2 aorta containing main feeding artery of the spinal cord was sutured to form an arterial tube, then anastomosed with the 10-mm branch for restoration blood flow to the spinal cord; (**D**) The proximal of the 4-branched aortic graft was anastomosed to the proximal thoracic aorta; (**E**) The distal end of 4-branched graft to anastomose the distal abdominal aorta

mesenteric artery, and left and right renal arteries. The left and right renal arteries were intermittently perfused with cold HTK solution. Branching vessels were used to reconstruct the celiac trunk or superior mesenteric artery. After anastomosis, blood return in the anastomosed superior mesenteric artery or abdominal arteries was observed. Then, the blood return from the non - anastomosed superior mesenteric artery or celiac artery was evaluated. Usually, the blood flow between the two arteries was sufficient, so a vascular clamp was used to block the other celiac artery, and immediate hemodynamic reconstruction wasn't always necessary. In rare cases where the blood return in the other celiac artery was low, suggesting limited communication between the two arteries, immediate branch vessel reconstruction was needed.

There was no set order for anastomosing the two renal arteries. Prioritizing one while the other continued to receive cold HTK perfusion sufficed. After reconstructing the visceral branches, the clamp above the celiac trunk was repositioned for proximal anastomosis, and the aorta was longitudinally dissected. The intercostal artery at the T9 - L1 level was preserved for reconstruction. Techniques like rolled and single - branch anastomosis were flexibly selected based on the intercostal artery diameter, blood return, and intraoperative positioning (Fig. 2).

Once the intercostal artery reconstruction was done, the proximal anastomotic stump was trimmed. The proximal aortic stump was anastomosed end - to - end with the four - branch artificial vessel, and the proximal clamp was opened, restoring blood supply to the intercostal arteries and visceral branches via aortic collateral perfusion. The sequence of distal anastomosis varied. One could start with visceral branches, anastomose the four - branch main vessel to the distal abdominal aorta, or reconstruct the right and left iliac arteries with branch vessels as per the aneurysm's involvement in the iliac arteries. Blood protection measures were essential throughout the procedure, and proper hemostasis was required after each anastomosis to avoid excessive bleeding, tissue damage, and intraoperative hypotension. The post - surgery state is shown in Fig. 3. Routine intraoperative monitoring showed no abnormalities during the surgical repair.

### Statistical analysis

The R software (http://www.R-project.org; Version 4.2.1) was used to create all the figures. The threshold for statistical significance was established as a $p$-value less than 0.05 or an adjusted $p$-value less than 0.05. Two groups were compared using both Student's t-test, a parametric test, and Mann-Whitney U test, a non-parametric test. The adjusted $p$-value was determined using the Benjamini-Hochberg correction, with the Chi-square test being employed for analyzing the categorical variables. Furthermore, statistical analysis was conducted using GraphPad Prism 9.0.0 software from GraphPad Software in San Diego, California, USA (www.graphpad.com).

## Results

From July 2019 to December 2023, there were 78 male patients (accounting for 69.03%) in the cohort, with 51 (70.83%) in the NIP group and 27 (65.85%) in the NABP group. The median age of patients in the NIP group was 39.00 [32.00, 50.00] years old, while in the NABP group it was 35.00 [30.00, 51.00]. Among the NIP group, 22 patients had Marfan syndrome (30.56%), 42 had hypertension (58.33%), and 11 had concomitant coronary artery disease (15.28%). In the NABP group, there were 7 patients (17.07%) with Marfan syndrome, 19 (46.34%) with hypertension, and 5 (12.20%) with coronary artery disease. There were no significant variations observed in age distribution, gender, presence of diabetes, or coronary artery disease (CAD) between the two groups (Table 1). Moreover, in 29 (25.66%) patients with Marfan syndrome (median age was 30 [27, 34.25]), there was no statistically significant difference in the range of aortic replacement compared to patients without a confirmed diagnosis of Marfan syndrome.

