

Vacuum-Assisted Venous Drainage Combined with Modified Femoro-Femoral Partial Bypass for Spinal Cord Protection in Redo Thoracoabdominal Aneurysm Repair: A Historical Cohort Study

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Abstract

Objective

This study aimed to evaluate the efficacy and safety of vacuum-assisted venous drainage (VAVD) combined with modified femoro-femoral partial bypass (MFFPB) for spinal cord protection in patients undergoing open repair of thoracoabdominal aortic aneurysms (TAAA) with prior aortic dissection surgery, comparing outcomes with a historical control group managed with conventional femoral-femoral bypass without VAVD.

Methods

A total of 48 patients with TAAA and a history of previous aortic dissection surgery who underwent open thoracoabdominal reconstruction at our center between January 2018 and December 2025 were retrospectively enrolled. Patients were divided into two groups according to the perfusion strategy used: a control group (n = 22, January 2018 to December 2021) receiving conventional femoral-femoral partial bypass without VAVD, and a study group (n = 26, January 2022 to December 2025) receiving VAVD combined with MFFPB. Intraoperative upper- and lower-extremity arterial pressures were continuously recorded. Spinal cord perfusion pressure (SCPP) was estimated as mean lower-extremity arterial pressure. Clinical outcomes included operative mortality, spinal cord ischemia (SCI), paraplegia, stroke, renal insufficiency, respiratory complications, and length of hospital stay.

Results

The study group achieved significantly higher mean dorsalis pedis artery pressure compared with the control group (67.4 ± 6.8 mmHg vs. 58.2 ± 7.5 mmHg, $P = 0.021$), corresponding to a higher estimated SCPP (85.6 ± 2.0 mmHg vs. 74.8 ± 5.2 mmHg, $P < 0.001$). The proportion of patients maintaining SCPP > 80 mmHg during the procedure was significantly greater in the study group compared with the control group (88.5% vs. 45.5%, $P = 0.002$). Operative mortality was 3.8% (1/26) in the study group versus 9.1% (2/22) in the control group ($P = 0.583$). The incidence of SCI was significantly lower in the study group (7.7%, 2/26) compared with the control group (22.7%, 5/22) ($P = 0.038$), with paraplegia rates of 3.8% (1/26) and 13.6% (3/22), respectively ($P = 0.321$). The study group also demonstrated a lower rate of renal insufficiency (3.8% vs. 13.6%, $P = 0.321$) and shorter median hospital stay (17.0 days, IQR: 13–22 vs. 24.5 days, IQR: 18–35, $P = 0.043$).

Conclusions

The addition of VAVD to modified femoro-femoral partial bypass during TAAA repair in patients with prior aortic dissection surgery was associated with improved intraoperative spinal cord perfusion, a

significantly lower incidence of spinal cord ischemia, and shorter hospital stay compared with conventional femoral-femoral bypass. These findings suggest that VAVD-assisted perfusion may represent a valuable strategy for spinal cord protection in this high-risk reoperative population. Prospective randomized studies are warranted to confirm these observations.

Introduction

Thoracoabdominal aortic aneurysms (TAAA) are relatively rare, with an estimated incidence of 0.6%–1.0%, yet they remain associated with substantial morbidity and mortality despite advances in vascular surgery [1, 2]. Current treatment modalities include open surgical repair with distal aortic perfusion, endovascular repair, or hybrid procedures combining open and endovascular techniques [3, 4]. For patients with a history of prior aortic surgery—such as Bentall procedure, aortic arch reconstruction, or distal trunk stent grafting—open repair often represents the primary therapeutic option; however, it carries a non-negligible risk of spinal cord injury (SCI) and other major complications [5].

With continued refinements in open surgical techniques, perioperative morbidity and mortality associated with TAAA repair have decreased considerably over recent decades [6, 7]. Nevertheless, the incidence of SCI, renal insufficiency, respiratory complications, cardiac events, and permanent stroke remains a major concern, as these complications critically determine long-term outcomes and quality of life in affected patients [8].

Preventing ischemic injury to the abdominal viscera, spinal cord, and lower extremities constitutes the cornerstone of complication avoidance during open TAAA repair [9]. Several strategies have been developed to maintain distal aortic perfusion during aortic cross-clamping, including left atrium-to-left femoral artery bypass, left ventricle-to-left femoral artery bypass, passive shunts (e.g., Gott shunt), partial cardiopulmonary bypass (femoral vein-to-femoral artery), and total cardiopulmonary bypass with hypothermic circulatory arrest [10]. Among these, partial cardiopulmonary bypass via femoral vein-to-femoral artery is most commonly employed, given the critical roles of temperature management and coagulation preservation in the complex TAAA repair process.

Adequate venous drainage is an essential prerequisite for effective partial cardiopulmonary bypass. However, femoral vein cannulation alone cannot always guarantee stable venous return from the right atrium, particularly in patients with prior sternotomy or distorted anatomy. To address this limitation, vacuum-assisted venous drainage (VAVD) has been introduced as an adjunct to partial cardiopulmonary bypass. By applying controlled negative pressure to the hardshell venous reservoir via a vacuum regulator, VAVD increases venous outflow and thereby enhances hemodynamic stability during the procedure [11]. Concurrently, given the potential for massive intraoperative blood loss requiring prompt transfusion, we have modified the conventional femoro-femoral partial bypass circuit by creating a direct connection between the arterial infusion line and the venous drainage line, allowing for rapid blood delivery and immediate volume resuscitation when needed.

In the present study, we sought to evaluate the efficacy of VAVD combined with this modified femoro-femoral partial bypass (MFFPB) for spinal cord protection in patients undergoing redo open TAAA repair. Specifically, we compared perioperative outcomes, with particular emphasis on SCI, between patients managed with this novel perfusion strategy and a historical control cohort treated with conventional femoral-femoral bypass without VAVD. Additionally, we explored potential risk factors for SCI in this high-risk reoperative population.

Methods

Study Design and Ethics Approval

This study was a retrospective cohort study conducted at the Department of Thoracic and Cardiovascular Surgery, Nanjing First Hospital, Nanjing Medical University. The study protocol was reviewed and approved by the Institutional Review Board of Nanjing First Hospital (approval number: ky2022-08-05-03). Due to the retrospective nature of the study, the requirement for written informed consent was waived by the ethics committee. All patient data were anonymized and analyzed in accordance with the principles of the Declaration of Helsinki.

