Extensive deployment of the stented elephant trunk is associated with an increased risk of spinal cord injury

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Objective: Thoracic aortic aneurysm repair with the stented elephant trunk technique seems to be associated with an increased risk of spinal cord injury. We investigated whether severe atherosclerosis of the distal landing zone or extensive deployment of the stented elephant trunk is associated with increased risk of spinal cord injury.

Methods: Twenty-five patients underwent thoracic aortic aneurysm repair with the stented elephant trunk technique. The study population included 19 men and had a mean age of 73 ± 7 years. All patients underwent a median sternotomy with cardiopulmonary bypass and selective cerebral perfusion. The elephant trunk was fixed with a Z-stent distal to the aneurysm during hypothermic circulatory arrest. Thirteen patients underwent concomitant total aortic arch replacement.

Results: Six (24%) patients had spinal cord injury. The presence of severe atherosclerosis at the distal landing zone demonstrated a tendency to increase the incidence of spinal cord injury (36% vs 9%, $P = .1218$). More distal deployment of the stented elephant trunk was significantly associated with increased risk of spinal cord injury ($T8.0 \pm 0.6$ vs $T6.5 \pm 1.1$, $P = .0043$). Univariate logistic regression analysis identified a history of abdominal aortic aneurysm repair ($P = .0296$) and the vertebral level of the distal landing zone ($P = .0249$) as significant independent risk factors for spinal cord injury, and only the latter was significant in multivariate analysis ($P = .0396$). The combination of a distal landing zone of T7 or greater and a history of abdominal aortic aneurysm repair was the strongest predictor for spinal cord injury (71% vs 6%, $P = .0047$).

Conclusions: Spinal cord injury after stented elephant trunk deployment might be related to occlusion of the excessive intercostal arteries or thromboembolism. Patients with a history of abdominal aortic aneurysm repair who require extensive deployment of the stented elephant trunk seem to be at a higher risk for spinal cord injury.

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Thoracic aortic aneurysm repair through a median sternotomy with deployment of a stent graft distal to the aneurysmal sac in a fashion similar to the elephant trunk technique¹ has been described as a good option of treatment, especially in patients with high-risk conditions.²⁻⁸ This type of operation, usually termed repair by the stented (or “frozen”) elephant trunk (SET) technique,⁹⁻¹¹ can simplify aortic reconstruction and reduce operative time, bleeding, and respiratory morbidity by avoiding a left thoracotomy. In spite of these advantages, spinal cord injury (SCI) has emerged as an unacceptable cause of morbidity after this type of operation. The incidence of SCI after SET repair seems considerably higher than one might expect, fluctuating from 4.5% to 12.5% in published literature covering more than 10 cases.^{7,8,10,11} However, the underlying mechanisms of this unpredictable complication are still not understood.

Abbreviations and Acronyms

AAA	= abdominal aortic aneurysm
COPD	= chronic obstructive pulmonary disease
CT	= computed tomography
SCI	= spinal cord injury
SET	= stented elephant trunk

Svensson and colleagues¹ recommended that the elephant trunk graft should be shorter than 10 to 15 cm from their experiences with 3 patients with SCI after deployment of a long elephant trunk. Chavan and coworkers¹¹ also recommended that the distal landing zone of the stent graft should be proximal to the 10th thoracic vertebral level for possible reduction in the incidence of SCI. Therefore we can speculate that the excessive occlusion of the intercostal arteries that augment the spinal cord blood flow might be responsible for SCI. Alternatively, thromboembolism to the intercostal arteries that might be provoked by insertion and deployment of SET might be involved in the mechanism of SCI. Recent advances in radiologic methods of aortic evaluation highlighted the relation between the presence of atheromatous plaques in the aortic wall and the probability of postoperative neurologic injury. Tenenbaum and associates,¹² who evaluated the aortic arch in addition to the thoracic descending aorta, have reported that a calcium deposit or clearly visualized area of hypoattenuation at least 4 mm thick adjacent to the aortic wall might become a source of iatrogenic thromboembolism and stroke. For the spinal cord, however, neither clinical nor experimental confirmation of this hypothesis in SET repair has been reported to date.

