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Extra-anatomic revascularization and a new cannulation strategy for preoperative cerebral malperfusion due to severe stenosis or occlusion of supra-aortic branch vessels in acute type A aortic dissection

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A R T I C L E I N F O

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Imaging cerebral malperfusion
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A B S T R A C T

Objectives: Acute type A aortic dissection (ATAAD) with severe stenosis or occlusion of the true lumen of aortic arch branch vessels often leads to an increased incidence of severe postsurgical neurological complications and mortality rate. In this study, we aimed to introduce our institutional extra-anatomic revascularization and cannulation strategy with improved postoperative outcomes for better management of patients with cerebral malperfusion in the setting of ATAAD.
Methods: Twenty-eight patients with ATAAD complicated by severe stenosis or occlusion of the aortic arch branch vessels, as noted on combined computed tomography angiography of the aorta and craniocervical artery, between January 2021 and June 2022 were included in this study. Basic patient characteristics, surgical procedures, hospitalization stays, and early follow-up results were analyzed.
Results: The median follow-up duration was 16.5 months (interquartile range: 11.5–20.5), with a 100% completion rate. The 30-day mortality rates was 7.1% (2/28 patients); two patients had multiple cerebral infarctions on preoperative computed tomography and persistent coma. Postoperative transient neurological dysfunction occurred in 10.7% (3/28) of the patients, and no new permanent neurological dysfunction occurred. Of all the patients, 3.6% (1/28) had novel acute renal failure. No other deaths, secondary surgeries, or serious complications occurred during the early follow-up period.
Conclusions: Use of extra-anatomic revascularization and a new cannulation strategy before cardiopulmonary bypass is safe and feasible and may reduce the high incidence of postoperative neurological complications in patients with ATAAD and cerebral malperfusion.

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1. Introduction

Acute type A aortic dissection (ATAAD) complicated by cerebral malperfusion (CM) is closely related to high mortality and a poor neurological prognosis. According to the International Registry of Acute Aortic Dissection, 15.1% (362/2402 patients) of patients with ATAAD have CM before surgery, and that their postoperative in-hospital mortality rate is 25.7% [1]. A meta-analysis by Wang et al. [2] showed that CM incidence in patients with ATAAD was 15.9%, and that the in-hospital mortality rate was 20.1% (73/363). Following antegrade and/or retrograde cerebral perfusion, 35.7% (71/199) of patients showed no improvement or further deterioration of the nervous system. However, the current strategies for the treatment of these patients remain controversial. The results from our previous clinical studies [3] and those of Inoue et al. [4] suggest a requirement for reducing the occurrence of postoperative neurological complications from preoperative neurological symptoms based on anatomical structure-oriented changes. Regardless of the preoperative neurological symptoms, abnormal carotid blood flow disorders secondary to stenosis or the occlusion of supra-aortic branch vessels (SABV) can lead to poor postoperative neurological outcomes [5–7]. To address this problem, several previous studies have reported the use of the branch-first technique. However, no systematic strategy for early extra-anatomic revascularization and cannulation is available [8–10]. After January 2021, we began using the newly proposed reconstruction strategy and completing extra-anatomic revascularization before cardiopulmonary bypass (CPB). The classic total arch replacement procedure using a four-branched graft with stented elephant trunk implantation showed excellent postoperative results in patients with ATAAD and has become the standard treatment for ATAAD at our center [11].

In this study, we aim to introduce this new extra-anatomic revascularization and cannulation strategy in patients with ATAAD and assess imaging cerebral malperfusion (ICM) as well as the efficacy and postoperative outcomes of the technique.

2. Patients and methods

2.1. Ethical statement

This retrospective study complied with the Declaration of Helsinki (2000) and was approved by the Institutional Review Board of the Xijing Hospital affiliated with the Fourth Military Medical University (approval number: KY20222224-C-1). Informed consent was obtained from each patient or their legal representative, and additional informed consent was obtained for publication of the images of human participants.