Table 2 presents the in-hospital outcomes of the study. There was no significant variance in the 30-day postoperative mortality rate between the two groups (7.96% vs. 11.11%, $P=0.152$). Notably, the median postoperative mechanical ventilation time was significantly shorter ($P=0.004$) in the NABP group (11.00 [8.00, 31.00]) compared to the NIP group (17.00 [12.75, 46.25]). The mean

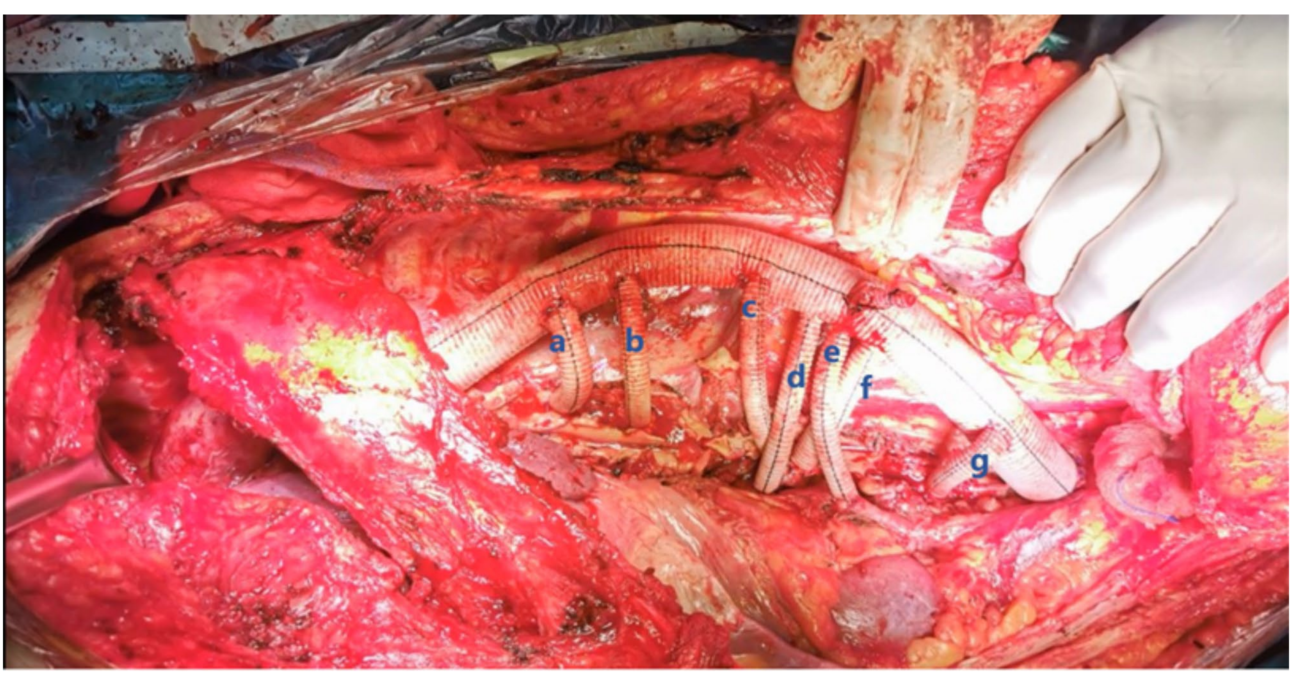


**Fig. 3** Surgery Completion Status. (**a**) (**b**) Reconstructed intercostal arteries. (**c**) Reconstructed superior mesenteric artery. (**d**) Reconstructed celiac artery. (**e**) Reconstructed left renal artery. (**f**) Reconstructed right renal artery. (**g**) Reconstructed inferior mesenteric artery

**Table 1** Demographical characteristics and clinical data of the patients

| Variables | Overall (*N* = 113) | NIP (*N* = 72) | NABP (*N* = 41) | *P*-value |
|---|---|---|---|---|
| Age, years, Median [IQR] | 39.00 [32.00, 50.00] | 39.50 [33.00, 50.00] | 35.00 [30.00, 51.00] | 0.441 |
| Male gender, n(%) | 78 (69.03%) | 51 (70.83%) | 27 (65.85%) | 0.735 |
| Extent II, n (%) | 61(53.98%) | 40(55.56%) | 21(51.22%) | 0.817 |
| Extent III, n (%) | 52(46.02%) | 32(44.44%) | 20(48.78%) | 0.776 |
| Smoking, n (%) | 19 (16.81%) | 15 (20.83%) | 4 (9.76%) | 0.191 |
| Marfan syndrome, n (%) | 29 (25.66%) | 22 (30.56%) | 7 (17.07%) | 0.176 |
| Hypertension, n (%) | 61 (53.98%) | 42 (58.33%) | 19 (46.34%) | 0.301 |
| Hyperlipidaemia, n (%) | 16 (14.16%) | 11 (15.28%) | 5 (12.20%) | 0.864 |
| Aortic dissection due to uncontrolled HTN, n(%) | 26(23.01%) | 18(25.00%) | 8(19.51%) | 0.675 |
| Prior ascending aortic repair, n (%) | | | | |
| Diabetes, n (%) | 12(46.15%) | 10(55.56%) | 2(25.00%) | 0.061 |
| Chronic renal failure, n (%) | | | | |
| History of stroke, n (%) | 2 (1.77%) | 2 (2.78%) | 0 (0.00%) | 0.534 |
| Coronary artery disease, n (%) | 6 (5.31%) | 5 (6.94%) | 1 (2.44%) | 0.414 |
| | 7 (6.19%) | 6 (8.33%) | 1 (2.44%) | 0.419 |
| | 16 (14.16%) | 11 (15.28%) | 5 (12.20%) | 0.864 |

