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Risk factors, outcomes, and clinical manifestations of spinal cord ischemia following thoracic endovascular aortic repair

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Objective: The purpose of this study was to assess the incidence, risk factors, and clinical manifestations of spinal cord ischemia (SCI) after thoracic endovascular aortic repair (TEVAR).

Methods: A retrospective review of a prospectively collected database was performed for all patients undergoing TEVAR at a single academic institution between July 2002 and June 2010. Preoperative demographics, procedure-related variables, and clinical details related to SCI were examined. Logistic regression analysis was performed to identify risk factors for the development of SCI.

Results: Of the 424 patients who underwent TEVAR during the study period, 12 patients (2.8%) developed SCI. Mean age of this cohort with SCI was 69.6 years (range, 44-84 years), and 7 were women. One-half of these patients had prior open or endovascular aortic repair. Indication for surgery was either degenerative aneurysm (n = 8) or dissection (n = 4). Six TEVARs were performed electively, with the remaining done either urgently or emergently due to contained rupture (n = 2), dissection with malperfusion (n = 2), or severe back pain (n = 2). All 12 patients underwent extent C endovascular coverage. Multivariate regression analysis demonstrated chronic renal insufficiency to be independently associated with SCI (odds ratio [OR], 4.39; 95% confidence interval [CI], 1.2-16.6; P = .029). Onset of SCI occurred at a median of 10.6 hours (range, 0-229 hours) postprocedure and was delayed in 83% (n = 10) of patients. Clinical manifestations of SCI included lower extremity paraparesis in 9 patients and paraplegia in 3 patients. At SCI onset, average mean arterial pressure (MAP) and lumbar cerebrospinal fluid (CSF) pressure was 77 mm Hg and 10 mm Hg, respectively. Therapeutic interventions increased blood pressure to a significantly higher average MAP of 99 mm Hg (P = .001) and decreased lumbar CSF pressure to a mean of 7 mm Hg (P = .30) at the time of neurologic recovery. Thirty-day mortality was 8% (1 of 12 patients). The single patient who expired, never recovered any lower extremity neurologic function. All patients surviving to discharge experienced either complete (n = 9) or incomplete (n = 2) neurologic recovery. At mean follow-up of 49 months, 7 of 9 patients currently alive continued to exhibit complete, sustained neurologic recovery.

Conclusion: Spinal cord ischemia after TEVAR is an uncommon, but important complication. Preoperative renal insufficiency was identified as a risk factor for the development of SCI. Early detection and treatment of SCI with blood pressure augmentation alone or in combination with CSF drainage was effective in most patients, with the majority achieving complete, long-term neurologic recovery. (J Vasc Surg 2011;54:677-84.)

Thoracic endovascular aortic repair (TEVAR) is increasingly being used for a diverse group of aortic pathologies. Results from the first multicenter U.S. Food and Drug Administration-sponsored trial for the Gore device (W. L. Gore & Associates, Flagstaff, Ariz) demonstrated significantly decreased perioperative mortality, respiratory failure, renal insufficiency, and spinal cord ischemia (SCI) in patients after TEVAR compared to a matched cohort of patients undergoing open repair of descending thoracic aortic aneurysms.[1] Najibi et al[2] likewise demonstrated less morbidity with endovascular intervention (26% vs 50%) relative to a historic nonrandomized control of patients with open repair. Other direct comparisons have shown similar trends favoring the endovascular approach.[3-6]

The conduct of TEVAR obviates the need for many of the critical physiological alterations that are believed to contribute to the development of SCI after open surgery such as aortic cross-clamping, reperfusion injury, and acute hemodynamic changes. Nevertheless, the risk of SCI after endovascular repair remains. The incidence of SCI after TEVAR is generally less when compared to open surgical repair but still occurs with a reported incidence of 0 to 13%.[4,7-12]

In the present study, we sought to evaluate the incidence and investigate risk factors for the development of SCI after TEVAR. We focused much of our investigation on the clinical manifestations of SCI with regard to its onset, severity, and pattern of recovery.