2.2. Study population and definitions

Between January 2021 and June 2022, 485 patients underwent emergency open surgery for ATAAD at The First Affiliated Hospital of the Fourth Military Medical University. ATAAD diagnosis was confirmed in all patients by combined computed tomography angiography (CTA) of the aorta and craniocervical artery. ICM was defined as unilateral or bilateral carotid arterial severe stenosis (90–99%) or occlusion (>99%) detected by combined CTA (Fig. 1). Based on the presence of preoperative neurological symptoms,

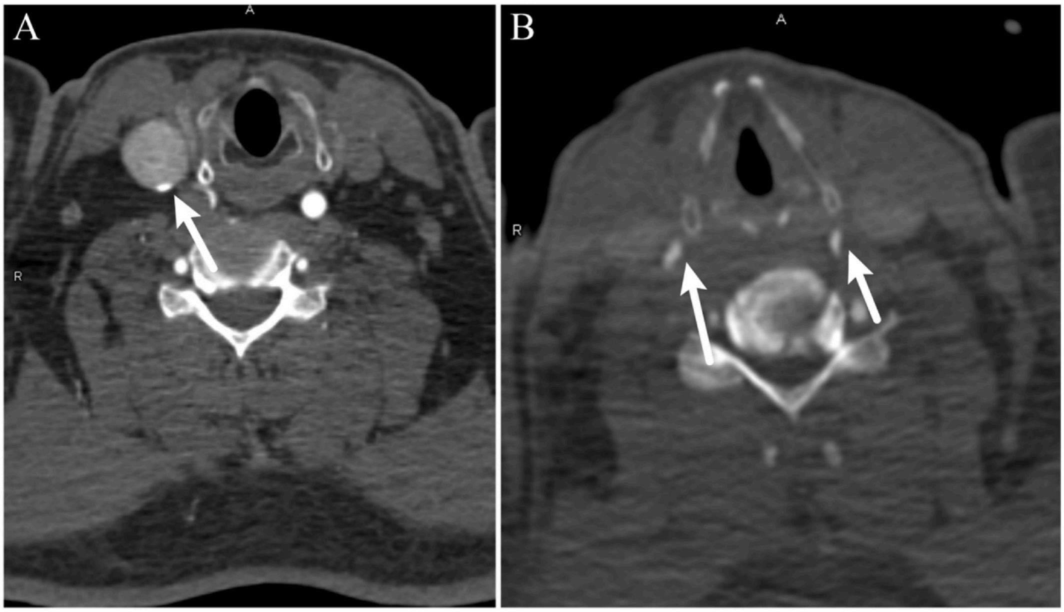

Fig. 1. Imaging findings of a patient with true lumen stenosis caused by dissection involving the right common carotid artery (A) and true lumen stenosis caused by dissection involving bilateral common carotid arterial stenosis or occlusion (B).

patients were divided into clinical symptom (clinical ICM) or no clinical symptom (subclinical ICM) groups [12]. Patients with preoperative coma underwent surgery regardless of the duration and degree of the coma. Finally, 28 patients who met the clinical or subclinical ICM criteria were included in this study. The preoperative clinical data, imaging results, surgical records, and postoperative clinical results of all patients were retrospectively analyzed. Postoperative permanent neurological deficit (PND) included any neurological symptom that did not completely cease before discharge, such as new-onset coma and sensory or motor disorders. Postoperative transient neurological dysfunction (TND) included disturbances of consciousness (including coma, drowsiness, and paralysis) and sensory or motor disorders, but with complete discontinuation of all neurological symptoms before discharge [13]. Stroke was defined as postsurgical thrombosis, embolism, or cerebral hemorrhage events causing persistent residual motor or cognitive dysfunction that did not subside within 24 h. Postoperative new renal insufficiency was defined as the absence of preoperative renal failure accompanied by the development of renal failure or the need for dialysis during postoperative hospitalization.

2.3. Preparation before cannulation

We carefully evaluated the combined CTA findings of the aorta and craniocervical artery and those from the top of the skull to the pubic symphysis, using second-generation dual-source CT equipment (SOMATOM Definition Flash, Siemens Healthineers, Forchheim, Germany).