Study Population

A total of 48 patients who underwent open repair of thoracoabdominal aortic aneurysms (TAAA) with a history of prior aortic dissection surgery at our center between January 2018 and December 2025 were retrospectively enrolled. Patients were divided into two chronological cohorts based on the implementation of vacuum-assisted venous drainage (VAVD) technology in our center. The control group comprised 22 patients who underwent surgery between January 2018 and December 2021, during which conventional femoral-femoral partial bypass without VAVD was the standard perfusion strategy. The study group comprised 26 patients who underwent surgery between January 2022 and December 2025, during which VAVD combined with modified femoro-femoral partial bypass (MFFPB) was routinely adopted .

Inclusion criteria were: (1) diagnosis of TAAA with prior aortic dissection surgery (including Bentall procedure, aortic arch reconstruction, or distal trunk stent grafting); (2) underwent open thoracoabdominal reconstruction via thoraco-phreno-laparotomy approach ; (3) complete clinical and perioperative data available. Exclusion criteria were: (1) emergency surgery; (2) ruptured aneurysms; (3) endovascular or hybrid procedures; (4) severe preoperative comorbidities with life expectancy < 6 months; (5) incomplete medical records.

Anaesthetization procedure

Routine intravenous-inhalation combined anesthesia was performed, with monitoring of left radial arterial blood pressure, left dorsal foot artery and venous oxygen saturation. Double-lumen endotracheal intubation was managed as the tube of oxygen supply. Throughout each operation, esophageal

ultrasound, brain oxygen saturation monitor and bispectral index were used to appraise cardiac function, depth of intraoperative anesthesia and cerebral oxygen saturation. The core body temperature was monitored by Foley catheter with a temperature probe in the bladder and external defibrillation electrodes was prepared to cope with sudden malignant arrhythmias during surgery. The patient is admitted on the day before in an intermediate care unit in order to introduce a spinal fluid catheter that will be used for cerebrospinal fluid (CSF) pressure monitoring and drainage.

Surgical Procedure

Surgical repair of TAAA using a “staged clamping” procedure. The basic steps of the operation are the same as the step of Coselli et al. [12]. All patients are placed in a right lateral supine position with the upper body at 60° and the lower body at 30°. A left thoracoabdominal joint incision at the sixth intercostal space, from the left side of the thoracic spine to the right side down 1 cm to the umbilical cord, is chosen as surgery approach. After entering the chest, the surgeon carefully transects the costal arch and frees the tissue outside the peritoneum and below the diaphragm. Meanwhile, the abdominal aorta behind the peritoneum to the distal anastomosis was also exposed. The diaphragm was cut 3 to 4 cm from the chest wall along the costophrenic angle, and then the thoracic aorta was freed to the upper edge of the normal aorta and the snare belt was placed. After fully mobilizing the thoracoabdominal aorta, heparin was injected through the deep vein (2.5 mg/kg). Prophylactic CSF drainage was routinely placed after the induction of anaesthesia and remained in place for 24–72 hours postoperatively; the target CSF pressure was 10 mmHg.

CPB Management

Femoro-Femoral Partial Bypass

In all cases, right femoral artery and vein are exposed in the groin. Cannulation of the right femoral artery is implemented via a transverse arteriotomy, accomplished after achieving proximal and distal control. Given the size of the artery and vein, a 20F to 22F femoral arterial is chosen and directed proximally into the iliac artery and 20F-24F vein cannula is delivered into the right atrium with the guide of esophageal ultrasound (Fig. 1.). The extracorporeal circuit was primed using Plasma-Lyte A (500mL), and hydroxyethyl starch 130/0.4 (1L), maintaining hematocrit (Hct) $\geq 25\%$ with red blood cells (RBCs), 20% albumin, methylprednisolone (500mg), mannitol, and low-molecular-weight heparin. Differ from CPB, partial bypass runs a fluctuation flow of 1.5 to 3 L/min/m² with a nasopharyngeal temperature of 32°C. Blood gases were sustained at target PCO₂ of 40–45mmHg with an α -stat strategy.

VAVD and modified femoro-femoral partial bypass

CPB was launched by draining the venous blood of the right atrium into a venous reservoir (maximum volume 4.5L) and performing oxygenation through a hollow fiber membrane oxygenator (Terumo,

Japan). VAVD (Medtronic, USA) was utilized during partial bypass so as to ameliorate the vein drainage, which can facilitate the process of partial bypass. In addition, we establish a direct access between the arterial perfusion tube and the venous drainage tube for rapid blood transfusion, mainly to encumber massive blood loss during the operation and ensure the running of CPB (blood flow: clamping, and opening. Figure 2).

Blood pressure management of operation

Referring to the experience of high-volume, mild hypothermia and maintain spinal cord perfusion pressure (≥ 80 mmHg) can be benefit for the prevent the injury of spine cord ischemia. Meanwhile, Dorsal foot blood pressure > 60 mmhg can indicate good perfusion of abdominal viscera and reduce kidney malfunction. Due to the massive blood loss during the operation, the conventional partial bypass hardly sustains the target value of blood pressure. Thanks to the tube of the arterial perfusion and the venous drainage, we can achieve the stable of perfusion press. VAVD can be well deal with the situation of hyperperfusion, which is the result of clamping proximally of thoracoabdominal aortic and can trigger the process of nervous system disorder.

Study definition

Crawford's classification was introduced to category the type of all aneurysms. Operative mortality was defined as death within one week after surgery. Postoperative respiratory complications include reintubation, a need for tracheostomy and mechanical ventilation for longer than 48 hours. Postoperative AKI was defined using the Kidney Disease, Improving Global Outcomes (KDIGO) standard. Neurologic deficit was defined as a new and permanent or temporary neurologic disability after surgery. Postoperative paraplegia (inability to move legs) and paraparesis (leg weakness) were the characteristic performance of spinal cord deficits. Spine cord perfusion pressure (SCPP) = MAPd (mean arterial pressure distal to clamp)-cerebrospinal fluid (CSF) pressure[13].