Thoracic endovascular aortic repairs (TEVAR)
(July 2002 - June 2010)

Excluded

Aortic arch hybrid: n=43
Abdominal debranching : n=6

TEVARs
n=424

Perioperative spinal cord ischemia (SCI)

Clinical manifestations of SCI

Yes
n=12

No
n=412

Retrospective Analysis

Patient demographics, thoracic aortic anatomy, intraoperative data,
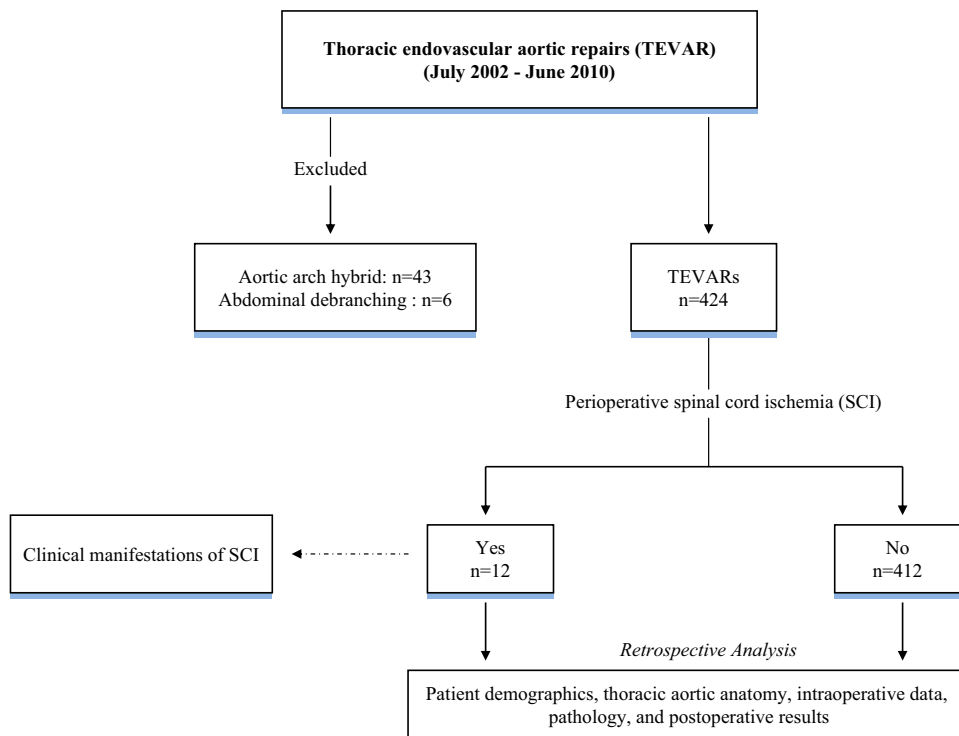pathology, and postoperative results

Fig 1. Study design.

METHODS

This study represents a cumulative experience that follows our previous report describing our experience from the stent graft trials of 1999-2004.[13] A protocol for managing SCI was consistently used by experienced personnel at our institution beginning in July 2002; this serves as the starting point for our analysis. A retrospective review of a prospectively collected database was performed for patients undergoing TEVAR at our institution between July 2002 and June 2010. Endovascular repairs involving aortic arch hybrid (n = 43) or abdominal debranching (n = 6) procedures were excluded. Preoperative patient demographics, comorbidities, thoracic aortic pathology, intraoperative procedure-related variables, postoperative outcomes, development of perioperative SCI, and clinical details related to SCI, including onset, severity, and recovery patterns, were examined (Fig 1).

Patients with a history of prior abdominal aortic aneurysm (AAA) repair, radiologic evidence of bilateral hypogastric artery occlusion, planned long extent coverage, or left subclavian artery (zone II) coverage without revascularization were deemed high-risk for the development of SCI. All patients in the present study with one or more of these risk factors had prophylactic lumbar cerebrospinal fluid (CSF) drainage, intraoperative somato-sensory-evoked potential (SSEP) monitoring, and/or maintenance of a higher perioperative mean arterial pressure (MAP), unless such interventions were not feasible due to acuity of presentation. The extent of endovascular coverage of the

descending thoracic aorta was classified into three groups: extent A was coverage from the origin of the left subclavian artery to the sixth thoracic vertebral level; extent B was coverage from the sixth thoracic vertebral level to the diaphragm; and extent C was coverage of the entire descending thoracic aorta from the left subclavian artery to the diaphragm.[14]