All procedures were performed during a median sternotomy. The innominate artery (IA) and the left common carotid artery (LCCA) were extensively dissected, and the severely narrowed or occluded blood vessels observed by imaging were fully exposed above the normal site. In addition, when one of the right subclavian arteries (RSCA) or right common carotid artery (RCCA) had severely narrowed or occluded, the other was fully dissected to aid reconstruction.

2.4. Cannulation strategy and surgical procedure

After cannulation at the femoral artery, the following steps were followed: the extracorporeal circulation arterial pump tubes were prepared, and their branches were separated through the "Y" joint; all visible thrombus in the false lumen was removed, and prosthetic graft anastomosis was performed above the occlusion level. The ends of the prosthetic grafts were then anastomosed to the extracorporeal circulation pump tube.

(1) If only the IA was severely narrowed or occluded, an 8–10 mm prosthetic graft was anastomosed above the occlusion level (Fig. 2A).
(2) If the RCCA and/or the RSCA were severely narrowed or occluded, the 8–10 mm IA prosthetic graft was end-to-end anastomosed to the 10-mm RCCA prosthetic graft, and the 8-mm RSCA prosthetic graft was end-to-side anastomosed to form a "Y" prosthetic graft to reconstruct the anatomical structure of the brachiocephalic trunk (Fig. 2B).
(3) If severe stenosis/occlusion of the true lumen of the LCCA alone existed, the LCCA was reconstructed using an 8–10 mm prosthetic graft. The IA end-side was anastomosed to the extracorporeal circulation arterial pump branch (Fig. 2C). If the brachiocephalic trunk was involved at the same time, step (1)/(2) (Fig. 2D) or step (2) (Fig. 2E) was repeated.

Venous intubation of the right atrium was performed to establish CPB, followed by total arch replacement combined with stented elephant trunk implantation [11]. The ascending aorta was cross-clamped. Aortic root procedures were performed during cooling. When the nasopharyngeal temperature decreased to 24–26 °C, the LSA was cannulated (Fig. 2A and B), the ascending aorta was opened, the left subclavian artery (LSA) was blocked, and deep hypothermic circulatory arrest (DHCA) was initiated. Following cardiac arrest, the aortic arch was incised, and the frozen elephant trunk stent was inserted and anastomosed with the distal main trunk of the

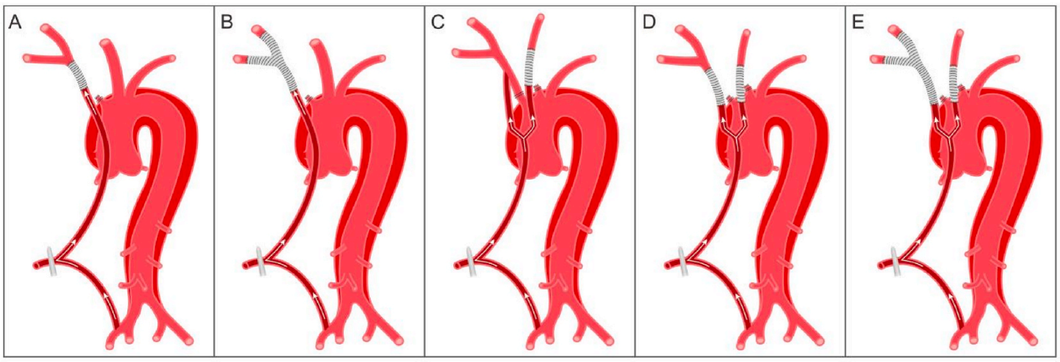

Fig. 2. Revascularization and cannulation sites in IA severe stenosis or occlusion (A); revascularization and cannulation sites for severe stenosis or occlusion of RCCA or/and RSCA (B); revascularization and cannulation sites in LCCA severe stenosis or occlusion (C); extra-anatomic revascularization and cannulation sites for LCCA combined with severe stenosis or occlusion of brachiocephalic trunk vessels (D) or (E). RSCA, right subclavian arteries; LCCA, left common carotid artery; IA, innominate artery.