Abbreviations: IQR, interquartile range; NIP, Normothermic iliac perfusion; NABP, Normothermic artery bypass and visceral-anastomosis-first strategy; HTN, Hypertension

**Table 2** Surgery and postoperative outcomes of the 2 groups

| Variables | Overall (*N* = 113) | NIP (*N* = 72) | NABP (*N* = 41) | *P*-value |
|---|---|---|---|---|
| Operating time(minutes) Mean (SD) | 470.19 (143.01) | 486.57 (143.79) | 441.41 (138.70) | 0.104 |
| Proximal aortic clamp time (minutes) | 12.40 [11.00, 17.30] | 12.80 [11.00, 17.80] | 12.00 [11.20, 16.80] | 0.13 |
| Spinal cord ischemia time (minutes) | 12.40 [10.00, 14.60] | 13.00 [11.00, 16.40] | 10.60 [8.80, 13.60] | < 0.001 |
| Lowest temperature (°C) | 35.00[34.50, 35.30] | 35.10[34.50, 35.30] | 35.00[34.50, 35.50] | 0.679 |
| Postoperative MV time (hours) | 16.00 [10.00, 40.00] | 17.00 [12.75, 46.25] | 11.00 [8.00, 31.00] | 0.004 |
| Postoperative hospital stay(days) | 15.00 [11.00, 21.00] | 15.00 [10.75, 19.25] | 16.00 [13.00, 23.00] | 0.206 |
| Postoperative ICU stay(hours) | 114.00 [68.00, 162.00] | 112.00 [69.00, 162.00] | 120.00 [68.00, 161.00] | 0.87 |
| Early death, n (%) | 9 (7.96%) | 8 (11.11%) | 1 (2.44%) | 0.152 |
| Reexploration for haemorrhage, n (%) | 15 (13.27%) | 13 (18.06%) | 2 (4.88%) | 0.081 |
| Paraplegia, n (%) | 7 (6.19%) | 7 (9.72%) | 0 (0.00%) | 0.047 |
| Transient cerebral dysfunction, n (%) | 1 (0.88%) | 1 (1.39%) | 0 (0.00%) | > 0.999 |
| Haemofiltration, n (%) | 19 (16.81%) | 13 (18.06%) | 6 (14.63%) | 0.837 |
| Gastrointestinal complication, n (%) | 36 (31.86%) | 33 (45.83%) | 3 (7.32%) | < 0.001 |
| Gastrointestinal ischemia, n (%) | 9(7.96%) | 9(12.50%) | 0(0.00%) | 0.025 |
| Gastrointestinal bleeding, n (%) | 9(7.96%) | 7(9.72%) | 2(4.88%) | 0.484 |
| Gastroplegia, n (%) | 19(16.81%) | 18(25.00%) | 1(2.44%) | 0.001 |
| Endotracheal intubation, n (%) | 6 (5.31%) | 5 (6.94%) | 1 (2.44%) | 0.414 |
| ECMO, n (%) | 1 (0.88%) | 1 (1.39%) | 0 (0.00%) | > 0.999 |

Abbreviations: SD, standard deviation; ICU, intensive care unit; MV, mechanical ventilation; ECOM, Extracorporeal Membrane Oxygenation

operative time in the NIP group was (486.57 ± 143.79) minutes compared to the NABP group (441.41 ± 138.70) minutes. There was no significant difference in median hospital stay and ICU stay between the two groups. There were 7 cases of perioperative paraplegia in the NIP group and no perioperative paraplegia in the NABP group (9.72% vs. 0.00%, $p = 0.047$). Based on the duration of SCI, it is classified into permanent SCI and transient SCI. Permanent SCI refers to cases where SCI symptoms persist until discharge or death, while transient SCI indicates that SCI symptoms are fully recovered before discharge. The 7 patients who developed paraplegia in the NIP group did not recover before discharge and were permanently paraplegic.

