Strategies for prevention of spinal cord ischemia in the management of thoracic and thoracoabdominal aneurysms

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How to cite this article: Gomes VC, Farber MA, Parodi FE. Strategies for prevention of spinal cord ischemia in the management of thoracic and thoracoabdominal aneurysms. Vessel Plus 2023;7:24. https://dx.doi.org/10.20517/2574-1209.2023.60

Received: 10 Jun 2023 First Decision: 11 Sep 2023 Revised: 18 Sep 2023 Accepted: 25 Oct 2023 Published: 30 Oct 2023

Abstract

Spinal cord ischemia (SCI) is undoubtedly the most devastating adverse event that occurs after either a thoracic aortic aneurysm (TAA) or thoracoabdominal aortic aneurysm (TAAA) repair. While open surgery techniques and minimally invasive endovascular options are now available for treating complex anatomy aortic aneurysms, spinal cord ischemia still occurs to a greater extent than desirable. Multiple risk factors have been associated with this adverse event, such as advanced age, perioperative hypotension, extent of the repair, and ligation of multiple intercostal and lumbar arteries during the surgical repair. The present literature review aims to analyze the contributing risk factors for SCI in the context of aortic surgery, explore the most relevant strategies for preventing postoperative SCI, and discuss the current management strategy when this complication occurs.

Keywords: Spinal cord ischemia, thoracic aneurysm, thoracoabdominal aneurysm, TEVAR, F/BEVAR, hypogastric artery patency, subclavian artery patency, lumbar drain, staged repair

INTRODUCTION

The incidence of thoracic aortic aneurysms is estimated at 6 cases per 100,000 per year\(^1\), 40% of them involving the descending thoracic aorta (TAA) and 10% the thoracoabdominal aorta (TAAA)\(^2\).
Bickerstaff et al. have estimated the incidence of TAAA at 0.37 cases per 100,000 per year\[^{[4]}\]. New cases of both TAA and TAAA are increasing\[^{[4]}\] due to the longevity of the population and the early detection of these pathologies, facilitated by the improvement in diagnostic tools. Spinal cord ischemia (SCI) is by far the most severe and devastating adverse event that can occur following the surgical repair of TAA or TAAA, as it significantly impacts the postoperative morbidity and mortality of these patients. Coselli et al., in a study considering 1,114 type II TAAA cases, observed an incidence of postoperative SCI of 13.6%\[^{[5]}\]. Patients with permanent paraplegia had poorer midterm survival (51.7% ± 4.2% at 3 years) compared to those without spinal ischemia after the repair (75.8% ± 1.4%). Spanos et al., in a study including 243 patients with complex anatomy aortic aneurysms undergoing endovascular repair, reported a 30-day mortality rate of 6.1% among the cases with postoperative paraparesis, and up to 40% in patients who developed postoperative paraplegia\[^{[6]}\]. The present literature review aims to analyze the critical risk factors for SCI in the context of aortic surgery, to explore the most relevant strategies for the prevention of this adverse event during the treatment of TAA and TAAA, and to discuss the management strategy recommended for the patients who develop SCI associated with their repair.

**INCIDENCE OF SCI AFTER TAA AND TAAA REPAIR**

The open surgery techniques have substantially evolved since the successful repairs of TAA and TAAA, as reported by DeBakey, CooleyField\[^{[24]}\], and EtheredgeField\[^{[9]}\]. However, the risk of spinal cord ischemia remains significant [Table 1].

Initially indicated only for patients with numerous comorbidities who were not suitable candidates for open procedures, endovascular repair has become the approach of choice in the treatment of complex anatomy aneurysms at centers of excellence\[^{[7]}\], and is currently recommended by the Clinical Practice Guidelines published by the European Society for Vascular Surgery in 2019\[^{[14]}\]. Prior published studies indicate that the risk of SCI associated with aortic surgery ranges from 3%-14% [Table 1].

**SPINAL CORD BLOOD SUPPLY REVIEW**

The spinal cord arterial supply is composed of a complex network connecting multiple vessels responsible for its blood supply, such as the vertebral arteries (VA), the intercostal and lumbar arteries, and the hypogastric arteries. Biglioli et al., in an experimental study with cadavers, described the collateral pathways that contribute to spinal cord perfusion\[^{[19]}\]. Three arteries run longitudinally along the length of the spinal cord, including one anterior spinal artery (ASA) and two posterior spinal arteries (PSA). The anterior spinal artery originates by the level of the foramen magnum and is responsible for the irrigation of the two anterior thirds of the spinal cord. The two posterior spinal arteries (PSA) originate either from the vertebral arteries or posterior inferior cerebellar arteries\[^{[20]}\]. The spinal arteries are primarily fed by the subclavian and vertebral arteries in the cervical segment of the spine. Segmental arteries in the thoracic and lumbar regions provide additional blood supply to the spinal arteries\[^{[21]}\], and the Adamkiewicz artery, which is the largest anterior segmental vessel, branching off the left side of the distal thoracic or proximal abdominal aorta between T8 and L2 in 75% of people. The primary blood flow supply for the distal spinal cord and cauda equina comes from the hypogastric arteries and their branches\[^{[22]}\]. The pial network, which covers the entirety of the spinal cord, allows communication between the anterior and posterior spinal arteries\[^{[23]}\].