In this work we present our experience in the management of 25 patients with thoracic aortic aneurysm who were treated by using the SET technique and assess whether postoperative SCI can be predicted by the presence of severe atherosclerosis or by the level of stent graft deployment.

Methods

Patients' Characteristics

From January 1996 through December 2004, 25 patients with thoracic aortic aneurysms underwent replacement of the diseased segment by means of SET repair. Inclusion criteria for this type of operation were related to elderly patients with multiple concomitant diseases, the presence of severe chronic obstructive pulmonary disease (COPD), the presence of a mega-aorta that must be repaired in one stage, the presence of severe atheromatous disease around the distal aneurysmal neck, and previous surgical intervention on the thoracic aorta. Patients with the same diagnosis but in relatively good clinical condition and without previous aortic surgery were selected to undergo conventional graft replacement of the diseased segment.

There were 19 (76%) male and 6 (24%) female patients. The mean age was 73 ± 7 years (range, 54-83 years). Preoperative risk

factors included previous cerebrovascular accident in 11 (44%) patients, hypertension in 21 (84%) patients, ischemic heart disease in 6 (24%) patients, diabetes mellitus in 2 (8%) patients, COPD in 11 (44%) patients, and a history of smoking in 20 (80%) patients. Renal dysfunction, defined as a serum creatinine level of 2 mg/dL or greater, was present in 3 (12%) patients.

Eight (32%) patients had a history of thoracic aortic repair. Only one of them was operated on through a median sternotomy for total arch replacement. Five of the patients underwent descending thoracic artery aneurysm repair, and the other 2 patients underwent thoracoabdominal aortic aneurysm repair. Ten (40%) patients had a history of infrarenal abdominal aortic aneurysm (AAA) repair, and one of them had a history of postoperative transient right lower leg monoparesis (this patient also had left lower leg monoparesis after SET repair).

Twenty-three (92%) patients underwent elective surgical repair of the proximal descending aorta by using the SET technique, and 2 (8%) patients were operated on in an emergency setting. There were 13 (52%) patients with concomitant aortic arch aneurysms, including one case of chronic DeBakey type I aortic dissection that became aneurysmal. In the other 12 (48%) patients, the aneurysm was located exclusively distal to the left subclavian artery. In 3 of these patients, anastomotic pseudoaneurysms developed after previous thoracic aortic repair. Two cases of proximal descending aortic aneurysm evolved to rupture, including 1 patient with acute DeBakey type IIIa aortic dissection. Associated operations included coronary artery bypass grafting in 3 (12%) patients, mitral valvuloplasty in 1 (4%) patient, and bypass grafting to the left subclavian artery in 1 (4%) patient.

The cause was atherosclerosis in 18 (72%) patients, chronic dissection in 5 (20%) patients, medial cystic necrosis in 1 (4%) patient, and Takayasu's disease in 1 (4%) patient.

Surgical Technique

The stent graft for thoracic aortic aneurysm repair by means of the SET technique is assembled from a 5-cm-long Gianturco stent (Cook, Bloomington, Ind) inserted into the distal segment of a Hemashield Gold graft (Boston Scientific, Natick, Mass) and fixed to it by interrupted stitches of polyester thread. The size of the graft depends on the length of the aneurysmal sac and the diameter of the landing zone at the aorta distal to the aneurysmal sac. This is determined by means of preoperative 3-dimensional computed tomography (CT). The diameter of the graft should be 110% of the diameter of the aortic segment chosen as the landing zone. The diameter of the stent depends on the graft diameter. A stent 40 mm in diameter is used for a 30-mm or larger graft, whereas a 30-mm stent is used for a 28-mm or smaller graft. The stent graft is then bound to a curved tube by a chain stitch.¹³

Our surgical protocol for the SET technique is the same protocol that we routinely use in cases of conventional aortic arch repair and has been previously described.^{14,15} An arterial cannula is placed in the proximal ascending aorta or the axillary artery (left, 5; right, 1; bilateral, 3) in case the ascending aorta is not suitable for cannulation. All 3 arch vessels are routinely perfused antegradely. After induction of circulatory arrest of the lower torso when the bladder temperature reaches 22°C, the aortic arch is transected. The stent graft is inserted into the descending thoracic aorta distal to the aneurysmal sac (Figure 1, A). The chain stitch is