It's worth noting that we conducted propensity score matching between the two groups but yielded a small cohort. For a detailed analysis of the patients' lactate levels at different time points (preoperatively, intraoperatively, and postoperatively), please refer to **Fig. 4**, which illustrates the mean ± 95% CI values. Although not statistically significant, lactate normalization post-surgery occurred more rapidly in the NABP group.

We monitored all 113 patients for a duration ranging from 4 to 57 months, with an average follow-up period

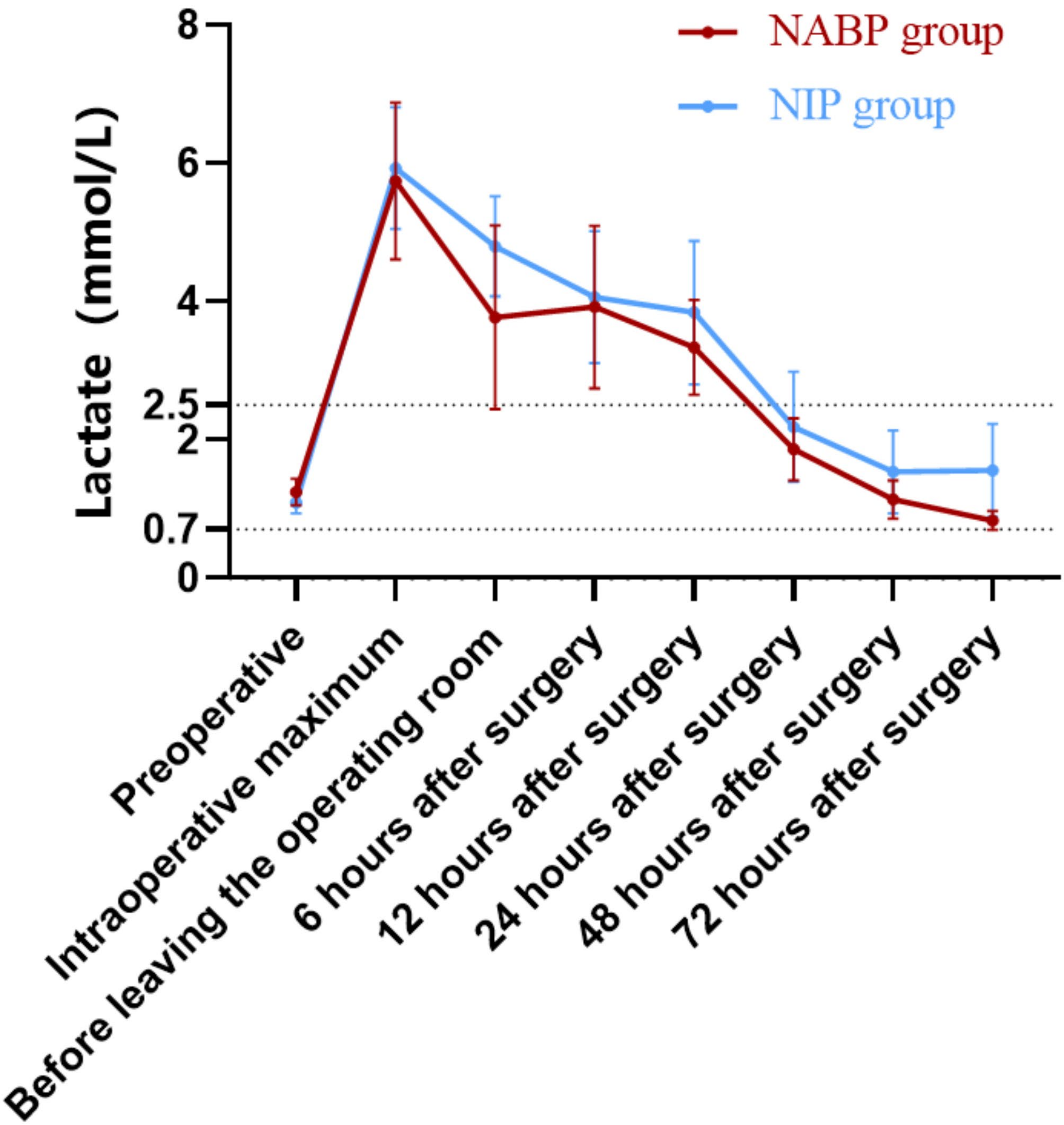


**Fig. 4** The mean ± 95% CI levels of lactate in 2 groups at different time points

of 26.58 ± 13.64 months. Aortic computed tomography (CTA) assessments were conducted at 6 months, 1 year, and 2 years post-procedure. Two patients passed away within the NIP group (One patient died from a heart attack while walking in the park, and the other patient died in a car accident.), while there were no instances of paraplegia or patient fatalities within the NABP group during the follow-up period.

## Discussion

Repairing thoracoabdominal aortic aneurysms represents one of the most challenging procedures in vascular surgery, characterized by a high rate of complications, with spinal cord injury being the most severe [11]. Current clinical approaches commonly utilized for spinal cord protection encompass cerebrospinal fluid drainage, intercostal artery reconstruction, nerve point monitoring, cryoprotection, distal perfusion, among others. Despite the implementation of these strategies, the incidence of spinal cord injury remains remarkably elevated [11–13].

In recent years, significant advancements have been made in endovascular interventions for thoracoabdominal aortic aneurysms (TAAA), offering a less invasive option with a lower complication rate. However, the occurrence of spinal cord injury post-endovascular treatment still stands at 8.8% [14], surpassing the incidence associated with surgical interventions, thereby maintaining surgical treatment as the definitive standard for TAAA management [15].

The spinal cord is known for its robust blood supply, with the concept of a "collateral network" gaining prominence in recent literature. Key sources of this blood supply entail the subclavian arteries, intercostal arteries in the thoracic and lumbar regions, and the internal iliac arteries, all vital for upholding spinal cord function. The effective perfusion pressure of the spinal cord is