All patients were admitted to the surgical intensive care unit (ICU) postoperatively in accordance with our previously described spinal protection protocol.[13] A focused neurologic assessment was performed on an hourly basis until recovery from anesthesia permitted a more thorough neurologic examination. Lower extremity motor function was classified according to the following modified Tarlov scale,[15] ranging from 0 to 5: 0, no lower extremity movement; 1, motion without gravity; 2, motion against gravity; 3, able to stand with assistance; 4, able to walk with assistance; and 5, normal. Spinal cord ischemia was defined as any new lower extremity motor or sensory deficit in the postoperative period not attributed to intracranial pathology. Paraplegia was defined as complete loss of motor strength in the bilateral lower extremities (Tarlov score = 0), whereas paraparesis was defined as motor weakness in any lower extremity muscle group or unilateral paraplegia (Tarlov score = 1-4 or, if present, a score of zero in a single lower extremity). A deficit noted upon awakening from anesthesia, regardless of severity, was defined as immediate-onset SCI. Development of a neurologic deficit after an initial discrete period of normal neurologic function in the

Table I. Preoperative predictors of spinal cord ischemia after TEVAR, univariate analysis

Variable	No SCI % (No.)	SCI % (No.)	P value
Demographics			
Age (mean ± SD)	70.6 ± 12	69.6 ± 13	.87
Gender, male	55 (204/368)	42 (5/12)	.38
Comorbidities			
Hypertension	91 (350/386)	100 (12/12)	.61
Stroke	15 (42/282)	17 (2/12)	1.00
Atrial fibrillation	22 (85/379)	0 (0/12)	.08
Prior MI	21 (55/256)	25 (3/12)	.74
CRI[a]	9 (34/378)	33 (4/12)	.02
COPD	35 (132/378)	33 (4/12)	1.00
PVD	41 (155/378)	17 (2/12)	.14
CHF	26 (97/374)	17 (2/12)	.74
Diabetes	19 (71/376)	17 (2/12)	1.00
Tobacco use	70 (184/264)	92 (11/12)	.07
Prior aortic surgery	32 (116/357)	50 (6/12)	.23
Perioperative variables			
Acuity, emergent/urgent	42 (163/384)	50 (6/12)	.77
Preoperative rupture	23 (84/373)	25 (3/12)	.74
Pathology type			.82
Aneurysm	73 (279/380)	67 (8/12)	
Dissection	20 (76/380)	33 (4/12)	
PAU	3 (10/380)	0 (0/12)	
Traumatic transection	4 (15/380)	0 (0/12)	
Vascular access			.42
Femoral	76 (260/340)	67 (8/12)	
Iliac	24 (80/340)	33 (4/12)	
Extent C coverage[b]	38 (131/346)	100 (12/12)	< .001
Zone II coverage[c]	21 (76/357)	25 (3/12)	.73

CHF, Congestive heart failure; *COPD,* chronic obstructive pulmonary disease; *CRI,* chronic renal insufficiency; *MI,* myocardial infarction; *PAU,* penetrating atherosclerotic ulcer; *PVD,* peripheral vascular disease; *SCI,* spinal cord ischemia; *TEVAR,* thoracic endovascular aneurysm repair.
[a]Creatinine ≥1.5 mg/dL.
[b]Stent coverage from origin of left subclavian artery to diaphragm.
[c]Endovascular coverage of the left subclavian artery.

postoperative setting was classified as delayed-onset SCI. Complete recovery was achieved upon full reversal of neurologic deficit and subsequent restoration of the patient's baseline neurologic status. Incomplete recovery, on the other hand, was associated with partial improvement of neurologic deficit without return to the patient's baseline neurologic status.

Goal MAPs were initially assigned by the surgeon in conjunction with the anesthesiologist and were based on intraoperative SSEP recordings, extent of endovascular aortic coverage, and overall estimated risk of SCI. Lumbar CSF was drained continuously in the operating room to achieve target CSF pressures of 10 to 12 mm Hg. Intermittent drainage was performed in the ICU to prevent excessive drainage that may predispose the patient to the risk of subdural hematoma. With careful monitoring and intermittent drainage, the fluctuations in CSF pressures are small, and CSF pressures are maintained in the range of 10 to 12 mm Hg. Lumbar drainage catheters were clamped at 24 hours and removed 48 hours after the operation if there was no evidence of any neurologic deficit. Upon detection of neurologic deficit, interventions directed at increasing spinal cord perfusion were immediately implemented according to our institutional protocol.[13] Volume expansion and/or vasopressors were used to assist in further augment-

ing MAP to 85 to 100 mm Hg or above. If a functioning lumbar CSF drain was already in place at the time of SCI onset, we then targeted a lower CSF pressure of 8 to 10 mm Hg. In those patients without a lumbar CSF drain, a drain was placed emergently if there was no significant improvement in neurologic examination after increase in arterial blood pressure. Because it is faster to augment blood pressure, and if we achieve immediate recovery with blood pressure augmentation alone, we may defer lumbar drain placement.