four-branch prosthetic graft. During this period, cerebral perfusion remained unchanged despite the cessation of lower body perfusion. After the anastomosis was completed, the descending aortic perfusion was restored by intubation of the four-branch prosthetic graft. After the end-to-end anastomosis to the LSA (LSA was reconstructed at this time if the degree of stenosis was ≥90%), CPB was performed gradually to achieve normal perfusion flow, and rewarming was initiated, as shown in Fig. 3. This was followed by anastomosis of the LCCA and IA prosthetic graft to the four-branch prosthetic graft Video 1.

Supplementary video related to this article can be found at https://doi.org/10.1016/j.heliyon.2023.e18251

Myocardial protection was achieved by antegrade cold blood del Nido cardioplegia. Cerebral oxygenation in the frontal cortex and the identification of potential cerebral hypoperfusion were monitored using near-infrared spectroscopy. The cerebral perfusion pressure was maintained at 60–70 mmHg, and the cerebral perfusion flow was approximately 5–10 mL/(kg·min).

2.5. Statistical analysis

Standard definitions were used for patient variables and outcomes. Categorical data are reported as frequencies (percentages) and continuous variables as medians (interquartile ranges [IQRs]) or means ± standard deviations. All statistical analyses were performed using SPSS, version 24 (IBM Corp., Armonk, NY, USA).

3. Results

Table 1 shows the preoperative data of the patients; their median age was 51 (IQR: 46–58) years, and 20 (71.3%) patients were male. All 28 patients underwent combined CTA of the aorta and craniocervical artery and were diagnosed with ATAAD with unilateral or bilateral severe stenosis (≥90%) or SABV occlusion. Preoperative imaging of 15 patients (60%) indicated the presence of multiple persistent cerebral infarction lesions. Eight patients (12.5%) had preoperative neurological deficits (ND), including four (14.3%) with preoperative TND and four (14.3%) with preoperative PND (coma); there were no patients with hemiplegia. The average time from symptom onset to admission was 9 (IQR: 7–13) h, and the average time from admission to surgery was 8.5 (IQR: 3.5–12) h. The other surgical sites and details are presented in Table 2.

3.1. Early outcomes

The median follow-up duration was 16.5 (IQR: 11.5–20.5) months, with a 100% follow-up completion rate. To date, 92.9% (n = 26) of the patients have survived. However, the two patients who died during the perioperative period had persistent preoperative

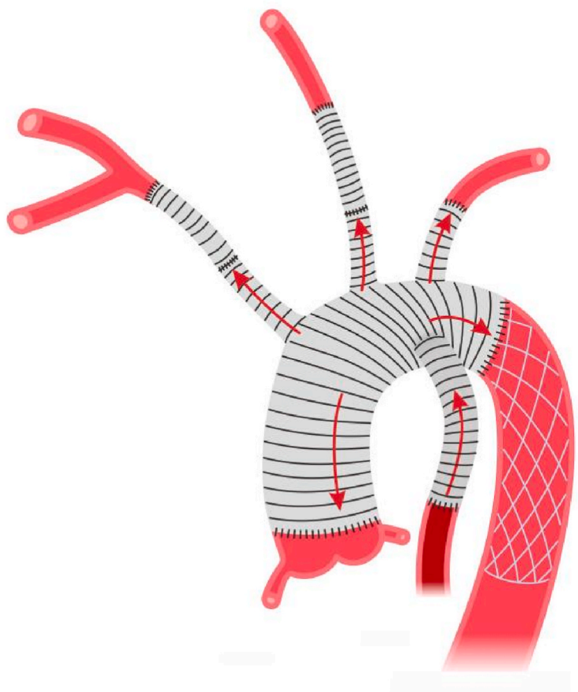

Fig. 3. Total arch replacement combined with stented elephant trunk implantation. Based on the strategy in Fig. 2D, the LSA, LCCA prosthetic graft, and IA prosthetic graft are anastomosed to a four-branch prosthetic graft. LSA, left subclavian artery; LCCA, left common carotid artery; IA, innominate artery.