Figure 1. Schema of thoracic aortic aneurysm repair by means of the stented elephant trunk (SET) technique: A, SET deployment after opening of the aortic aneurysmal sac; B, repair of a descending thoracic aortic aneurysm by means of the SET technique; C, concomitant reconstruction of an aortic arch and descending thoracic aortic aneurysm by means of the SET technique.

released, and then the stent graft is expanded and fixed to the aortic wall by a balloon catheter advanced and inflated at the distal attachment site. No fluoroscopic monitoring is used during the deployment. The proximal end of this trunk is anastomosed to the proximal neck of the aneurysmal sac (Figure 1, B). When total arch replacement is necessary, a commercially available 4-branched Gelseal (Sulzer Vascutek, Renfrewshire, Scotland) prosthesis is attached to the proximal end of the SET by continuous suturing with 4-0 polypropylene sutures, which includes the aneurysmal wall. After distal anastomosis, a clamp is placed on the branched aortic prosthesis, systemic blood perfusion is resumed through the fourth side branch, and the patient is gradually rewarmed. Proximal aortic anastomosis is then carried out, and coronary blood flow is restored. The remaining 3 branch grafts are anastomosed to the 3 arch vessels in an end-to-end fashion, and selective cerebral perfusion is discontinued (Figure 1, C). Concomitant operations, such as coronary artery bypass grafting, can be performed during either the cooling or rewarming period.

Postoperative Examination

The level of deployment of the distal end of the SET was checked by means of chest radiography. All patients were subjected to postoperative neurologic examination, and brain CT was indicated if a neurologic deficit was detected.

All patients underwent 3-dimensional CT to evaluate the proximal anastomosis and distal attachment site of the stent graft. Information regarding long-term follow-up was obtained during examination of patients at the outpatient clinic or by telephone interview with the patients or their relatives.

The aortic wall quality and the level at which the SET was landed were assessed by means of preoperative CT according to the criteria of Tenenbaum and associates¹² and postoperative chest radiography, respectively, to predict the possibility of postoperative SCI.

Statistical Analysis

All values are expressed as means $\pm$ standard deviation. Statistical analysis was performed with the Statview 5.0 program (SAS Institute Inc, Cary, NC). The Student *t* test was used for comparison of the continuous variables, and a χ^2 test was used for comparison of frequencies between the groups. Survival was estimated by using the Kaplan-Meier method. By using logistic regression, preoperative, intraoperative, and postoperative variables were analyzed to identify risk factors for SCI (see Appendix 1 for variables evaluated). Then a *P* value of less than .10 was defined for selecting variables for entry into the multivariate model.

Results

Spinal Cord Injury

Ischemic SCI was present in 6 (24%) patients who experienced lower limb paraparesis or monoparesis, 3 patients each, including 1 patient with left lower limb monoparesis who had a concomitant stroke. This patient had multiple small cerebral infarctions at the bilateral cerebellum, the bilateral occipital lobe, and the left temporal lobe that did not seem to be responsible for his left lower limb monoparesis. The postoperative CT scan did not provide evidence of fresh intracranial brain injury in the remaining patients with monoparesis. Two patients with monoparesis experienced total recovery.

The distal end of the stent graft was deployed at the T5 level in 3 patients, at the T6 level in 7 patients, at the T7 level in 7 patients, at the T8 level in 6 patients, and at the T9 level in 2 patients. In the group of 6 patients who presented with postoperative SCI, the SET was deployed at the T7 level in 1 patient, at the T8 level in 4 patients, and at the T9 level in 1 patient (Figure 2). There was a significant difference ($P = .0043$) regarding the mean value of the thoracic vertebral level, where the distal end of the SET was deployed between those patients with ($T8.0 \pm 0.6$) and without ($T6.5 \pm 1.1$) SCI.

According to the criteria of Tenenbaum and coworkers,¹² severe atherosclerosis was found in the SET landing zone in 14 patients in our series; among them, 5 (36%) patients had postoperative SCI. In the remaining 11 patients, only 1 (9%) had postoperative SCI. This patient underwent an emergency operation for rupture. The difference between the incidence of SCI among patients with or without severe atherosclerosis was not significant ($P = .1218$, Figure 3).