Statistical Analysis

SPSS Statistics version 24.0 (SPSS, Chicago, IL, USA) was utilized for data analysis. The characteristics of the patient are given as the median with interquartile range (IQR). Differences between groups and relationships between different indices were analyzed using non-parametric tests. Categorical data were represented as frequency distributions and percentages. To identify the risk factors for SCI, statistically significant variables were analyzed with multivariate logistic regression with a backward stepwise method; the inclusion criterion was a p -value <0.05 and the exclusion. For all analyses, all p -values were two-sided of less than 0.05 was considered statistically significant.

Results

Comparison of Baseline Characteristics Between the Two Groups

A total of 48 patients were included in this study, with 22 patients in the control group (conventional femoral-femoral bypass without VAVD) and 26 patients in the study group (VAVD combined with MFFPB). As shown in Table 1, there were no statistically significant differences in baseline characteristics between the two groups, including age (56.5 ± 9.8 vs. 54.2 ± 11.2 years, $P = 0.451$), sex distribution (male: 72.7% vs. 76.9%, $P = 0.737$), BMI (24.8 ± 3.5 vs. 25.3 ± 3.8 kg/m², $P = 0.639$), and comorbidities such as hypertension (86.4% vs. 84.6%, $P = 0.862$), diabetes mellitus (18.2% vs. 19.2%, $P = 0.927$), and COPD (22.7% vs. 15.4%, $P = 0.517$). The distribution of prior aortic surgery types (Bentall procedure: 36.4% vs. 34.6%; aortic arch replacement: 40.9% vs. 30.8%; distal trunk stent grafting: 22.7% vs. 34.6%, $P = 0.652$) and the interval from prior surgery (36.2 ± 18.5 vs. 40.8 ± 24.2 months, $P = 0.465$) were also comparable between groups. Crawford classification ($P = 0.885$), preoperative laboratory parameters, LVEF ($58.6 \pm 7.2\%$ vs. $59.8 \pm 6.5\%$, $P = 0.547$), and ASA score ($P = 0.738$) did not differ significantly between the two groups. These findings indicate that the baseline characteristics of the two groups were well balanced and comparable.

Table 1
Comparison of Baseline Characteristics Between the Control Group and Study Group

Characteristic	Control Group (n = 22)	Study Group (n = 26)	t/ χ^2 /Z value	P value
Age (years, mean $\pm$ SD)	56.5 $\pm$ 9.8	54.2 $\pm$ 11.2	0.761	0.451
Male [n (%)]	16 (72.7)	20 (76.9)	0.113	0.737
BMI (kg/m ² , mean $\pm$ SD)	24.8 $\pm$ 3.5	25.3 $\pm$ 3.8	0.472	0.639
Smoking history [n (%)]	12 (54.5)	15 (57.7)	0.049	0.825
Hypertension [n (%)]	19 (86.4)	22 (84.6)	0.030	0.862
Diabetes mellitus [n (%)]	4 (18.2)	5 (19.2)	0.008	0.927
COPD [n (%)]	5 (22.7)	4 (15.4)	0.420	0.517
Prior aortic surgery type [n (%)]			0.856	0.652
Bentall procedure	8 (36.4)	9 (34.6)		
Aortic arch replacement	9 (40.9)	8 (30.8)		
Distal trunk stent grafting	5 (22.7)	9 (34.6)		
Interval from prior surgery (months, mean $\pm$ SD)	36.2 $\pm$ 18.5	40.8 $\pm$ 24.2	0.738	0.465
Crawford classification [n (%)]			0.245	0.885
Type I	8 (36.4)	10 (38.5)		
Type II	9 (40.9)	9 (34.6)		
Type III	5 (22.7)	7 (26.9)		
Preoperative laboratory values				
Hemoglobin (g/L, mean $\pm$ SD)	128.5 $\pm$ 15.6	131.2 $\pm$ 16.8	0.575	0.568
Serum creatinine (μ mol/L, mean $\pm$ SD)	82.4 $\pm$ 18.6	78.9 $\pm$ 20.5	0.616	0.541
eGFR (mL/min/1.73m ² , mean $\pm$ SD)	85.6 $\pm$ 16.2	89.3 $\pm$ 15.8	0.794	0.432
LVEF (% , mean $\pm$ SD)	58.6 $\pm$ 7.2	59.8 $\pm$ 6.5	0.607	0.547
ASA score [n (%)]			0.112	0.738
III	14 (63.6)	15 (57.7)		
IV	8 (36.4)	11 (42.3)		

2.2 Comparison of Intraoperative Data Between the Two Groups

Intraoperative data comparisons between the two groups are summarized in Table 2. No significant differences were observed in operation time (405.2 ± 48.6 vs. 393.2 ± 43.8 min, $P = 0.367$), cardiopulmonary bypass time (98.5 ± 38.2 vs. 93.0 ± 32.6 min, $P = 0.591$), or intraoperative temperature (32.2 ± 1.3 vs. $32.4 \pm 1.1^{\circ}\text{C}$, $P = 0.564$) between the control and study groups.

However, patients in the study group demonstrated significantly higher dorsalis pedis artery pressure compared with the control group (67.4 ± 6.8 vs. 58.2 ± 7.5 mmHg, $P < 0.001$), corresponding to a significantly higher estimated spinal cord perfusion pressure (85.6 ± 2.0 vs. 74.8 ± 5.2 mmHg, $P < 0.001$). Notably, the proportion of patients achieving SCPP > 80 mmHg during the procedure was significantly greater in the study group than in the control group (88.5% vs. 45.5%, $P = 0.002$).

Urinary volume was significantly higher in the study group (262.3 ± 27.6 vs. 235.5 ± 32.8 mL, $P = 0.003$), while hemoglobinuria showed a lower trend in the study group (46.2% vs. 72.7%), although this difference did not reach statistical significance ($P = 0.065$). No significant differences were observed between the two groups in red blood cell transfusion requirements, ultrafiltrate output, or the number of reimplanted intercostal/lumbar arteries (all $P > 0.05$). The distribution of reimplanted intercostal and lumbar artery levels was similar between the two groups.