More recently, Griepp et al. introduced the collateral network concept, which encompasses the existence of an extensive network of arteries that supply blood to the cord and paraspinal muscles, presenting the unique capability of adapting if faced with interruption\[^{[24]}\]. It has been demonstrated that after interruption of segmental arteries\[^{[24]}\], an early vasodilation of the ASA is observed, followed by a definitive increment in the size and density of small arterioles associated with modifications in the direction of the blood flow. This
Table 1. Incidence of SCI reported in the current literature, considering different extensions of aortic repair performed either open or endovascularly

<table>
<thead>
<tr>
<th>Author</th>
<th>Type of procedure</th>
<th>Number of patients included in the study</th>
<th>Reported incidence of SCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open surgery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nishi et al. [10]</td>
<td>Open total arch replacement</td>
<td>61</td>
<td>6.6%</td>
</tr>
<tr>
<td>Chiesa et al. [11]</td>
<td>Open repair of descending thoracic aneurysms</td>
<td>194</td>
<td>4.6%</td>
</tr>
<tr>
<td>Coselli et al. [12]</td>
<td>TAAA open repair</td>
<td>3,309</td>
<td>4%-13.9%</td>
</tr>
<tr>
<td>Liang et al. [13]</td>
<td>Endovascular arch repair</td>
<td>40</td>
<td>2.5%</td>
</tr>
<tr>
<td>Endovascular procedures</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liang et al.</td>
<td>Thoracic endovascular aneurysm repair (TEVAR)</td>
<td>160</td>
<td>5.6%</td>
</tr>
<tr>
<td>Motta et al. [15]</td>
<td>Fenestrated/branched repair (F/BEVAR) of complex anatomy aortic aneurysms</td>
<td>150</td>
<td>2.6%</td>
</tr>
<tr>
<td>Aucoin et al. [16]</td>
<td>Fenestrated/branched repair (F/BEVAR) of complex anatomy aortic aneurysms</td>
<td>1,681</td>
<td>7.1%</td>
</tr>
</tbody>
</table>

later enables blood flow in a cranial or caudal direction from the hypogastric or subclavian arteries as needed. Finally, the concept of vascular territories organizes the spinal cord perfusion in four arterial supply territories: cervical arteries (fed mainly by the subclavian and vertebral arteries), intercostal arteries, lumbar arteries, and hypogastric arteries [25]. These territories can communicate through the aforementioned massive collateral network in the occasion of segmental artery occlusion.

PATHOPHYSIOLOGY & CLINICAL/SURGICAL RISK FACTORS FOR SCI IN THE CONTEXT OF AORTIC SURGERY

In the past, interruption of the artery of Adamkiewicz was considered the primary cause of SCI after aortic surgery. This theory has become less popular with the emergence of the collateral network concept. Other causes implicated in the multifactorial genesis of SCI have been extensively analyzed in literature [Table 2]. Regardless of the type of aortic repair performed, the collateral network initiates the compensatory mechanisms after the interruption of the feeding arteries to the spinal cord occurs, so the collateral supply can adapt to the loss of feeding segmental vessels. When this mechanism is insufficient, SCI can occur.

CLINICAL MANIFESTATIONS OF SCI AFTER TAA AND TAAA REPAIR

As for the clinical presentation, SCI symptoms can range from mild muscle weakness to paraplegia [40]. The symptoms may develop immediately as observed by Spanos et al. or in a delayed fashion as reported by Alizadegan et al. and components of the autonomic nervous system may become involved [6, 41, 42].