Statistical analysis. Statistical analysis was performed using SPSS, version 17.0 (SPSS, Chicago, Ill). Univariate analysis was performed using χ^2 tests to correlate baseline demographics, comorbidities, and perioperative factors with SCI. A multivariate logistic regression model was then used with SCI as the dependent variable. Any *P* values less than .05 were considered statistically significant for all analyses.

RESULTS

Of the 424 patients undergoing TEVAR with stent grafting confined to the thoracic aorta, 12 patients (2.8%) developed SCI. Univariate analysis of patient demographics, comorbidities, and perioperative factors on the risk of SCI are summarized in Table I. Preoperative chronic renal

Table II. Preoperative predictors of spinal cord ischemia after TEVAR, multivariate analysis

Variable	Odds ratio (95% CI)	P value
CRI[a]	4.39 (1.16-16.58)	.029
Extent C coverage[b]	0.00	.995

CI, Confidence interval; *CRI,* chronic renal insufficiency; *TEVAR,* thoracic endovascular aneurysm repair.
[a]Creatinine ≥1.5 mg/dL.
[b]Stent coverage from origin of left subclavian artery to diaphragm.

insufficiency (CRI; $P = .02$) and extent C coverage ($P < .001$) were significant predictors of SCI. Multivariate logistic regression analysis confirmed that CRI (odds ratio [OR], 4.39; 95% confidence interval [CI], 1.16-16.58; $P = .03$) was significantly and independently associated with the risk for SCI (Table II).

One-half of the cohort with SCI had prior aortic interventions, including open or endovascular AAA repair (n = 5) or open type III thoracoabdominal aortic aneurysm repair (n = 1).

Mean aneurysm size was 6.6 cm (range, 5.8-9.0 cm). One-half of the TEVARs were performed electively, with the remaining done either urgently (n = 4) or emergently (n = 2) due to severe back pain, contained rupture, or acute dissection with malperfusion. The mean length of surgery was 198 ± 72 minutes. Median estimated blood loss was 255 mL, with 9 patients receiving a mean of 2.5 units of blood postoperatively.

Immediate technical success with TEVAR was achieved in all patients, with no type I or type III endoleaks, aborted procedures, or conversions to open repair. Four different devices were used in this cohort: TAG (W L Gore & Associates, Flagstaff, Ariz), Talent (Medtronic Vascular, Santa Rosa, Calif), Zenith TX2 (Cook Medical, Bloomington, Ind), and Relay (Bolton Medical, Sunrise, Fla). To achieve sufficient proximal landing zones, 2 of 12 patients required a preoperative left carotid-subclavian bypass procedure. Coverage of the celiac artery was performed in 1 patient to achieve an adequate distal seal, but no visceral revascularization was needed. The mean length of the thoracic aorta covered by stent graft was 38 ± 18 cm.

Intraoperative neuromonitoring using lower extremity SSEPs was used in two-thirds of the SCI cohort, all of whom demonstrated transient intraoperative SSEP changes consistent with temporary occlusion of blood flow to the femoral or iliac arteries during sheath insertion. Changes in intraoperative lower-extremity SSEPs resolved in all patients upon closure of the arteriotomy and reperfusion. Acuity of presentation prohibited the utilization of intraoperative neuromonitoring in the remaining one-third of patients. Seventy-five percent (n = 9) of the cohort had prophylactic lumbar CSF drainage at the time of the procedure.

Onset of SCI occurred at a median of 10.6 hours (range, 0-229 hours) postprocedure. The onset of SCI was delayed in the majority of patients (n = 10), whereas 2

patients exhibited clinical signs of SCI immediately upon awakening from general anesthesia. Twenty-five percent of patients (n = 3) reported lower extremity sensory deficits. At SCI onset, average MAP and CSF pressure was 77 ± 13 mm Hg and 10 ± 4 mm Hg, respectively. Therapeutic interventions increased blood pressure to a significantly higher average MAP of 99 ± 11 mm Hg ($P < .001$) and decreased CSF pressure to a mean of 7 ± 4 mm Hg ($P = .30$) at the time of neurologic recovery (Fig 2).