Table 2
Comparison of Intraoperative Data Between the Control Group and Study Group

Variable	Control Group (n = 22)	Study Group (n = 26)	t/ χ^2 /Z value	P value
Operation time (min, mean $\pm$ SD)	405.2 $\pm$ 48.6	393.2 $\pm$ 43.8	0.912	0.367
Cardiopulmonary bypass time (min, mean $\pm$ SD)	98.5 $\pm$ 38.2	93.0 $\pm$ 32.6	0.542	0.591
Intraoperative temperature ($^{\circ}$ C, mean $\pm$ SD)	32.2 $\pm$ 1.3	32.4 $\pm$ 1.1	0.581	0.564
Pressure of radial artery (mmHg, mean $\pm$ SD)	97.8 $\pm$ 9.2	99.1 $\pm$ 8.7	0.506	0.615
Pressure of dorsalis pedis artery (mmHg, mean $\pm$ SD)	58.2 $\pm$ 7.5	67.4 $\pm$ 6.8	4.508	< 0.001
Spinal cord perfusion pressure (mmHg, mean $\pm$ SD)	74.8 $\pm$ 5.2	85.6 $\pm$ 2.0	9.836	< 0.001
SCPP > 80 mmHg [n (%)]	10 (45.5)	23 (88.5)	10.128	0.002
RBCs transfused (units, mean $\pm$ SD)	5.5 $\pm$ 3.8	4.2 $\pm$ 2.9	1.336	0.188
Urinary volume (mL, mean $\pm$ SD)	235.5 $\pm$ 32.8	262.3 $\pm$ 27.6	3.093	0.003
Hemoglobinuria [n (%)]	16 (72.7)	12 (46.2)	3.404	0.065
Ultrafiltrate output (mL, mean $\pm$ SD)	122.8 $\pm$ 68.5	113.0 $\pm$ 62.8	0.518	0.607
No. of reimplanted intercostal/lumbar arteries (mean $\pm$ SD)	1.9 $\pm$ 1.1	2.1 $\pm$ 1.3	0.576	0.568
Reimplanted artery level [n]				
TH6	1	1	—	—
TH7	1	1	—	—
TH8	4	4	—	—
TH9	3	5	—	—
TH10	1	2	—	—
TH11	4	4	—	—
TH12	1	1	—	—
L1	4	5	—	—

Data are presented as mean $\pm$ SD, n (%), or n. SCPP: spinal cord perfusion pressure; RBCs: red blood cells; TH: thoracic; L: lumbar. P values were calculated using independent t-test, Mann-Whitney U test, or χ^2 test as appropriate. Statistically significant P values (< 0.05) are shown in bold.

2.3 Comparison of Postoperative Outcomes Between the Two Groups

Postoperative outcomes are summarized in Table 3. The incidence of spinal cord ischemia (SCI) was significantly lower in the study group compared with the control group (7.7% [2/26] vs. 22.7% [5/22], $P = 0.038$). Paraplegia occurred in 3.8% (1/26) of patients in the study group versus 13.6% (3/22) in the control group, although this difference did not reach statistical significance ($P = 0.321$). Paraparesis was observed in 3.8% (1/26) and 9.1% (2/22), respectively ($P = 0.581$).

Operative mortality was 3.8% (1/26) in the study group compared with 9.1% (2/22) in the control group ($P = 0.583$). The incidence of cardiac events (3.8% vs. 9.1%, $P = 0.583$), stroke (7.7% vs. 13.6%, $P = 0.651$), renal insufficiency (3.8% vs. 13.6%, $P = 0.321$), respiratory complications (11.5% vs. 22.7%, $P = 0.441$), reintubation (7.7% vs. 22.7%, $P = 0.217$), and sepsis (7.7% vs. 18.2%, $P = 0.397$) were all lower in the study group, but these differences were not statistically significant.

Regarding postoperative recovery, patients in the study group had a significantly shorter hospital length of stay compared with the control group (17.0 [IQR: 13.0–22.0] vs. 24.5 [IQR: 18.0–35.0] days, $P = 0.003$). The study group also showed trends toward shorter intensive care duration (5.0 vs. 7.0 days, $P = 0.058$), shorter duration of intubation (2.0 vs. 3.0 hours, $P = 0.085$), and shorter postoperative awaken time (6.0 vs. 7.5 hours, $P = 0.063$), although these differences did not reach statistical significance.

Table 3
Comparison of Postoperative Outcomes Between the Control Group and Study Group

Variable	Control Group (n = 22)	Study Group (n = 26)	t/ χ^2 /Z value	P value
Primary outcome				
Spinal cord ischemia [n (%)]	5 (22.7)	2 (7.7)	4.286	0.038
Paraplegia [n (%)]	3 (13.6)	1 (3.8)	1.521	0.321
Paraparesis [n (%)]	2 (9.1)	1 (3.8)	0.565	0.581
Secondary outcomes				
Operative mortality [n (%)]	2 (9.1)	1 (3.8)	0.583	0.583
Cardiac events [n (%)]	2 (9.1)	1 (3.8)	0.583	0.583
Stroke [n (%)]	3 (13.6)	2 (7.7)	0.461	0.651
Renal insufficiency [n (%)]	3 (13.6)	1 (3.8)	1.521	0.321
Respiratory complications [n (%)]	5 (22.7)	3 (11.5)	1.083	0.441
Pneumonia [n (%)]	7 (31.8)	4 (15.4)	1.828	0.176
Reintubation [n (%)]	5 (22.7)	2 (7.7)	2.173	0.217
Sepsis [n (%)]	4 (18.2)	2 (7.7)	1.209	0.397
Postoperative recovery				
Intensive care duration (days, median [IQR])	7.0 [4.0–10.0]	5.0 [4.0–7.0]	1.893	0.058
Duration of intubation (h, median [IQR])	3.0 [2.0–5.0]	2.0 [1.0–4.0]	1.723	0.085
Hospital length of stay (days, median [IQR])	24.5 [18.0–35.0]	17.0 [13.0–22.0]	2.932	0.003
Postoperative awaken time (h, median [IQR])	7.5 [5.5–10.0]	6.0 [4.5–8.0]	1.856	0.063

Data are presented as n (%), mean $\pm$ SD, or median [IQR]. IQR: interquartile range. P values were calculated using independent t-test, Mann-Whitney U test, χ^2 test, or Fisher's exact test as appropriate. Statistically significant P values (< 0.05) are shown in bold.

2.4 Organ Function Parameters

As shown in Table 4, no significant differences were observed between the two groups in any of the measured organ function parameters at either preoperative or postoperative time points (all P > 0.05). Within-group comparisons also revealed no significant changes from preoperative to postoperative

values (all $P > 0.05$), indicating that both perfusion strategies were similarly effective in preserving hepatic, cardiac, and renal function in the early postoperative period.