Table 1
Preoperative data (n = 28).

Variables	Value (%)
Age (years)	51 (46–58)
Male sex	22 (78.6)
Body mass index (kg/m^2)	25.6 ± 3.7
Hypertension	20 (71.4)
Diabetes mellitus	0
Chronic obstructive pulmonary disease	0
Previous coronary artery disease	3 (12.7)
Previous cardiac surgery	0
Renal insufficiency	9 (32.1)
Permanent dialysis	0
Connective tissue disease	0
Left ventricular ejection fraction	54.3 ± 4.2
Aortic valve insufficiency (≥moderate)	12 (42.8)
Shock	4 (14.3)
Organ malperfusion	6 (21.4)
Central nervous system dysfunction	8 (35.7)
Transient	4 (14.3)
Persistent	4 (14.3)
Coma (GCS ≥8)	4 (14.3)
Hemiplegia	0
Organ malperfusion	
Coronary	6 (21.4)
Visceral	2 (7.1)
Extremities	3 (12.7)
Creatinine (μmoI/L)	128.2 ± 70.1
Troponin I (ng/mL)	8.3 ± 12
Distal extent of aortic dissection	
Aortic arch	1 (3.6)
Descending aorta	0
Abdominal aorta	7 (25)
Iliac artery	20 (71.4)
Entry site	
Aortic root–sinotubular junction	11 (39.3)
Ascending aorta	10 (35.7)
Aortic arch	4 (14.3)
Unknown	3 (10.70)

Results are represented as n (%), means ± SDs, or medians with first and third quartiles.
GCS, Glasgow coma scale; SD, standard deviation.

coma, and CT suggested multiple preoperative cerebral infarctions and permanent loss of consciousness. Both patients showed persistent deep coma after surgery. One died of multiple organ failure caused by infection, and the other died of multiple organ ischemia (Table 2). No additional secondary surgeries or deaths occurred during the follow-up period.

No postoperative bleeding leading to sternotomy was observed, and four patients (14.3%) required a percutaneous tracheotomy for assisted breathing. One patient (3.6%) developed acute renal failure and required temporary dialysis. Three patients (10.7%) showed signs of postoperative new TND (Table 2), including delirium (n = 1), transient unconsciousness (n = 1), and transient coma (n = 1). However, no new PND disorders were observed during the follow-up period. The median length of overall hospitalization was 13.5 (IQR: 11.0–20.0) days, and the average length of the intensive care unit stay was 4.5 (IQR: 3.0–6.0) days. Additionally, surgical procedures and comprehensive intraoperative data were meticulously documented and are presented in Table 2.

4. Discussion

The incidence of postoperative PND in patients with ATAAD is reportedly 13–15.3%, resulting in poor short-term postoperative outcomes that affect the patients' long-term quality of life [14,15]. Postoperative PND is closely related to preoperative cerebral perfusion [16,17]. From an imaging perspective, SABV involvement is a potential influencing factor for persistent cerebral hypoperfusion [18–21].

We have previously attempted to improve the neurological prognosis by changing the cannulation site; however, the incidence of new ND in patients with true lumen stenosis was not significantly changed. Therefore, new ND in patients with ATAAD may be unaffected by the choice of the arterial cannulation site [22]. Continuing axillary artery perfusion while ignoring aortic arch branch vascular abnormalities may result in CM and other catastrophic results [23,24]. Thus, to improve the existing treatment strategies, the key role of SABV in cerebral perfusion cannot be ignored. However, restoring cerebral blood flow in patients with severe stenosis or SABV occlusion by conventional ATAAD repair caused by true lumen collapse and false lumen thrombosis may be difficult [8]. We believe that under the existing conditions, it is important to perform complete extra-anatomic revascularization and improve the

Table 2
Intra- and postoperative data (n = 28).