delineated as the mean arterial pressure minus the cerebrospinal fluid pressure [16], necessitating actions to elevate the effective perfusion pressure of the spinal cord. This involves increasing perioperative mean arterial pressure and reducing cerebrospinal fluid pressure, forming the theoretical foundation for cerebrospinal fluid drainage as the solitary strategy that has shown efficacy in spinal cord preservation [17].

Spinal cord injuries predominantly result from the interruption of blood flow to the spinal cord during thoracoabdominal aortic aneurysm (TAAA) surgery, either due to aortic clamping or perioperative hypotension, leading to decreased spinal cord perfusion [5, 18]. Therefore, minimizing the duration of spinal cord ischemia during aortic clamping is crucial for exploring surgical approaches. The most commonly utilized technique for distal perfusion is left heart bypass, while alternative methods include femoral-femoral bypass [19–20], main iliac artery bypass [4, 10], and left auriculofemoral artery bypass [21]. These methods share the common goal of providing distal arterial blood supply to areas affected by proximal blockage, such as the spinal cord, gastrointestinal tract, and lower extremities.

To exemplify the implications of blood supply and pressure for the spinal cord during surgery using left heart bypass as an illustration: following proximal occlusion, distal perfusion is initiated with blood supply to the spinal cord primarily relying on the subclavian artery. The distal thoracolumbar intercostal arteries and internal iliac arteries receive blood supply through left heart bypass, typically maintaining a mean arterial pressure exceeding 60 mm Hg, though this diverges from normal physiological conditions. Subsequently, upon completing the proximal anastomosis and aneurysm repair, the subclavian artery becomes the sole supplier of blood to the spinal cord, rendering other segments ischemic. Following intercostal artery reconstruction, blood flow to these arteries is reinstated, with enhanced supply compared to the prior step once visceral artery reconstruction is finalized. The return of blood flow to the spinal cord segment supplied by the internal iliac artery occurs post lower limb arterial reconstruction. Nevertheless, the segments distal to the thoracic level inherently receive nonphysiological blood supply during the entirety of the procedure or experience ischemia, significantly elevating the risk of spinal cord injury [22].