Table 4
Preoperative and Postoperative Organ Function Parameters by Group

Variable	Control Group (n = 22)	Study Group (n = 26)		Group Comparison	
	Preoperative	Postoperative	Preoperative	Postoperative	P value*
ALT (U/L, mean $\pm$ SD)	22.6 $\pm$ 5.9	23.0 $\pm$ 6.1	22.2 $\pm$ 5.5	22.6 $\pm$ 5.8	0.765
AST (U/L, mean $\pm$ SD)	21.3 $\pm$ 4.1	21.0 $\pm$ 4.2	21.1 $\pm$ 3.8	20.8 $\pm$ 3.9	0.443
LVEF (% , mean $\pm$ SD)	60.1 $\pm$ 5.0	59.5 $\pm$ 5.4	60.5 $\pm$ 4.6	60.0 $\pm$ 5.0	0.662
Creatinine (mg/dL, mean $\pm$ SD)	0.84 $\pm$ 0.2	0.81 $\pm$ 0.3	0.80 $\pm$ 0.2	0.77 $\pm$ 0.3	0.379
BUN (mg/dL, mean $\pm$ SD)	89.5 $\pm$ 22.0	90.0 $\pm$ 22.5	88.0 $\pm$ 21.0	88.5 $\pm$ 21.5	0.402
BNP (pg/mL, mean $\pm$ SD)	525.0 $\pm$ 50.0	535.0 $\pm$ 52.0	518.5 $\pm$ 48.0	526.8 $\pm$ 50.0	0.517
eGFR (mL/min/1.73m ² , mean $\pm$ SD)	115.5 $\pm$ 12.5	112.0 $\pm$ 12.0	118.0 $\pm$ 11.5	115.0 $\pm$ 11.8	0.671

*Data are presented as mean $\pm$ SD. ALT: alanine aminotransferase; AST: aspartate aminotransferase; LVEF: left ventricular ejection fraction; BUN: blood urea nitrogen; BNP: B-type natriuretic peptide; eGFR: estimated glomerular filtration rate. *P value for between-group comparison of postoperative values (Control vs. Study). Within-group comparisons (preoperative vs. postoperative) were all non-significant (all $P > 0.05$).

2.5 Comparison of Survival Rates Between the Two Groups

Kaplan-Meier survival analysis was performed to compare the 1-year and 3-year survival rates between the two groups (Fig. 1). The 1-year survival rate was 100% (26/26) in the study group and 95.5% (21/22) in the control group. The 3-year survival rate was 96.2% (25/26) in the study group and 86.4% (19/22) in the control group. Although the study group demonstrated numerically superior survival at both time points, the differences did not reach statistical significance (1-year: log-rank $P = 0.315$; 3-year: log-rank $P = 0.134$).

2.6 Univariate Analysis of spinal cord injury in these eligible subjects

Univariate analysis (Table 5) identified significant risk factors for SCI, including intraoperative blood loss ($P = 0.029$), pulmonary complications ($P = 0.015$), CSF pressure ($P = 0.011$), intraoperative haemoglobin ($P = 0.001$), mean SCPP ($P = 0.024$), and RBC transfusion requirements ($P = 0.037$). No significant associations were observed for sex, age, BMI, operation time, or clamp times (all $P > 0.05$).

Multivariate analysis (Table 6) revealed that lower SCPP (OR = 0.752, 95%CI:0.612–0.924, $P = 0.007$), greater blood loss (OR = 1.043 per 100mL, 95%CI:1.008–1.079, $P = 0.015$), and elevated CSF pressure (OR = 1.237, 95%CI:1.021–1.499, $P = 0.030$) were independently associated with increased SCI risk.

Table 5
Univariate Analysis of Risk Factors for Spinal Cord Injury (SCI)

Variable	Non-SCI (n = 41)	SCI (n = 7)	P value
Male sex [n (%)]	25 (61.0)	5 (71.4)	0.452
Age (years, mean $\pm$ SD)	57.2 $\pm$ 11.8	57.4 $\pm$ 12.0	0.663
BMI (kg/m ² , mean $\pm$ SD)	23.0 $\pm$ 4.3	23.7 $\pm$ 4.3	0.440
Operation time (min, mean $\pm$ SD)	579.6 $\pm$ 134.8	650.9 $\pm$ 109.1	0.581
Proximal aortic clamp time (min, mean $\pm$ SD)	19.3 $\pm$ 11.5	21.6 $\pm$ 12.7	0.274
Intercostal artery clamp time (min, mean $\pm$ SD)	27.5 $\pm$ 12.0	33.4 $\pm$ 14.2	0.771
Intraoperative blood loss (mL, mean $\pm$ SD)	3467.3 $\pm$ 1325.6	4927.3 $\pm$ 1402.6	0.029
Pulmonary complications [n (%)]	20 (48.8)	4 (57.1)	0.015
CSF pressure (mmHg, mean $\pm$ SD)	11.6 $\pm$ 3.6	16.7 $\pm$ 3.9	0.011
Haemoglobin during operation (g/L, mean $\pm$ SD)	99.5 $\pm$ 16.5	96.3 $\pm$ 16.0	0.001
Average SCPP (mmHg, mean $\pm$ SD)	92.1 $\pm$ 3.4	75.6 $\pm$ 2.9	0.024
Suspended RBCs infusion (units, mean $\pm$ SD)	6.3 $\pm$ 3.9	7.8 $\pm$ 4.2	0.037

Data are presented as n (%), mean $\pm$ SD, or median [IQR]. BMI: body mass index; CSF: cerebrospinal fluid; SCPP: spinal cord perfusion pressure; RBCs: red blood cells. P values were calculated using independent t-test, Mann-Whitney U test, or χ^2 test as appropriate. Statistically significant P values (< 0.05) are shown in bold.

Table 6
Multivariate Logistic Regression Analysis of Risk Factors for SCI

Variable	β	OR	95% CI	P value
SCPP (per 1 mmHg decrease)	-0.285	0.752	0.612–0.924	0.007
Intraoperative blood loss (per 100 mL)	0.042	1.043	1.008–1.079	0.015
CSF pressure (per 1 mmHg)	0.213	1.237	1.021–1.499	0.030

Adjusted for age, sex, and operation time. SCPP: spinal cord perfusion pressure; CSF: cerebrospinal fluid; OR: odds ratio; CI: confidence interval.