Five of 12 patients had a functioning lumbar CSF drain at onset and 4 others subsequently had drains placed, including 2 of the 3 patients who did not have intraoperative lumbar drainage as a result of emergent/urgent procedure. Of the remaining 3 patients who did not have lumbar drains inserted after SCI onset, 2 patients rapidly achieved complete neurologic recovery with blood pressure augmentation alone, and 1 patient who did not receive a lumbar drain after initial attempt at drain placement, returned purulent CSF that was concerning for primary infection. One-half of the patients improved with intravenous fluid and/or colloid resuscitation alone, only 2 of which had a lumbar CSF drain at the time of recovery. A summary of procedural details, intraoperative interventions, and neurologic deficits for the cohort of 12 patients with SCI is featured in Table III.

Thirty-day mortality for patients with SCI was 8% (1 of 12 patients). The isolated in-hospital death occurred in a 65-year-old woman with a history of prior open type III thoracoabdominal aortic aneurysm repair several months earlier that underwent urgent TEVAR for a symptomatic 5.8-cm saccular thoracic aortic aneurysm complicated by intraoperative ventricular fibrillation arrest. After recovering from a cardiac standpoint, she did not regain lower extremity motor function and later developed respiratory failure. The family decided to withdraw care on postoperative day 7.

The 11 patients with SCI surviving to hospital discharge, experienced complete (n = 9) or incomplete (n = 2) neurologic recovery. Sensory deficits resolved in all cases. Median ICU and total hospital length of stay was 7 days (range, 3-18 days) and 12 days (range, 5-58 days), respectively. Most patients (n = 8) required rehabilitation upon hospital discharge.

Interval follow-up was performed via review of medical records, social security death index, and telephone contact with the patient, family, or patients' primary care physician. There were two late deaths after TEVAR in the SCI group, both from unknown causes. At a mean follow-up period of 49 ± 18 months, mean postoperative survival for patients with SCI surviving to hospital discharge was 32 ± 26 months (range, 0.30-78 months). Of the 9 patients with SCI who underwent follow-up imaging, 2 patients had evidence of type II endoleaks. None of these patients required any secondary intervention. Seven of the 9 patients currently alive continue to exhibit complete, sustained neurologic recovery. The remaining 2 patients continue to function independently despite stable mild right lower extremity paraparesis.
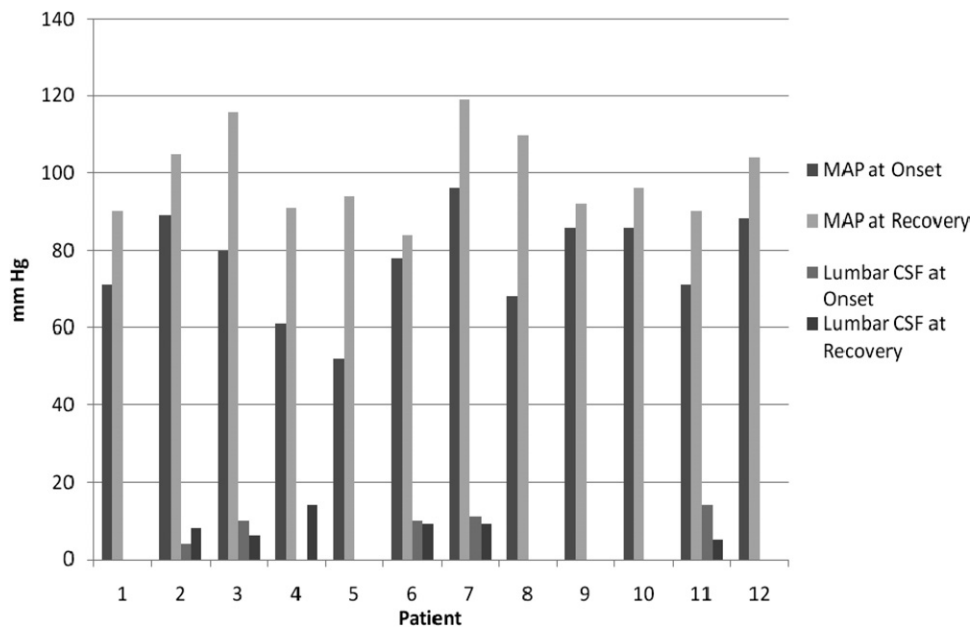
Fig 2. Mean arterial pressure (*MAP*) and lumbar cerebrospinal fluid (*CSF*) pressure, when available, at spinal cord ischemia onset and recovery for the cohort of 12 patients.