PREOPERATIVE PLANNING

Subclavian artery patency relevance

As previously mentioned, the subclavian arteries significantly contribute to spinal cord perfusion. In most cases, the vertebral arteries branch off the posterosuperior aspect of the first segment of the subclavian arteries, bilaterally [43], and therefore the subclavian artery patency is a crucial piece of information during the planning of the surgical treatment of TAA and TAAA. Moreover, in aortic aneurysms affecting zones 2 and 3 [44] of the aortic arch [45], the repair would compromise the origin of the left subclavian artery (LSA). The current medical literature is inconclusive concerning LSA revascularization prior to a TEVAR. Rehman et al., in a systematic review of the management of the LSA during TEVAR for the treatment of thoracic aortic dissections, described a relative reduction of 84% in the prevalence of SCI with statistical significance in patients that underwent TEVAR that did not cover the LSA compared to patients that had
Hypogastric arteries during aortic surgery in those cases with aneurysmal degeneration affecting the iliac branched grafts have been used as a safe and successful strategy of antegrade blood flow preservation to the overall risk of SCI.

The importance of preserving hypogastric perfusion cannot be stressed enough. For over a decade now, iliac artery occlusion of spinal cord feeding vessels with air produces hypertension proximal to the clamp, increased central venous pressure, and distal ischemia. Hypogastric arteries during the endovascular procedure, highlighting the relevance of the internal iliac arteries patency in the context of SCI risk factors, especially in the context of TEVAR with LSA coverage.

Conversely, other studies report that LSA coverage is well tolerated during TEVAR procedures, even without revascularization. In a retrospective multicenter study including 1,189 patients submitted to TEVAR for the treatment of TAA, Maldonado et al. concluded that LSA revascularization was not protective against SCI, and reported an increased risk of cerebrovascular accidents in female patients submitted to LSA revascularization. Riesenman et al., in a retrospective analysis including 112 TEVAR patients, did not report SCI events among the 24 cases with endograft implanted in zone 2, even though none of them underwent LSA revascularization. Coverage of the LSA is contraindicated without prior revascularization in situations such as the presence of a dominant left vertebral artery. It is also critical to evaluate the contribution from the circle of Willis’ anatomy during the surgical planning of procedures that involve the subclavian arteries. Table 3 summarizes the SVS recommendations for LSA revascularization in the context of TEVAR with LSA coverage.

Hypogastric artery patency relevance

The patency of the hypogastric arteries plays a vital role in the context of SCI risk factors, especially in patients submitted to extensive aortic repair, as these arteries significantly contribute to the perfusion of the distal spinal cord. Picone et al., described seven patients who developed spinal cord ischemia after abdominal aortic surgeries, five of whom had unilateral or bilateral hypogastric occlusion during the procedures. Eagleton et al., in a study including TEVAR (n = 201), FEVAR (n = 227), BEVAR (n = 472), and EVAR (351), reported an incidence of SCI of 2.8% (n = 36). Of these affected patients, fourteen had preoperative unilateral or bilateral hypogastric occlusion, and seven had coverage of at least one hypogastric artery during the endovascular procedure, highlighting the relevance of the internal iliac arteries patency in the overall risk of SCI.

The importance of preserving hypogastric perfusion cannot be stressed enough. For over a decade now, iliac branched grafts have been used as a safe and successful strategy of antegrade blood flow preservation to the hypogastric arteries during aortic surgery in those cases with aneurysmal degeneration affecting the iliac
Table 3. SVS Practice Guidelines (2010)\textsuperscript{[52]}: recommendations of LSA revascularization for TEVAR patients with LSA coverage (GRADE 1, level C)

<table>
<thead>
<tr>
<th>Recommendation</th>
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<tbody>
<tr>
<td>Left vertebral dominance\textsuperscript{[51]} (absent, atretic, or occluded right vertebral artery, absence of communication between the left VA and the circle of Willis with termination of the left VA artery into the posterior inferior cerebellar artery)</td>
</tr>
<tr>
<td>Compromised collateral spinal cord perfusion</td>
</tr>
<tr>
<td>Prior ligation of lumbar and middle sacral arteries during infrarenal aortic surgery</td>
</tr>
<tr>
<td>Planned coverage of the descending thoracic aorta longer than 200 mm</td>
</tr>
<tr>
<td>Hypogastric artery occlusion</td>
</tr>
<tr>
<td>Prior left internal mammary-to-coronary artery bypass</td>
</tr>
</tbody>
</table>

bifurcation\textsuperscript{[66]}. Simonte et al. reported no occurrence of spinal cord ischemia in a study including 157 consecutive cases in which iliac branch devices were utilized\textsuperscript{[67]}. Schneider et al., in a study on long-term outcomes of iliac branch endografts, reported primary patency of 95.1\% of the internal iliac artery limb and freedom of secondary intervention of 90.5\% at the 5-year landmark, demonstrating that the iliac branch grafts are a valuable tool in the preservation of the hypogastric artery flow\textsuperscript{[54]}.