Discussion

Redo TAAA surgery after prior aortic operation presents formidable challenges. Aortic dissection may necessitate one or more reoperations following initial repair [14, 15]. The etiologies of late aortic pathology after prior aortic surgery include anastomotic leakage, false aneurysm formation, recurrent dissection, residual dissection progression, and aortic aneurysm expansion [16]. The overall reoperation rate for type A dissection has been reported as 8.7%, but this rate is substantially higher—up to 38.3%—in patients with Marfan syndrome [17, 18]. Notably, 7 of the 48 patients (14.6%) in our cohort had Marfan syndrome. Aortic replacement surgery does not halt the progressive aortic dilation in Marfan patients, which is primarily attributable to cystic medial degeneration, fragmentation of elastic fibers, and weakening of the aortic wall, predisposing to recurrent aortic root aneurysm or dissection [18]. Previous studies have confirmed that stent-graft placement cannot prevent late aortic dilation or the development of extensive thoracoabdominal aortic aneurysms [19]. Consequently, endovascular treatment is generally not recommended for this patient subset, and open surgical repair remains the treatment of choice for TAAA in patients with prior aortic surgery.

To mitigate the adverse effects of simple aortic cross-clamping, extracorporeal perfusion techniques are routinely employed to facilitate repair. Distal aortic perfusion during TAAA repair provides continuous perfusion to vital distal organs, including the liver, kidneys, mesenteric viscera, and spinal cord. Compared with simple cross-clamping and passive shunts, distal aortic perfusion significantly reduces ischemic complications [20]. Currently, four principal techniques are available for distal aortic perfusion during TAAA surgery: left atrium-to-left femoral artery bypass, left ventricle-to-left femoral artery bypass, passive shunt (Gott shunt), partial cardiopulmonary bypass (femoral vein-to-femoral artery), and total cardiopulmonary bypass with hypothermic circulatory arrest. Each of these adjunctive measures has been introduced to eliminate or, at minimum, mitigate the known sequelae associated with open surgical repair. Partial cardiopulmonary bypass offers several unique advantages, including enhanced oxygenation in patients with compromised pulmonary function, the potential for systemic hypothermia, and spinal cord protection, making it the preferred distal perfusion technique in high-volume aortic centers [21, 22].

Single femoral vein drainage during partial cardiopulmonary bypass cannot always guarantee adequate venous return to maintain stable bypass flow, which may compromise perfusion to vital organs and the spinal cord, potentially leading to ischemia. In some extreme cases, partial cardiopulmonary bypass must be abruptly discontinued owing to insufficient venous return from the right atrium. Additionally, massive intraoperative blood loss resulting in inadequate venous return and subsequent hemodynamic instability represents another critical factor that can disrupt the smooth conduct of partial cardiopulmonary bypass. To address these limitations, we employed vacuum-assisted venous drainage (VAVD) to ensure adequate venous drainage volume, achieving satisfactory outcomes. Notably, the mean reservoir blood volume during operation was approximately 1 L, which facilitated effective management of partial cardiopulmonary bypass [24]. Moreover, partial cardiopulmonary bypass was successfully completed in all 48 patients. Our results demonstrated that VAVD significantly improved femoral vein drainage and facilitated the conduct of partial cardiopulmonary bypass, which is consistent with previously published findings [24]. To further manage the risk of massive intraoperative blood loss, we modified the conventional femoro-femoral partial bypass circuit by creating a direct connection between the arterial infusion line and the venous drainage line. This modification enabled rapid blood transfusion when needed, thereby maintaining stable perfusion pressure to the heart, brain, and spinal cord.

The mortality rate observed in our study compares favorably with those previously reported from large registries. Our analysis of 48 patients revealed an overall in-hospital mortality rate of 3.8% in the study group, which is substantially below the 22.3% reported from a high-volume center [25]. Several factors may contribute to this discrepancy. First, the limited sample size (48 patients) may have influenced the results. Second, mortality varies considerably by TAAA extent and Crawford classification. Nevertheless, the overall survival at 1 and 3 years of follow-up in our analysis was 96.2% and 86.4%, respectively, which is encouraging and compares favorably with previously published data [25]. Although these results differ from previous reports, the disparity is likely attributable to the small sample size and the relatively selective nature of our cohort.

Femoro-femoral partial bypass is conducted using a membrane oxygenator, a standard cardiopulmonary bypass component. With a flow rate of 1.5 to 3 L/min/m², the partial bypass provides supplemental oxygenation and facilitates single-lung ventilation during aneurysm repair. Furthermore, the direct connection between the arterial infusion line and the venous drainage line allows oxygenated blood to be delivered into the right atrium when needed, reducing the pulmonary workload and providing additional oxygenation support. During aortic cross-clamping, the mesenteric vessels, kidneys, and intercostal arteries are also perfused with oxygenated blood via the bypass circuit [26].

Spinal cord ischemic injury, manifesting as paraparesis or paraplegia, remains a major complication following TAAA repair. Several studies have demonstrated significant protective effects of mild systemic hypothermia (32°C) and maintenance of spinal cord perfusion pressure (SCPP $\geq$ 80 mmHg) during aortic occlusion [27]. In our study, the mean intraoperative bladder temperature was $32.3 \pm 1.2^\circ\text{C}$, and the mean estimated SCPP was 85.6 ± 2.0 mmHg, exceeding the widely accepted threshold of 80 mmHg. These

findings support the potential spinal cord protective benefits of this perfusion strategy. The reported incidence of paraparesis and paraplegia in TAAA repair ranges from 3% to 10% and 5% to 12%, respectively. In our cohort, the overall SCI rate was 14.6% (7/48), with a paraplegia rate of 8.3% (4/48). These rates are slightly higher than those reported in some large series, which may be explained by the high-risk nature of our cohort (all patients had prior aortic surgery) and the relatively small sample size. Nonetheless, the cardiac event rate (6.25%), stroke rate (12.5%), renal insufficiency rate (6.25%), and respiratory complication rate (18.75%) in our study were consistent with previously reported findings. Importantly, our data demonstrated that the incidence of adverse events attributable to systemic hypothermia was not increased with the use of femoro-femoral partial bypass, as systemic cooling also confers protective effects on the myocardium and abdominal viscera.