Table III. Summary of procedural details, intraoperative interventions, and neurologic deficits for cohort of 12 patients with postoperative spinal cord ischemia

			Procedural details			Intraoperative interventions		Neurologic deficit		
Patient	Aortic pathology	Acuity	Endograft used	LSA coverage	Aortic length coverage (cm)	CSF drainage[a]	SSEP[b]	Onset[c] (hrs)	Severity	Recovery
1	Dissection	Emergent	Gore TAG	No	15	No	No	Immediate (3.8)	Paraplegia	Incomplete
2	Aneurysm	Elective	Relay	No	25	Yes	Yes	Immediate (0.0)	Paraparesis	Complete
3	Aneurysm	Elective	Gore TAG	No	40	Yes	Yes	Delayed (19.3)	Paraparesis	Complete
4	Dissection	Urgent	Gore TAG	Yes	50	Yes	Yes	Delayed (56.3)	Paraparesis	Complete
5	Dissection	Emergent	Gore TAG	Yes	55	Yes	Yes	Delayed (229)	Paraplegia	Incomplete
6	Dissection	Urgent	Gore TAG	No	40	Yes	Yes	Delayed (23.7)	Paraparesis	Complete
7	Aneurysm	Urgent	Zenith	No	41	Yes	Yes	Delayed (6.8)	Paraplegia	No recovery[d]
8	Aneurysm	Elective	Talent	No	23	No	No	Delayed (13.3)	Paraparesis	Complete
9	Aneurysm	Urgent	Gore TAG	No	15	No	No	Delayed (2.8)	Paraparesis	Complete
10	Aneurysm	Elective	Zenith	No	41	Yes	Yes	Delayed (44.8)	Paraparesis	Complete
11	Aneurysm	Elective	Gore TAG	Yes	80	Yes	Yes	Delayed (8.0)	Paraparesis	Complete
12	Aneurysm	Elective	Talent	No	34	Yes	No	Delayed (0.8)	Paraparesis	Complete

CSF, Cerebrospinal fluid; *LSA,* left subclavian artery; *SSEP,* somato-sensory-evoked potential.
[a]Use of prophylactic intraoperative CSF drainage to achieve lumbar CSF pressure ≤12 mm Hg.
[b]SSEP changes occurred in all patients consistent with temporary occlusion of blood flow to the femoral or iliac arteries during sheath insertion. These SSEP changes resolved after arteriotomy closure and reperfusion.
[c]Time after arrival to intensive care unit after procedure.
[d]In-hospital mortality.

DISCUSSION

Our experience with performing over 400 TEVARs since the application of a routine spinal cord protection protocol yielded an incidence of SCI of 2.8% (12 of 424), a figure that is consistent with previous reports.[4,7-12] Comparing outcomes after thoracic aortic endovascular interventions can be difficult, however, given the heterogeneity of the procedures performed. Drinkwater et al[16] recently demonstrated a significant rise in the risk of SCI with increasing magnitude of procedure type; TEVAR (stent graft confined to the thoracic aorta) was associated with the least risk at 1.8%; arch hybrid 10%, fenestrated/branched graft 14.3%, and visceral hybrid 20%. Although we aimed to maximize validity by intentionally choosing to focus on a single procedure type, we also observed an increase in the incidence of SCI within our excluded patient subgroups;

SCI was noted to occur in 14% of patients (6 of 43) undergoing aortic arch hybrid and 17% of patients (1 of 6) undergoing abdominal debranching procedures during our study period. In total, our global incidence of SCI was 4% (19 of 473).

The extent of neurologic deficits attributed to SCI after TEVAR can range from mild paraparesis to flaccid paralysis. At one extreme of this clinicopathologic spectrum, patients with complete paralysis are those who have suffered irreversible SCI because of spinal cord infarction. Patients at the opposite end of the spectrum represent a less severe form of cord ischemia with the potential for reversibility and full neurologic recovery. Delayed-onset SCI, which can occur up to several weeks after TEVAR, is also typically due to ischemia of the spinal cord with the potential for recovery.[13,17-19] Whereas a deficit noted immediately upon emergence from anesthesia would be attributed to an intraoperative cause, a delayed neurologic deficit observed after a period of normal neurologic function is secondary to a postoperative event. Indeed, several postoperative events have been linked to the development of delayed-onset SCI, including hypotension, thrombosis, hematoma, embolization, and elevated CSF pressures.[17,20-22]

The majority of patients (9 of 12) in our study manifested SCI in the form of paraparesis, with all of these patients achieving complete neurologic recovery. Recovery was significantly worse in the remaining 3 patients who manifested SCI in the form of paraplegia: 2 patients achieved only partial neurologic recovery, whereas the other patient did not regain any motor strength. The patient with no recovery of deficit represented the single mortality in this cohort. Our findings support the notion that patients with paraparesis fare much better relative to those with paraplegia, both in terms of the underlying severity of SCI and the potential for reversibility of spinal cord malperfusion.