The importance of the repair extension and intercostal/lumbar arteries coverage

Covering an extensive segment of the thoracoabdominal aorta could compromise intercostal and lumbar contribution to the spinal cord, and increase the risk of SCI. Feezor et al., in a study including 326 TEVAR patients, observed an incidence of 10\% of SCI and concluded that patients who developed permanent deficits had a higher length of aortic coverage\textsuperscript{[59]}. Flores et al., in a study including 25 patients undergoing TAA repair with the stented elephant trunk technique, reported that the combination of a distal landing zone below T7 and a history of prior AAA repair was the strongest predictor for the occurrence of SCI, with an odds ratio of 5.46 ($P = 0.0047$)\textsuperscript{[60]}. Czerny et al. observed that simultaneous obliteration of at least two independent vascular territories associated with intraoperative hypotension is a significant risk factor for SCI\textsuperscript{[61]}. In a study including 1096 TAA and TAAA cases submitted to open repair, Afifi et al. reported that ligation of intercostal arteries between the T8 and T12 significantly increased the risk of paraplegia\textsuperscript{[62]}. The authors report that reimplantation of intercostal arteries only minimally increases the procedure duration. Therefore, this would potentially reduce the risk of SCI without significantly impacting the overall procedure risk. Lastly, it has been reported that total aortic coverage longer than 205 mm is associated with the development of SCI\textsuperscript{[63,64]}.

Staged strategy

Especially for complex TAA and TAAA that would require an extended coverage of the thoracic and abdominal aorta, the staged strategy is an essential tool in preventing SCI, either for open or endovascular repairs. The rationale behind this approach consists of dividing the repair into two shorter and less morbid interventions, so the collateral network has enough time to compensate for the reduction of blood flow, potentially diminishing the risk of postoperative SCI. Etz et al., in a study including 90 TAAA patients submitted to open procedures, observed a significantly lower rate of paraparesis and paraplegia after staged TAAA repair compared to non-staged patients\textsuperscript{[65]}. Interestingly, this result was observed despite a significantly higher number of intercostal and lumbar arteries being sacrificed in the staged group. In a study including 87 TAAA patients submitted to endovascular repair, O’Callaghan et al. observed a significantly lower incidence of SCI in patients undergoing staged repair compared to patients who underwent non-staged repair, even though the length of aortic coverage was significantly greater in the staged group\textsuperscript{[66]}. Moreover, all the SCI symptoms in the staged group were temporary. A recent publication by Dias-Neto et al., including 1,947 patients from the International Aortic Research Consortium, demonstrated that the staged strategy significantly reduced the risk of permanent paraplegia after fenestrated/branched repair of extension I-III TAAA\textsuperscript{[67]}. This body of evidence highlights the potential for
SCI risk reduction of the staged strategy, either for open or endovascular repair of TAAA.

Minimally invasive segmental artery coil embolization

Minimally invasive segmental artery coil embolization (MISACE) is a technique aimed to provide a preconditioning to ischemia prior to the TAA or TAAA repair. The rationale behind this strategy is to improve spinal cord vascularization through neo-angiogenesis before the index procedure, either open or endovascular. Geisbush et al., demonstrated in a swine model that the coiling of 2-4 segmental arteries significantly prevented paraplegia after extensive thoracoabdominal aneurysm repair[68]. Etz et al. described the first-in-man successful experience with this technique performed in two patients: one planned for an open repair of a type III TAAA, and the second planned for an endovascular repair of a type II TAAA[69]. Both patients developed no neurologic injuries either after MISACE or the TAAA repair. Branzan et al., in a study including 57 TAAA cases reported the embolization of 77.7% of the segmental arteries and no occurrence of SCI using the MICACE technique[70]. According to a study published by Addas et al., the imaging planning prior to the MISACE technique consists of observing anatomical landmarks close to the site of segmental arteries’ origin to assist in selecting target arteries during the procedure[71]. Preoperative images also guided coil sizing, fluoroscopy positioning and angulation. The authors utilized the transfemoral approach in all the 17 patients included in their study. Once the target vessel was selected, the coils were deployed in the proximal section of the chosen segmental artery, proximal to its branching point. The mean time window between the MISACE and the TAAA repair was 51.2 days (5-110 days).

Although the studies mentioned above provide encouraging results, numerous complications can occur in the context of the MISACE technique, such as the incomplete occlusion of the targeted segmental arteries usually associated with the use of antiplatelet therapy or anticoagulants, loss of coils in the aorta, and the most severe of all, SCI. In addition, anatomical challenges related to the segmental arteries, such as large vessel diameter and tortuosity, and the long duration of these procedures associated with high contrast volume administration should be considered before the application of the MISACE technique[71]. A clinical trial that started in Europe in November 2018, with a completion date estimated for March 2023, will assess the clinical safety and efficacy of the MISACE procedure[72].