Univariate logistic regression analysis identified vertebral level of distal landing zone ($P = .0294$) and history of AAA repair (50.0% vs 6.7%, $P = .0296$, Figure 4) as the

Figure 2. Relationship between postoperative spinal cord injury and level of stented elephant trunk deployment at the descending aorta. *T*, Thoracic vertebral level. *Open bar graphs*, Patients without spinal cord injury; *filled bar graphs*, patients with postoperative spinal cord injury.

significant independent risk factors for SCI. Multivariate logistic regression analysis identified only the former as a significant independent risk factor for SCI ($P = .0396$; odds ratio, 5.462; 95% confidential interval, 1.084-27.514). When distal landing zone at T7 or a more distal point and history of AAA repair were combined, this was the strongest significant independent predictor for SCI (71.4% vs 5.6%; $P = .0047$; odds ratio, 5.462; 95% confidence interval, 1.084-571.963; Table 1 and Figure 5; see Appendix 1 for variables evaluated).

Figure 3. Relationship between postoperative spinal cord injury and atherosclerosis of the descending thoracic aorta for distal landing zone. *Open bar graphs*, Patients without spinal cord injury; *filled bar graphs*, patients with postoperative spinal cord injury.

Other Postoperative Complications

There were 3 (12%) hospital deaths. One patient died on the 29th postoperative day after an anaphylactic shock against contrast media during a CT scan. One octogenarian patient who had severe COPD died on the 24th postoperative day because of respiratory failure. The other patient died from a hemorrhagic shock after rupture of his descending aortic aneurysm while waiting for a second operation because the SET was deployed shorter than planned. This was the only death directly related to SET repair. There were 4 (16%) cases of stroke and 2 (8%) cases of left recurrent nerve injury. Prolonged ventilatory support (>72 hours) was required in 3 patients.

Long-Term Follow-up

The mean follow-up was 35 ± 13 months (range, 2-48 months). During the follow-up, 4 patients died. One patient died from unknown cause 20 months after the operation. Another patient died after AAA repair in another institute 14 months after our operation. The other 2 patients died from pneumonia in postoperative months 17 and 44, respectively. Actuarial survival was 70% at 2 years and 60% at 4 years (Figure 6).

Discussion

Although recent advances in the surgical treatment of aortic arch disease have achieved acceptable outcomes, there remains a higher rate of mortality and morbidity in patients with extensive disease and high-risk conditions in relation to comorbidities.^{16,17} Since the report of the pioneer experiences in the management of these high-risk subgroups of patients with SET repair in 1996,^{2,3} several works that mention the advantages of this technique in comparison with conventional graft replacement or endovascular surgery have been published.^{4-8,9-11} In the case of aneurysm or

Figure 4. Relationship between postoperative spinal cord injury and history of previous abdominal aortic aneurysm repair. *Open bar graphs*, Patients without spinal cord injury; *filled bar graphs*, patients with postoperative spinal cord injury.

TABLE 1. Univariate and multivariate logistic regression analysis to identify risk factors for spinal cord injury

Variable	SCI	P value	Univariate		P value	Multivariate	
			OR	95% CI		OR	95% CI
Distal landing zone level	SCI (+): T8.0 $\pm$ 0.6 SCI (-): T6.5 $\pm$ 1.1	.0249	5.153	1.23-21.591	.0396	5.462	1.084-27.514
History of AAA repair	Yes: SCI = 5/10 (50.0%) No: SCI = 1/15 (6.7%)	.0296	14	1.299-150.924	.0606	18.272	0.879-379.876
Distal landing zone level $\geq$ T7 and history of AAA repair	Yes: SCI = 5/7 (71.4%) No: SCI = 1/18 (5.6%)	.0047	5.462	1.084-571.963			

SCI, Spinal cord injury; OR, odds ratio; CI, confidence interval; AAA, abdominal aortic aneurysm.