Recent evidence has highlighted the critical role of venous congestion in cardiac surgery-associated acute kidney injury (CS-AKI). A retrospective analysis demonstrated that elevated central venous pressure (CVP), rather than cardiac index or systolic blood pressure, was associated with decreased estimated glomerular filtration rate (eGFR) in patients undergoing cardiovascular surgery with cardiopulmonary bypass [27]. Based on the 2012 KDIGO diagnostic criteria for AKI, only one patient in our study was diagnosed with CS-AKI, a rate substantially lower than previously reported by Sabreen and colleagues [27]. This favorable finding is consistent with our previous research [28] and may be attributable to the improved venous drainage and reduced venous congestion achieved with VAVD.

The pathophysiological mechanisms underlying SCI are not fully elucidated but are thought to involve a complex interplay of surgical, hemodynamic, and patient-related factors [29]. In our univariate analysis, significant risk factors for SCI included intraoperative blood loss, pulmonary complications, CSF pressure, intraoperative haemoglobin, SCPP, and RBC transfusion requirements. Multivariate analysis identified lower SCPP, greater intraoperative blood loss, and elevated CSF pressure as independent risk factors for SCI. These findings are consistent with the established understanding that SCPP (calculated as mean arterial pressure minus CSF pressure) is a critical determinant of spinal cord perfusion. Elevated CSF pressure may compromise spinal cord perfusion and contribute to postoperative SCI. Similarly, lower intraoperative haemoglobin levels may impair oxygen delivery to spinal cord tissue, leading to ischemia, hypoxia, edema, and subsequent neurologic injury. Dong et al. reported that improving hemostasis, correcting coagulopathy to reduce bleeding, and maintaining a hematocrit > 23% both intraoperatively and postoperatively were important strategies for mitigating SCI in TAAA repair [30].

Hemolysis remains a recognized morbidity associated with cardiopulmonary bypass, related to mechanical circulation and its components, including pump revolutions, oxygenator shear forces, foreign surfaces, and blood suction recovery from the operative field. Although only one patient in our cohort developed AKI, 72 of 96 patients (75%) had hemoglobinuria. We postulate that massive blood loss requiring extensive suction recovery in the operative field may have contributed to this phenomenon. Micro-embolism represents another potential complication, with 12 of 96 patients (12.5%) experiencing

stroke—a rate comparable to that reported with conventional femoral-femoral partial bypass. Collectively, these findings support the overall safety of VAVD in the management of TAAA repair.

Several limitations of this study warrant acknowledgment. First, this was a retrospective, single-center study with a relatively small sample size ($n = 48$), which may introduce selection bias and limit the generalizability of our findings. Second, the small number of SCI events ($n = 7$) constrained our ability to perform a comprehensive multivariate analysis with multiple covariates, potentially leading to overfitting of the regression model. Third, the lack of a standardized protocol for CSF drainage and the absence of long-term neurologic follow-up (beyond 3 years) may have influenced our assessment of spinal cord outcomes. Fourth, the study was conducted at a single institution with a specialized aortic surgery team, which may limit the applicability of our findings to lower-volume centers. Fifth, failure to detect independent risk factors for overall mortality may be attributable to the small sample size and relatively short follow-up duration. Finally, although we observed statistically significant improvements in SCI and hospital length of stay, these findings require confirmation in larger, prospective, multicenter studies. Despite these limitations, we believe our findings provide valuable insights into the potential benefits of VAVD combined with MFFPB for spinal cord protection in this high-risk reoperative TAAA population.

Declarations

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Author Contribution

YiHuiYu.LeiWang. and ZhenHongWang. wrote the main manuscript text and XinYi Xie,ZuoYingHu prepared figures 1-3. All authors reviewed the manuscript.

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Figures

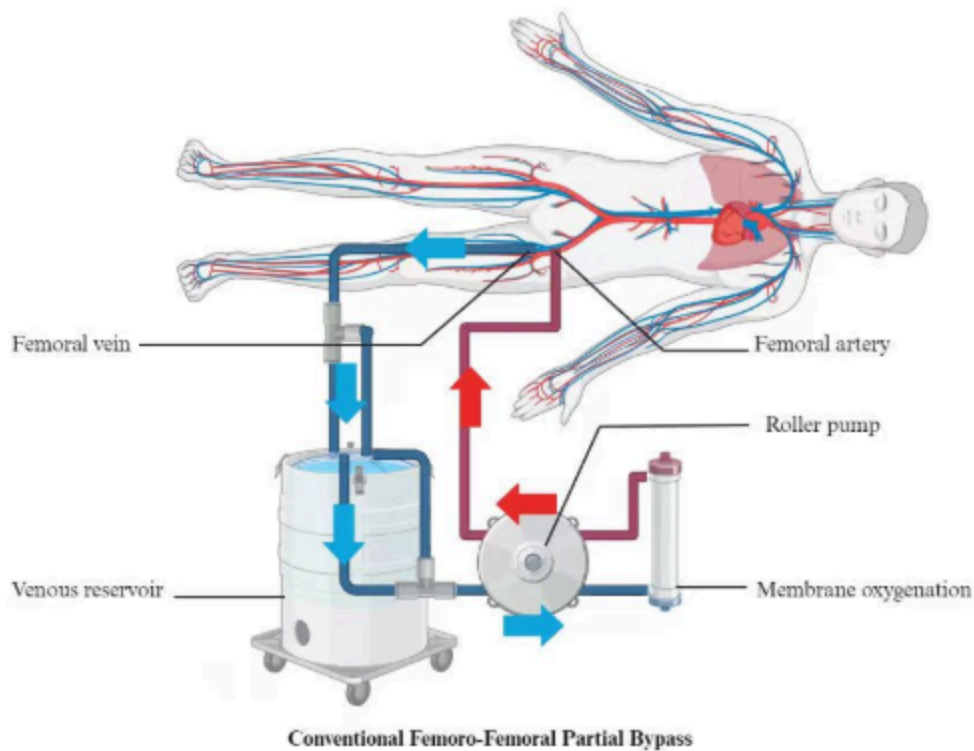


Figure 1

Coventional femoro-femoral partial bypass. A 20F–22F arterial cannula was inserted into the right femoral artery and advanced to the iliac artery, and a 20F–24F venous cannula was positioned in the right atrium under TEE guidance.