PERIOPERATIVE STRATEGIES FOR SCI PREVENTION: LUMBAR DRAIN UTILIZATION, THE ROLE OF NEUROMONITORING AND INTRAOPERATIVE HEMODYNAMICS MANAGEMENT

Spinal drain utilization as a strategy for SCI prevention

The perfusion of the spinal cord relies on numerous factors including mean arterial pressure (MAP), cerebrospinal fluid pressure (CSFP), and central venous pressure (CVP). Spinal cord perfusion pressure (SCPP) is directly proportional to the MAP and inversely proportional to the CSFP and CVP, corresponding to the neuraxial outflow pressure[31]. Coselli et al., in a randomized controlled trial including 145 TAAA patients submitted to open repair, demonstrated an 80% relative risk reduction of postoperative deficits in the group with CSF drain placed preoperatively[73]. Suarez-Pierre et al., in a retrospective analysis of 4,287 patients included in the TEVAR module of the Vascular Quality Initiative (VQI), concluded that preoperative spinal drainage placement significantly reduced the risk of SCI[74].

However, Aucoin et al., in a study including eight of the Principal Investigators of the US Aortic Research Consortium (US-ARC)[75,76], discuss that the indications of prophylactic CSF drain placement are evolving due to potentially severe complications related to drain placement. These authors recommend the placement of a preoperative drain in Type I-III TAAA cases, in patients with prior history of aortic infrarenal repair, cases with "shaggy aorta", hypogastric artery abnormalities (unilateral occlusion or...
bilateral stenosis), or abnormalities in the vertebral arteries. Our current practice is changing to therapeutic drain only.

As for the complications related to spinal drain placement, Kärkkäinen et al., in a study including 187 patients submitted to 240 procedures (F/BEVAR or first-stage TEVAR) with the prophylactic placement of CSF drain, observed 6% of intracranial hypotension and 3% of spinal hematomas resulting in paraplegia or transient paraparesis in 2% [77]. A meta-analysis conducted by Rong et al. observed a polled event rate of 6.5% for overall CSF drainage-related events and 2.5% for CSF drainage-related severe complications such as intracranial hemorrhage, meningitis, epidural hematoma, and neurological deficits [78].

In light of the described complications, in some institutions, a therapeutic strategy is being considered the best option in F/BEVAR cases [75], using perioperative neuromonitoring to detect SCI before the onset of symptoms postoperatively. In some institutions, prophylactic spinal drains are placed only in high-risk situations, such as patients with preoperative bilateral hypogastric occlusion requiring extensive repair, or cases with prior neurological deficits. More recently, the US-ARC has advocated a therapeutic-drain-only approach to patients undergoing endovascular TAAA repair.

**Hemodynamic management for spinal cord protection during TAA And TAAA repair**

To promote appropriate perfusion and oxygen delivery to the spinal cord during TAA and TAAA repair, a cardiac index (CI) above 2.5 L/min/BSA is recommended [79]. Attention is needed to avoid attempts of CI increment based on excessive volume infusion or on the excessive use of vasoactive drugs. The former could provoke elevation of the central venous pressure, which is inversely proportionate to the spinal perfusion pressure. The latter could produce undesirable vasoconstriction in the spinal cord microcirculation [80].

As for blood pressure management, intraoperative hypotension is a well-known risk factor for SCI after TAA and TAAA repair [81]. Aucoin et al., in the aforementioned study on the SCI prevention practices adopted by the US-ARC, report that the authors recommend permissive hypertension starting before the index procedure [75]. It should be maintained in the first 2 to 4 postoperative weeks, which is especially relevant for patients that postoperatively presented reversible symptoms of SCI. To achieve this goal, angiotensin receptor blockers and angiotensin-converting enzyme inhibitors should be withheld preoperatively at least 48 h before surgery. As for the alfa- and beta-blockers, there was no consensus among the PIs about discontinuing or not these medications, and in most cases, the beta-blockers were continued throughout the perioperative period. The spinal cord perfusion pressure (SCPP) is directly proportionate to mean arterial pressure [82], hence the hazardous effect of hypotension over the SCPP. A goal of SCPP > 80 mmHg is recommended. To fulfill this goal, a MAP > 90 mmHg is desired, and in cases in which a lumbar drain has been placed preoperatively, the targeted CSF pressure should be kept at < 10 mmHg.

Optimizing hemoglobin levels perioperatively also plays a significant role in the SCI strategy. Behzadi et al., in a study including 174 TAA and suprarenal AAA patients submitted to either open or endovascular repair, observed that preoperative hemoglobin < 9 mg/dL was a risk factor for the occurrence of SCI [83]. Perioperative hemoglobin ≥ 10 mg/dL has been reported in the literature as part of protocols for SCI prevention in TAAA patients submitted to F/BEVAR [84].