The pathogenesis of SCI after TEVAR is poorly understood and likely multifactorial. Spinal cord perfusion is a complex, dynamic process dependent on both collateral circulation and single segmental arteries. As a result, the spinal cord is particularly prone to compromised blood flow during periods of hemodynamic instability.[23,24] The largest series to date, reported by the European Collaborators on Stent/Graft Techniques for Aortic Aneurysm Repair investigators, cited left subclavian artery coverage without revascularization, concomitant abdominal aortic surgery, and the use of three or more stent grafts to be associated with SCI.[10] These three clinical variables each have a well-established relationship to the blood supply of the spinal cord. Coverage of the left subclavian artery, for instance, compromises the proximal collateral circulation to the spinal cord, including the vertebral and internal thoracic arteries. Extensive coverage of long segments of the thoracic aorta using multiple stent grafts may also significantly limit spinal cord perfusion by compromising important intercostal (T7-L1) and lumbar segmental arteries supplying the anterior spinal artery.[9,11,17,25,26] Prior AAA repair can similarly lead to diminished spinal cord perfusion by compromising pelvic and hypogastric collaterals.[13,25,27,28] Moreover, degenerative aneurysms have been associated with an increased risk for SCI, given that these patients tend to have fewer patent intercostal arteries compared to those with postdissection thoracic aneurysms.[29]

In the present study, patients with preoperative CRI were significantly more likely to develop SCI. European Collaborators on Stent/Graft Techniques for Aortic Aneurysm Repair investigators noted similar findings in their prospective analysis of 606 patients who underwent TEVAR for aneurysms or dissections of the thoracic aorta.[10] Paraplegia or paraparesis occurred in 15 of these patients (2.5%). Researchers demonstrated renal failure (OR, 3.6; $P = .02$) to be an independent risk factor for SCI. In addition, a multicenter cohort study of 72 patients who underwent TEVAR for treatment of degenerative thoracic aortic aneurysm disease after prior AAA repair also noted an association between renal function and development of SCI.[27] Symptoms of SCI occurred in 12.5% of these patients, with renal insufficiency again serving as an important risk factor for SCI ($P = .011$). Although renal insufficiency has also long been noted to be a major risk factor for SCI after open thoracoabdominal aortic aneurysm repair,[30-32] the precise mechanism is less clear. It has been postulated that renal insufficiency serves as a marker of more severe, widespread peripheral atherosclerotic disease and, by extension, such patients may have a compromised collateral network of blood supply to the spinal cord at baseline.[10] Given the findings of the present study, we now consider CRI as yet another risk factor for SCI and, as a result, we now recommend prophylactic lumbar CSF drainage in patients with elevated preoperative creatinine levels.

Numerous studies have attempted to identify additional demographic and perioperative variables that may increase the risk of SCI after TEVAR. Additional independent risk factors include age, number of patent lumbar arteries, emergent procedure, duration of procedure, general endotracheal anesthesia, and iliac artery injury.[13,25,29,33,34] Although prior aortic surgery, surgical acuity, aneurysm morphology, and extent C coverage were not statistically significant risk factors in our study, they were common in the subgroup of patients who developed SCI. Application of a clinical protocol for selective use of lumbar CSF drainage, intraoperative SSEP monitoring, and maintenance of a higher perioperative MAP in high-risk patients may have attenuated the incidence of SCI in this subgroup and eliminated them as statistically significant predictors of SCI.

Our previous work demonstrated postoperative hypotension and increased CSF pressure to be associated with increased risk of neurologic deficits after TEVAR.[13] These results are predictable based on the physiological principle that spinal cord perfusion pressure equals the difference between MAP and CSF pressure. Cheisa et al[35] also noted the deleterious effects of perioperative hypotension in their review of 103 patients who underwent elective TEVAR for thoracic aortic lesions. Perioperative hypotension, defined as MAP <70 mm Hg, was a significant risk factor for postoperative neurologic deficit in their analysis. In the

present study, only 3 of the 12 patients with SCI had MAP <70 mm Hg at the onset of neurologic deficit, with no apparent relationship between hypotension and arrhythmic, infectious, or hemorrhagic complications. Nevertheless, blood pressure augmentation immediately upon recognition of neurologic deficit played an important role in improving spinal cord perfusion pressure and permitting reversibility of SCI in these patients, as evidenced by the significantly higher MAP at SCI recovery relative to the observed MAP at onset. Of note, however, we do not preemptively augment a patient's blood pressure unless the patient is considered high-risk or there is clinical evidence of SCI. Most of our patients are elderly with multiple medical comorbidities and, as a result, the risk of complications related to the maintenance of significantly elevated blood pressures must be weighed against the small risk of developing SCI.