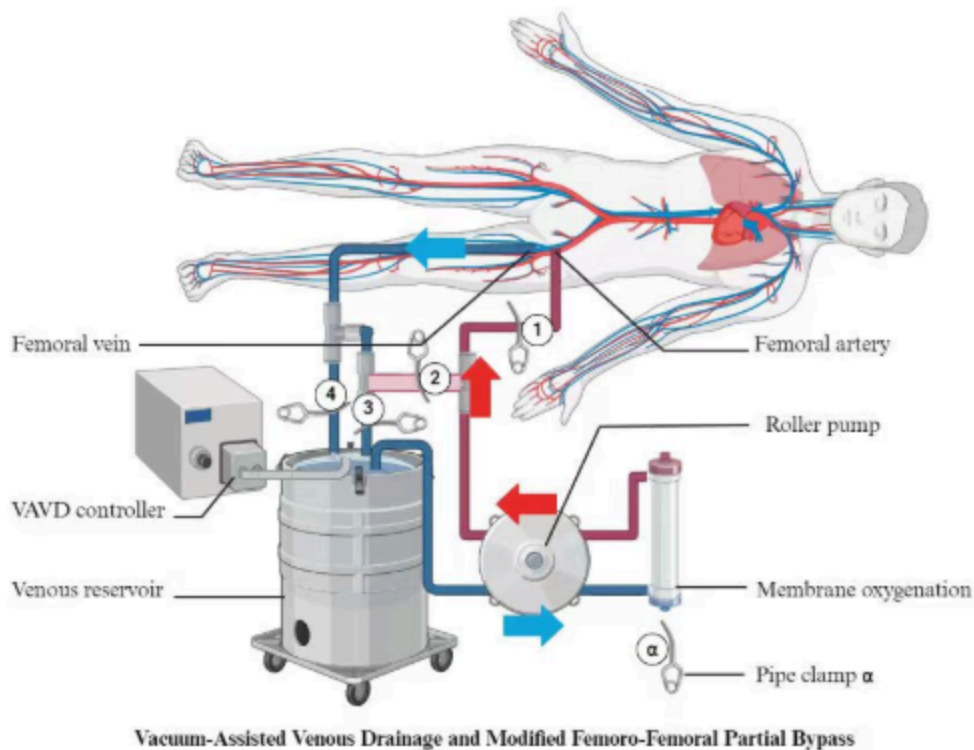


Figure 2

VAVD-assisted venous drainage and modified femoro-femoral partial bypass. The circuit consisted of a venous reservoir, oxygenator, and VAVD device. A shunt between the arterial and venous lines allowed rapid transfusion during massive hemorrhage, maintaining stable bypass flow (1.5–3 L/min/m²).

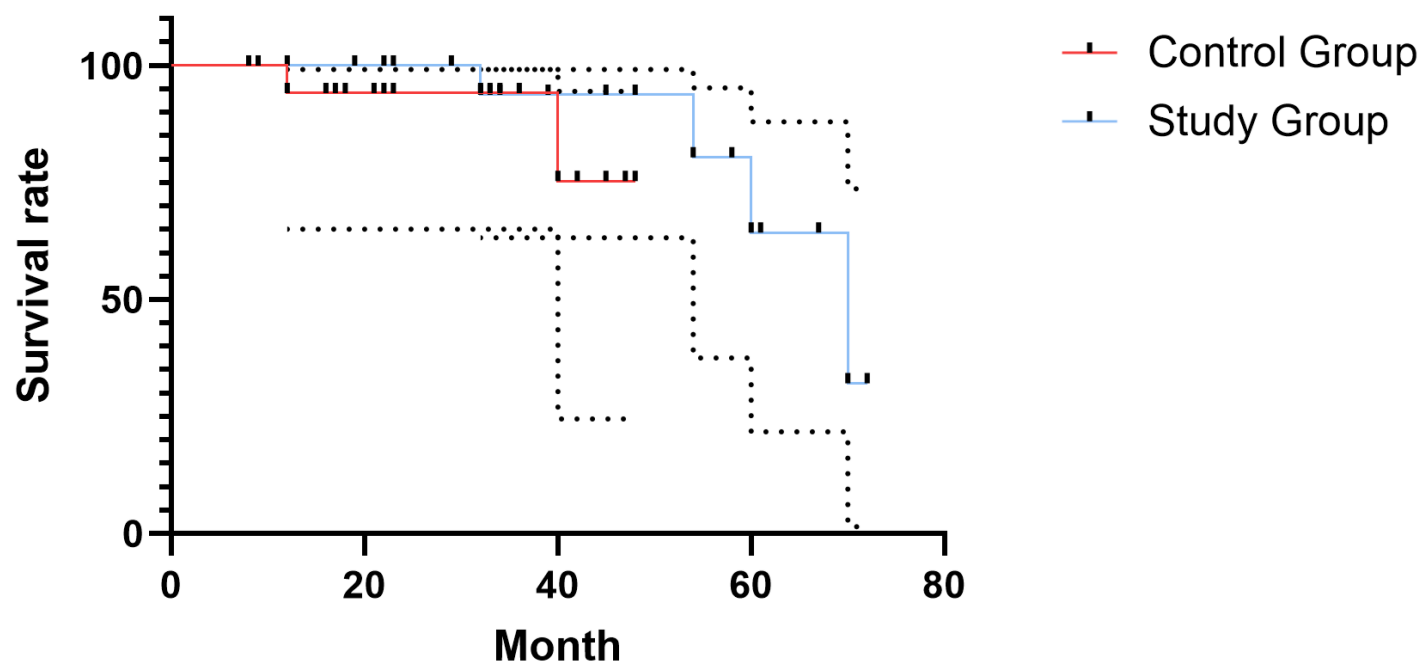


Figure 3

Kaplan-Meier survival curves for the control and study groups. The study group showed numerically higher survival rates at 1 year (100% vs. 95.5%) and 3 years (96.2% vs. 86.4%), but the differences were not statistically significant (log-rank $P = 0.315$ and $P = 0.134$, respectively). VAVD: vacuum-assisted venous drainage.