Another valuable tool for spinal cord protection during aortic surgery is epidural cooling for regional spinal cord hypothermia. Tabayashi et al., in a study including 37 patients submitted to open thoracic or thoracoabdominal aorta replacement for TAAA or aortic dissection, concluded that epidural cooling is a safe method of effectively reducing postoperative SCI [85]. The authors utilized a catheter placed into the
epidural space to infuse precooled saline. The epidural cooling was initiated 30 min before aortic clamping, maintaining the temperature at 25 °C. Moreover, Bobadilla et al. suggest that mild intraoperative hypothermia, keeping body temperature between 32-35 °C, could improve spinal cord ischemic tolerance and aid in preventing SCI[86].

As for the pharmacological options that would potentially help, the use of mannitol (18% mannitol, 0.5 g/kg, infusion rate: 300 mL/h) can contribute to reducing the CSF pressures, as previously demonstrated in the literature[87,88]. Among the Principal Investigators of the Aortic Research Consortium, doses between 12.5 and 25 g of mannitol have been used intraoperatively during F/BEVAR procedures[75]. An experimental study also suggests that mannitol can function as a free radical scavenger; therefore, it would potentially contribute to reducing the risk of spinal cord ischemic injury in the context of TAA and TAAA repair. Naloxone is another drug that could be favorable in this context. Kunihara et al. observed that the intraoperative administration of this medication (1 microg/kg/h) has been shown to reduce the levels of excitatory neurotransmitters in the CSF, such as glutamate, which is significantly elevated in patients that presented SCI after TAA and TAAA repair, and can be considered an independent predictor of SCI in the context of aortic surgery[89].

Perioperative glucose monitoring has been shown to decrease the risk of neurological deficits related to spinal cord ischemia. Hiramoto et al., in a study involving individuals who underwent branched endovascular aneurysm repair (BEVAR), reported a reduced incidence of postoperative lower extremity weakness in patients who were prescribed a perioperative insulin infusion protocol. The authors suggest that tight glycemic control should be considered for patients who will be submitted to extensive aortic coverage and therefore are at higher risk of SCI[90].

Finally, the role of steroids deserves attention, as their actions on the recovery after SCI[91] have been extensively debated in the literature. Laschinger et al. observed encouraging results in an experimental model in which animals submitted to aortic cross-clamping were analyzed[92]. The ones that received methylprednisolone intraoperatively and a second dose postoperatively presented no clinical evidence of neurological deficit, contrasting with the 67% incidence of permanent paraplegia observed in a control group that underwent the same duration of cross-clamping but did not receive the drug. Prior publications on SCI prevention in the context of aortic surgery suggest the intraoperative administration of steroids as part of a protocol of SCI prophylaxis. Bobadilla et al., in a study including 94 patients submitted to TEVAR mainly for the treatment of aneurysms or dissections, reported an incidence of SCI as low as 1.1% and attributed these results to the implementation of a proactive spinal cord protective protocol, which included the administration of methylprednisolone 30 mg/kg[86]. Similarly, Acher et al. observed a very low incidence of SCI (0.65%) in 155 patients submitted to TEVAR, encouraging the simultaneous use of numerous spinal cord protective measurements, including the intraoperative administration of methylprednisolone 30 mg/kg[93]. Pasqualucci et al., in a study including 50 patients submitted to endovascular repair of TAAA, reported the use of high doses of epidural steroids just before anesthesia induction, and observed 5 cases of temporary neurological deficit, all of them completely reversed up to the fifth postoperative day[94]. Although it could be challenging to precisely describe the steroids’ contribution to the overall spinal cord protection strategy in the context of aortic surgery, many successful published protocols include the use of these drugs. However, there is no consensus to date recommending the use of steroids as a prophylactic or rescue tool for SCI in the context of aortic surgery.
The role of neuromonitoring in the context of TAA and TAAA repair

Intraoperative neuromonitoring (IONM) has become a valuable aid in the context of complex anatomy aortic aneurysm repair. As recent publications have demonstrated, it can support intraoperative decision-making, either during open or endovascular repair\cite{36,95}. Motor-evoked potentials (MEP) monitor the integrity of the descending corticospinal pathway, whereas somatosensory-evoked potentials (SSEP) assess the functionality of the dorsal column somatosensory tract for proprioception and vibration\cite{96}.