In the 12-year-period study by Coselli, 312 (43.9%) patients underwent left heart bypass. Paraplegia and paraparesis rates in patients with extent I and II TAAAs, respectively, were 4.9% (6 of 123) and 4.8% (9 of 189) [23]. In another retrospective clinical cohort study with cross sectional follow-up, three of the 57 patients (5.3%) who underwent left heart bypass developed paraplegia [24]. An extensive review by Dr. Kouchoukos et al. comprising 285 TAAA repairs conducted under deep hypothermic circulatory arrest revealed a 5.3% incidence of spinal cord injury, with permanent paraplegia observed in 4.2% of cases and mild lower extremity paralysis in 1.1% [25]. Notably, Fuwai Hospital reported a 5.5% incidence of permanent paraplegia, while Anzhen Hospital reported a 5.7% spinal cord injury rate employing main iliac artery bypass for type II TAAA repair [4, 10]. These statistics underscore the heightened vulnerability to spinal cord injury irrespective of the distal perfusion or spinal cord preservation methods adopted.

Although the aforementioned methods utilize different auxiliary approaches, a common characteristic is the anastomosis sequence progressing from proximal to distal. This presents certain drawbacks that may be associated with spinal cord injury. To begin with, distal perfusion, either through aortic cannulation or lower limb arteries, involves retrograde perfusion. Owing to the potential presence of thrombosis, entrapment, and other factors, the efficacy of retrograde perfusion remains uncertain, leaving the adequacy of spinal cord perfusion pressure in doubt. Moreover, the reconstruction of intercostal arteries incompletely restores all crucial intercostal arteries; most are ligated, with only a few reconstructed vessels relied upon to supply blood following the completion of visceral artery and lower limb arterial anastomoses. This, in turn, prolongs the spinal cord's ischemic period. Additionally, hypotension is frequently observed during thoracoabdominal aortic aneurysm (TAAA) repair. Premature completion of intercostal artery reconstruction results in low-pressure perfusion in the reconstructed arteries, heightening the risk of spinal cord ischemia.

Addressing these aforementioned shortcomings, our team has enhanced the anastomotic sequence by giving precedence to reconstructing distal vessels such as visceral arteries. This approach ensures that intercostal arteries receive a physiological blood supply, maintaining them in a high-pressure state. Subsequently, the intercostal arteries and proximal anastomoses are reconstructed, securing the longest duration of physiological blood supply to the spinal cord. This theoretically reduces the incidence of spinal cord injury, as evidenced by the absence of spinal cord injuries among the 41 patients treated using this method. Less intraoperative visceral ischemia time predicts a faster recovery with a lower complication rate, which also significantly reduces the duration of mechanical ventilation. While distal priority anastomosis has previously been documented in the literature through case reports with a focus on visceral protection [26], our team has, for the first time systematically introduced the normothermic autoarterial diversion distal priority strategy for TAAA. This strategy diminishes the risk of spinal cord injury and indeed achieves organ protection. For NIP group, although the overall paraplegia rate in this study was higher than that previously reported, which we believe to be due to objective factors such as blood supply constraints. We selected the same period and type of patients for the retrospective study in order to reduce bias. Subsequent prospective studies and larger cohorts are needed to demonstrate the reliability of the findings.

In our study, the normothermic artery bypass and visceral - anastomosis - first strategy (NABP) showed advantages in reducing gastrointestinal complications. Compared with the control group, the NABP group had a shorter gastrointestinal ischemia time, which contributed to fewer gastrointestinal complications. As reported in the literature, the overall incidence of postoperative gastrointestinal complications after thoracoabdominal aortic aneurysm surgery is 7%, while for abdominal aortic repairs involving the infrarenal segment (Crawford extent II - IV), it is 9.7% [27]. The incidence of gastrointestinal complications in the NABP group of our study is close to the latter, indicating that our new strategy can effectively reduce the impact of temperature on the gastrointestinal tract under normothermic conditions. However, more research is needed to fully understand the relationship between temperature and gastrointestinal complications.

The technical aspects of the treatment strategy for thoracoabdominal aortic aneurysms (TAAA) are outlined as follows: firstly, ensuring that the proximal end can occlude the anastomosis is crucial; otherwise, the procedure may necessitate deep hypothermic circulatory arrest. Secondly, achieving a free occlusion over the abdominal trunk can ensure optimal blood supply to the spinal cord for an extended duration. Thirdly, the choice of proximal cannulation site can include the left axillary artery, the proximal aorta of the proximal anastomosis, and the distal aneurysm of the proximal anastomosis. Each site is viable for cannulation, with the primary differentiator being the potential for distal organ ischemia at the time of the proximal anastomosis. Based on our experience, such ischemia does not significantly impact postoperative outcomes; therefore, current preference is given to aortic cannulation over the proximal aorta of the proximal anastomosis, with the distal aneurysm of the proximal anastomosis serving as a secondary preference.