Variables	Value (%)
Branch vascular reconstruction site	
Only innominate artery	16 (57.1)
Innominate artery + right common carotid artery and/or right subclavian artery	9 (32.1)
Only left common carotid artery	1 (3.5)
Bilateral	2 (7.1)
Operative procedures	
Aortic root repair	17 (60.7)
Aortic root replacement	11 (39.3)
Hemiarch repair	0 (0)
Total arch repair	28 (100)
CABG	7 (25)
Foramen ovale repair	2 (8)
Perfusion data	
Operative time (min)	436.4 ± 77.6
CPB time (min)	220.3 ± 43.6
Cross-clamp time (min)	110.2 ± 19.8
Circulatory arrest (min)	35.7 ± 7
Lowest esophageal temperature (°C)	25.1 ± 0.42
Early outcomes	
30-day mortality	2 (7.1)
Early death (1 year)	0 (0)
Postoperative new neurological deficits	
Temporary new neurological deficits	3 (12.7)
Permanent new neurological deficits	0 (9)
Duration of ventilation ≥48 h	15 (52.6)
Hospital stay (days)	13.5 (11–20)
Intensive care unit stay (days)	4.5 (3–6)
Renal failure requiring hemofiltration	1 (3.6)
Percutaneous tracheostomy	4 (14.3)
Postoperative ECMO therapy	0 (0)
Re-exploration for bleeding	0

Results are represented as n (%), mean ± SDs, or median with first and third quartiles.
CABG, coronary artery bypass grafting; CPB, cardiopulmonary bypass; ECMO, extracorporeal membrane oxygenation.

previous cannulation methods to ensure a complete solution to this problem and minimize the incidence of postoperative neurological complications.

First, we must effectively identify high-risk patients with postsurgical ND. For patients with severe stenosis or lumen occlusion caused by a dissection involving the cervical branch vessels, cervical vascular reconstruction may be necessary if neurological ischemia-related presurgical symptoms are present. Even without neurological-related presurgical symptoms, screening potential high-risk patients is necessary to enable more thorough treatment measures. Our previous studies have confirmed the feasibility and advantages of combined CTA of the aorta and craniocervical artery [25]. All patients with ATAAD, especially those with CM, underwent careful monitoring using combined CTA of the aorta and craniocervical artery to determine the true lumen stenosis of the SABV, and corresponding surgical strategies for different stenosis degrees and sites were employed.

Although the collateral circulation of the Circle of Willis (CoW) can alleviate cerebral ischemia in patients with ICM, previous studies have revealed that the total percentage of patients with incomplete CoW function is approximately 47.09–73%. The CoW integrity continues to decrease with age [26,27]. A disadvantage of unilateral perfusion is that only one of the three branches supplies the entire cerebral circulation, which requires excessive pressure to achieve normal blood flow [28,29]. The primary advantage of the branch-first technique is that it fully utilizes the three branches and CoW to ensure continuous antegrade cerebral perfusion and significantly reduces the ischemic time experienced by the heart and distal organs [9,22]. Several studies on ATAAD examined techniques for further improving vascular perfusion of the neck to relieve severe SABV stenosis or occlusion. Furukawa et al. [10] demonstrated that patients with neurological symptoms or CM should undergo carotid artery reperfusion promptly to prevent or reverse CM. Our methods differ from those of Gomibuchi et al. [12] with respect to early direct reperfusion and direct reconstruction after CPB. Luehr et al. [8] used a prosthetic graft to perform extra-anatomical distal aorto-carotid bypass prior to CPB.

Since January 2021, we used extra-anatomic revascularization and a new cannulation strategy in patients with SABV severe stenosis or occlusion. The severely affected SABV is revascularized before extracorporeal circulation. Compared with the previous procedure, an advantage of the new technique is that the underestimated complications caused by true lumen collapse and false lumen thrombosis of the aortic arch branch can be completely eliminated. Additionally, bilateral continuous and sufficient perfusion of the blood flow in the brain in DHCA is ensured. In addition, the postoperative hemodynamics are closer to the normal physiological state, thus avoiding the high incidence of complications of the previous axillary artery cannulation strategy in such patients.