Kolesár et al. experimentally demonstrated a region-specific sensitivity of the spinal cord to ischemia\cite{97}, reporting that motoneurons in the ventral horns are more sensitive to ischemia than neurons in other segments of the spinal cord, which can explain why MEP is more sensitive for SCI monitoring than SSEP. MEP are significantly reduced or not detectable within two minutes of acute ischemia\cite{98}, providing intraoperative real-time information to the surgeons and anesthesiologists. Bianchi et al., in a study including 100 patients submitted to TAAA repair, observed that the percentage of cases with postoperative SCI was significantly higher in those patients who presented irreversible MEP deterioration during the procedure compared to the ones with reversible deterioration\cite{99}. The authors concluded that actions intended to reverse MEP deterioration seem to be worthwhile in the endeavor of reducing the SCI risk. It is essential to highlight that MEP and SSEP have some limitations, such as: (1) volatile anesthetics interfering with the amplitude of the SSEP; therefore, their use should be kept to a minimum so this IONM modality can be accurately used; (2) the limb ischemia produced by the introducers and sheaths used during the endovascular interventions can significantly interfere with the evoked potentials interpretation; and (3) MEP and SSEP are not able to differentiate between moderate and severe SCI\cite{64,100}. The use of MEP or SSEP is recommended with a level B of evidence by a multi-society guideline on the management of patients with thoracic aortic disease\cite{26}.

Near-infrared spectroscopy (NIRS) is another IONM option in the context of aortic surgery. NIRS is a method for indirectly evaluating spinal cord oxygenation and perfusion, as it indicates the blood oxygen saturation in the tissue underneath the NIRS sensor\cite{101}. Considering the collateral network concept, numerous connections exist between the intraspinal and paraspinal networks\cite{102}. Therefore, multiple electrodes placed at the thoracic and lumbar levels on the surface of paraspinal muscles could provide an indirect assessment of the oxygenation and perfusion of the spinal cord\cite{102}. It has the advantage of being a noninvasive modality that can be applied not only during the surgical procedure but also during the postoperative management in the intensive care unit. Despite the encouraging publications on the use of NIRS in the context of aortic surgery, Vanpeteghem et al. stated in a review study that there is no sufficient evidence available for a precise cutoff that should be considered for SCI\cite{103}. No consensus has been established recommending the clinical applicability of NIRS in aortic surgery to date.

**RESCUE STRATEGIES WHEN SCI IS DIAGNOSED IN THE PERIOPERATIVE PERIOD OF TAA AND TAAA REPAIR** [Table 4]

SCI with intraoperative onset

During the TAA or TAAA repair, constant attention to the neuromonitoring data is crucial to prompt maneuvers intended to improve spinal cord perfusion. Decreased MEP or SSEP should immediately trigger actions to increase MAP > 90 mmHg, such as the careful infusion of volume and the use of vasopressors, as well as the increase in CSF drainage to keep CSFP < 10 mmHg in the high-risk patients who received a lumbar drain preoperatively. If persistent changes in IONM are observed, maneuvers such as reimplantation of intercostal arteries during open repair or temporary aneurysm sac perfusion (TASP) and modification of the sequence of implantation of components during endovascular approach could aid in increasing the blood flow to the spinal cord.
Table 4. Rescue strategies

<table>
<thead>
<tr>
<th>Intraoperative strategies</th>
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<tbody>
<tr>
<td>Keep MAP &gt; 90 mmHg through careful infusion of volume and use of vasopressors</td>
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<tr>
<td>Keep hemoglobin ≥ 10 mg/dL</td>
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<tr>
<td>If prophylactic spinal drain is in place, keep CSFP &lt; 10 mmHg</td>
</tr>
<tr>
<td>Reimplantation of intercostal arteries (if open repair) open repair</td>
</tr>
<tr>
<td>TASP (in endovascular repair)</td>
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<tr>
<td>Modification of the sequence of implantation of components during endovascular repair</td>
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<tr>
<td>Postoperative strategies</td>
</tr>
<tr>
<td>Keep MAP &gt; 90 mmHg through careful infusion of volume and use of vasopressors</td>
</tr>
<tr>
<td>Keep hemoglobin ≥ 10 mg/dL</td>
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<tr>
<td>Therapeutic spinal drain (goal: CSFP &lt; 10 mmHg)</td>
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<tr>
<td>Possible use of high-dose steroids</td>
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</table>

CSFP: Cerebrospinal fluid pressure; TASP: temporary aneurysm sac perfusion.

During open cases, the reimplantation of intercostal arteries has been demonstrated to be an effective tool in reducing the risk of SCI, without significantly increasing the duration of the procedure\footnote{62}.