The use of routine intraoperative lumbar CSF drainage has generally been limited to select high-risk patients.[3,36] Hnath et al[37] conducted the only prospective TEVAR analysis evaluating a standardized approach of mandatory CSF drainage compared to selective CSF drainage. The researchers concluded that selective CSF drainage may offer the same benefit as mandatory drainage. Although we and others have noted the therapeutic effects of CSF drainage in the management of SCI after open thoracoabdominal aneurysm repair, the precise impact of CSF drainage in the setting of TEVAR was not appreciated in the present study, as there was no significant difference between the mean CSF pressures at SCI onset and recovery.[13,19,30,38,39] Moreover, 5 of the 12 patients in our cohort were capable of achieving neurologic recovery in the absence of a functioning lumbar drain. We postulate that spinal drainage may have a lesser role in the management of SCI after TEVAR compared to open repair. Indeed, we have become more selective over time with CSF drainage given both the low incidence with which we see SCI after TEVAR, and due to the observed efficacy of blood pressure augmentation alone in the few patients who do go on to develop lower extremity neurologic deficits after TEVAR.

Our recommendation for capping lumbar drains at 24 hours and removal at 48 hours was based on our previous work investigating SCI after open thoracoabdominal aortic surgery.[20] In that experience, median onset time for delayed SCI was 21.6 hours, with 75% (6 of 8 episodes) occurring within 48 hours of operation. Similarly, 10 of 12 patients in the current series experienced SCI within the first 48 hours postoperatively. The utility of extending the duration of lumbar CSF drainage beyond 48 hours diminishes over time because the number of SCI episodes beyond 48 hours are infrequent, prolongs ICU length of stay, and requires that patients remain supine. Moreover, risk of lumbar drain-related complications such as infection and persistent CSF leak increase with duration of drainage. Reason for capping the drain 24 hours before removal is to permit CSF pressure to normalize so as to ensure that SCI does not occur at normal CSF pressures and to prevent CSF

hypotension after removal (due to obligate CSF leak upon catheter removal).

Application and effectiveness of intraoperative neuromonitoring is controversial and typically performed based on institutional practice. At our institution, SSEPs are monitored because of ease of use in the operating room given that signals are not attenuated by standard balanced general anesthetic technique with full neuromuscular blockade. Intraoperative attenuation of SSEP signals can prompt diagnosis of SCI (bilateral lower extremity loss) or vascular insufficiency (unilateral lower extremity signal loss in cannulated limb) and thereby assist in guiding blood pressure and CSF drainage goals. Based on our experience in open thoracoabdominal cases, 90% of patients with delayed SCI had sensory deficits. Although motor-evoked potential monitoring may be more sensitive for detecting SCI, anesthetic and instrumentation artifacts may decrease its specificity for SCI (eg, is the decrease in motor-evoked potential amplitude due to anesthetic, neuromuscular blockade, instrument fidelity, or SCI?).[40]

In conclusion, SCI is a clinicopathologic entity that varies widely vis-à-vis severity, onset, and potential for recovery. Several patient demographic and perioperative variables have been shown to be independently associated with development of SCI, including CRI in this study, but the underlying mechanism of SCI after TEVAR remains unclear. Our data suggest that blood pressure augmentation plays an important role in the recovery of SCI after TEVAR. Whereas lumbar CSF drainage should continue to be part of the clinician's armamentarium in managing postoperative SCI, ongoing data support selective rather than empiric placement in all patients. As the application of TEVAR continues to expand, the need to better define the phenomena of SCI after TEVAR and the optimum treatment/management strategy is paramount.

AUTHOR CONTRIBUTIONS

Conception and design: BU, AC, RF, BJ, EW, JB, AP, GW
Analysis and interpretation: BU, AC, GW
Data collection: BU, GW
Writing the article: BU, AC, GW
Critical revision of the article: BU, AC, RF, BJ, EW, JB, AP, GW
Final approval of the article: BU, AC, RF, BJ, EW, JB, AP, GW
Statistical analysis: BU, GW
Obtained funding: Not applicable
Overall responsibility: GW

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