Yang et al. [29] demonstrated that patients with ATAAD can be treated in stages, i.e., the interventional recovery of organ perfusion can be performed first, followed by open surgery after improved organ perfusion. Kawahito et al. [30] also revealed that emergency reperfusion of affected organs could be considered to further improve the prognosis of patients with malperfusion and ATAAD, and that central repair can be performed subsequently. However, because some patients have other branch vascular lesions and long-term ischemia of important organs leading to serious organ dysfunction, the comprehensive assessment does not include the “aorta priority” condition.

We comprehensively evaluated patients with malperfusion of other internal organs (from dysfunctions in the coronary, superior mesenteric, renal, and lower extremity arteries) according to the number of ischemic organs, ischemic time, and degree of ischemia. We observed three cases of lower limb malperfusion using the branch intervention priority technique; renal artery perfusion was poor in one case, and two cases had poor superior mesenteric artery perfusion. However, long-term multicenter results are needed to prove the effectiveness of this method.

In our study, we observed a 30-day mortality rate of 7.1% and no new PND, additional deaths, or other related complications during the follow-up period. Thus, encouraging early-stage clinical results were achieved, suggesting that this technique may be safe and feasible. Thus, anatomical reconstruction and early perfusion before CPB may reduce the risk of new ND development after surgery.

Estrera et al. [31] reported that ATAAD complicated by stroke requires immediate surgical repair, with 10 h as a critical time point. Tsukube et al. [32] suggested that surgery immediately after coma symptoms (within 5 h) is the preferred method of treating such patients. Xue et al. [33] reported that immediate surgery is recommended for patients with transient coma. Overall, coma duration greater than 12.75 h is associated with a poor prognosis. In our study, two patients who died after the operation had preoperative persistent coma and multiple cerebral infarctions; their respective times from symptom onset to surgery were 21 and 28 h. The other two patients with preoperative coma showed significant improvement after surgery, although the time from the onset of symptoms to surgery was similar. Therefore, we suggest that even in patients with preoperative coma, emergency surgery should remain the gold standard.

4.1. Limitations

This study had several limitations. This was a retrospective, single-center, observational study with a small sample size. We did not conduct a control study to perform multivariable analysis to identify independent predictors of PND. We hope that this new extra-anatomic revascularization and cannulation strategy can provide satisfactory clinical outcomes and improve the quality of life of patients with ATAAD and severe stenosis or SABV occlusion.

5. Conclusion

The new extra-anatomic revascularization and cannulation strategy can effectively address the challenges posed by preoperative CM caused by true lumen severe stenosis or ATAAD involving SABV occlusion. Moreover, the combined CTA of the aorta and cranial carotid artery provided enhanced diagnostic information. This strategy is safe and feasible and may reduce the incidence of postoperative neurological complications and mortality in these high-risk patients.

Author contribution statement

Jingwei Sun: Conceptualization, Data curation, Resources, Writing – original draft, and Writing – review & editing. Chao Xue, Jinglong Zhang, Chen Yang: Conceptualization, Writing – original draft, and Writing – review & editing. Kai Ren, Hanzhao Zhu, Bin Zhang, Xiayun Li: Data curation, Writing–original draft, and Writing–review & editing. Hongliang Zhao, Zhenxiao Jin, Jincheng Liu, Weixun Duan: Conceptualization, Supervision, and Writing – review & editing. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

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Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

ATAAD	Acute type A aortic dissection
CM	Cerebral malperfusion
PND	Permanent neurological deficit
SABV	Supra-aortic branch vessels
CTA	Computed tomography angiography
ICM	Imaging cerebral malperfusion
TND	Transient neurological dysfunction
IA	Innominate artery
RCCA	Right common carotid artery
RSCA	Right subclavian artery
LCCA	Left common carotid artery
CPB	Cardiopulmonary bypass
IQR	Interquartile range
ND	Neurological deficits
CoW	Circle of Willis

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