As for the rescue maneuvers during endovascular procedures, the rationale behind TASP is the prevention of the complete aneurysm sac thrombosis and maintenance of blood inflow to the spinal cord through intercostal and lumbar arteries achieved by intentionally leaving at least one target vessel non-scented. Kasprzak et al., in a study with 83 patients submitted to BEVAR for TAAA treatment\footnote{104}, reported that the cases submitted to TASP had a significantly lower incidence of severe SCI or paraplegia compared to those that did not undergo this technique. These authors observed a median of 48 days (range 1-370 days) between the index procedure and completion of repair. Harrison et al. described an interval of 7-10 days between the TAAA repair and the complete exclusion of the aneurysm. TASP can also be obtained by leaving the contralateral limb of a bifurcated device incomplete\footnote{84,105}.

Another intraoperative option to improve spinal cord perfusion during F/BEVAR for TAAA is the modification of the implantation sequence of the components during the repair. This maneuver aims to provide early pelvic and limb reperfusion by deploying the bifurcated component and iliac limbs and removing the large caliber sheaths from the iliac system before deploying the target vessel stents through an axillary access. Maurel et al., analyzed 204 TAAA patients submitted to endovascular repair and observed a significantly lower rate of SCI in patients who were submitted to early pelvic reperfusion using this technique\footnote{106}.

Finally, in those cases presenting intraoperative SCI that did not have a spinal drain placed preoperatively, a therapeutic drain can also be indicated by the time the surgical intervention ends. According to the recommendations reported by Aucoin et al. on behalf of the US-ARC, keeping hemoglobin ≥ 10 mg/dL, MAP ≥ 90 mmHg, and obtaining an immediate image of the spine to rule out hematomas are also essential rescue maneuvers in this context\footnote{75}.

The use of high-dose steroids has also been documented in this scenario in conjunction with the aforementioned techniques, but there is no consensus recommending this practice\footnote{107}.

**SCI with postoperative onset**

The multidisciplinary team must be attentive to the hemodynamic and neurologic status during the whole postoperative period of TAA and TAAA patients. A low threshold to trigger rescue strategies intended to prevent permanent neurologic deficits is recommended to reduce the recovery time from SCI in those
presenting this adverse event. NIRS can be maintained in the intensive care unit for monitoring high-risk patients, although there is no consensus recommending its use and no sufficient evidence available for a precise cutoff that would be concerning for SCI.

The maneuvers described above should also be implemented for the cases with postoperative SCI. MAP above 90 mmHg and hemoglobin above 10 mg/dL are goals that should be pursued in these cases. If a prophylactic spinal drain was inserted, a therapeutic drain should be placed with the purpose of keeping CSFP below 10 mmHg. If the neurologic deficits do not improve as expected, lower CSFP values can be attempted as a heroic maneuver up to the discretion of the surgical team assisting the patient. However, in addition to the high risk of intracranial bleeding from aggressive CSF drainage, there is no consensus recommending this practice to date.

The use of therapeutic CSF drainage can also be indicated even in those cases presenting delayed-onset SCI symptoms, with satisfactory results reported in the literature\[108\]. Weissler et al. suggest that permissive hypertension (systolic blood pressure up to 150 mmHg) during the first month after TEVAR could also aid in the protection against SCI\[109\].

Finally, the use of high-dose steroids as part of a rescue protocol is described in the literature, even in cases with a delayed presentation of SCI\[110\], but there is no consensus recommending this practice.

CONCLUSION
Spinal cord ischemia prevention in the context of TAA or TAAA repair requires meticulous surgical planning including a thorough analysis of the contributions to spinal cord perfusion and repair extension, always evaluating the need for a staged approach. Careful perioperative strategies including hypotension avoidance and neuromonitoring, weighing the advantages and disadvantages of preoperative lumbar drain implantation are paramount in these cases. The strategies for preventing SCI discussed in this review can be applied in a combined fashion, depending on the patient’s anatomy and the planned repair. Vascular and cardiothoracic surgeons dedicated to the treatment of TAA and TAAA should be comfortable with all the SCI protective and rescue strategies in order to reduce the risk of this adverse event in this patient population.

DECLARATIONS
Authors’ contributions
Literature review; data interpretation; manuscript preparation; critical revision of the manuscript; approval of the manuscript: all authors.

Availability of data and materials
Not applicable.

Financial support and sponsorship
None.

Conflicts of interest
Vivian Carla Gomes: no disclosures; Federico Ezequiel Parodi: Stock options from Centerline Biomedical; Mark A Farber: WL Gore - Consulting, Clinical Trial Support; Getinge - Consulting; Cook - Research support, Clinical Trial support; ViTTA - Consulting, Clinical Trial support; Centerline Biomedical - Stock options, Clinical Trial support.
Ethical approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

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J Thorac Cardiovasc Surg 2018;155:1372-1378.e1. DOI


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