Additionally, the sequence of visceral anastomoses offers flexibility, with the guiding principle being the minimization of ischemic durations for visceral arteries. The left renal artery may be prioritized if easily accessible; similarly, it can take precedence over the inferior mesenteric artery. In cases where the left renal artery is not readily accessible, perfusion becomes necessary, and a different visceral artery anastomosis can be prioritized initially. Hemoprotection during TAAA surgical repair is critical, given the association of postoperative complications with significant bleeding and subsequent transfusions. By minimizing the ischemic time organically, meticulous hemostasis can be achieved throughout each phase of the procedure, thereby reducing the risk of bleeding.

Furthermore, swift redirection of blood from the operative field back into systemic circulation can be facilitated through the venous system, utilizing blood pumps or rapid transfusion devices. This approach helps prevent complications such as hypovolemic hypotension and embolisms within the body's circulation. Although this strategy offers notable advantages, including the absence of organ ischemia time, it is imperative to note its limitations. Specifically, this technique is suitable only for select types of TAAA that allow for occlusion over the proximal anastomosis and the celiac trunk, acknowledging the potential for complications related to arterial cannulation.

## Conclusions

Normothermic artery bypass and visceral-anastomosis-first strategy represents a secure and replicable method, particularly when executed at an experienced center, can produce remarkable outcomes, which reduced the risk of spinal cord injury complications. Long-term follow-up and additional prospective cohort studies are necessary to further evaluate the clinical outcomes of this surgical approach.

## Limitations

Although this study was a retrospective cohort study, the small sample size necessitates the inclusion of a larger number of patients in future studies. Additionally, due to insufficient sample size, surgical variations among different cases may have an impact on outcomes. And, the disease spectrum of our admitted patients may not be the same as other aortic centers. Our patients were younger than those in America or Europe, possibly due to differences in aortic pathology and poor blood pressure control, leading to a higher proportion of Chinese TAAA patients with Marfan syndrome and aortic dissection. Furthermore, this study is confined to the findings of a solitary, prominent tertiary referral center, potentially limiting the generalizability of the results to other institutions.

### Abbreviations

| | |
|---|---|
| ACT | Activated clotting time of whole blood |
| AD | Aortic dissection |
| BMI | Body mass index |
| CA | Celiac axis |
| CAD | Coronary Artery Disease |
| CPB | Cardiopulmonary bypass |
| CI | Confidence interval |
| CT | Computed tomography |
| CTA | Computed tomography angiography |
| HTK | Histidine-tryptophan-ketoglutarate |
| ICU | Intensive care unit |
| IQR | Interquartile range |
| MV | Mechanical ventilation |
| NABP | Normothermic artery bypass and visceral-anastomosis-first |
| NIP | Normothermic iliac perfusion |
| RA | Renal arteries |
| SCI | Spinal cord injury |
| TAAA | Thoracoabdominal aortic aneurysms |

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### Author contributions
SZ collected and analyzed the data and was a major contributor in writing the manuscript, JS and XQ was in charge of the study design and manuscript modification. YL, YZ, XS and CY was in charge of the administrative support. HG, YC and DZ analyzed and interpreted the patient data. All authors reviewed and approved the final manuscript.

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### Data availability
The data underlying this article are NOT available in a repository via a DOI link or in a repository using a unique identifier. The data underlying this article cannot be shared publicly due to institutional policy. The data will be shared on reasonable request to the corresponding author.

## Declarations

### Ethics approval and consent to participate
This study had been approved by institutional review board of Fuwai hospital, Peking union medical college and Chinese academy of medical sciences (Approval No. 2023–2085). All research methods were conducted strictly in accordance with the guidelines. The written informed consent was obtained from all participants. The permission to access and use the raw data was granted by Prof. Xiangyang Qian.

### Consent for publication
The patient provided signed informed consent forms.

### Competing interests
The authors declare no competing interests.

### Clinical trial number
Not applicable.

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