dissection extending from the distal arch into the distal descending aorta, endovascular deployment of a stent graft is usually a difficult maneuver. Conventional prosthesis replacement can be performed through a sternotomy, thoracotomy, or combination of both. However, distal exposure is not optimal through a sternotomy alone, and the risk of stroke is high through a thoracotomy alone in the presence of severe atheromatous disease. One of the benefits of SET repair, particularly in the case of a previous left thoracotomy, is the avoidance of rethoracotomy, which might present the potential risks of excessive bleeding, prolonged surgical time, and respiratory failure. Furthermore, severe adhesion might prevent adequate mobilization of the distal anastomosis site from a midline sternotomy approach. In all of our patients, left thoracotomy and lung compression, which are hazardous to patients with COPD, were avoided. Stent graft fixation to the descending aortic wall can avoid creation of a distal hand-sewn anastomosis, which can be a difficult maneuver through a sternotomy. When severe atheromatous disease exists around the distal aneurysmal neck, a conventional hand-sewn anastomosis might entail the

great risks of not only massive distal embolization but also excessive bleeding. Furthermore, the proximal anastomosis is performed by means of conventional suture at a level at which endovascular stent graft attachment would be hazardous.

In spite of the benefits mentioned above, this procedure was associated with a high incidence of SCI. From our analysis, the underlying mechanism might be excessive sacrifice of intercostal arteries or thromboembolism. Some cases of postoperative SCI might be related to occlusion of the critical intercostal arteries that perfused the spinal cord by the distal end of the stent grafts. However, it is known that the Adamkiewicz artery enters the vertebral canal between T9 and T12 in 76% of cases and between T7 and T8 in 12% of cases.^{18,19} In our group only 2 patients underwent SET repair extended distally to the T9 level. Therefore it seems reasonable to speculate that extensive sacrifice of intercostal arteries that do not directly supply spinal cord blood flow but augment collateral blood flow might be an underlying mechanism predisposing to SCI. Svensson and colleagues¹ or Chavan and coworkers¹¹ also recommended that extensive deployment of the elephant trunk or SET should be avoided to reduce potential risk of postoperative

Figure 5. Relationship between postoperative spinal cord injury and combination of distal landing zone level at T7 or greater and history of previous abdominal aortic aneurysm repair. Open bar graphs, Patients without spinal cord injury; filled bar graphs, patients with postoperative spinal cord injury.

Figure 6. Kaplan-Meier survival curve after thoracic aortic aneurysm repair by means of the stented elephant trunk technique.

SCI. This speculation was supported by the fact that the risk of SCI was even higher when the SET was deployed extensively in patients with a history of previous AAA repair. Even in the endovascular approach alone, it has been reported that preventive cerebrospinal fluid drainage has been used to reduce the risk of SCI for patients with a history of previous AAA repair.²⁰

Another mechanism might include atheroembolism to the spinal cord.^{12,21,22} Although the difference between the incidence of SCI among patients with or without severe atherosclerosis was not significant, there was a tendency for development of SCI in the former group (36% vs 9%, Figure 3). Except for the case of rupture, the remaining 5 patients with postoperative SCI reported in this series presented with protruding atherosclerotic lesions located at the descending aorta distal to the aneurysmal sac that might be dislodged during stent graft deployment or subsequent to the re-establishment of the aortic blood flow. This speculation is strongly supported by a report from Usui and co-workers.¹⁰ In their 3 patients with postoperative SCI after SET repair, the spinal cord was injured at a level remote from the SET landing zone (lower thoracic, fourth-fifth lumbar, and sacral level), which suggested that an embolic event was responsible for their SCI.

Compared with other alternatives of treatment of thoracic aortic aneurysm, such as endovascular repair, in which the blood flow is not interrupted and the systolic pressure is maintained around its normal value throughout the procedure,²³ the SET technique involves cardiac arrest during deep hypothermia and temporary interruption of systemic blood perfusion during the distal deployment. The inflammatory response to cardiopulmonary bypass and the free radicals originating in the ischemia-reperfusion injury lead to increased capillary pressure and microvascular permeability, producing fluid extravasation in several organs, including the spinal cord.^{24,25} Because the spinal cord sheath, the dura, and the surrounding bony vertebral channel are non-distensible, the spinal cord is subjected to a compartment syndrome,²⁶ which could increase the possibility of SCI. Cerebrospinal fluid drainage might attenuate this negative effect of cardiopulmonary bypass, but at our department, we do not use this method in cases of deep hypothermic circulatory arrest because of the potential risk of intracranial hemorrhage.²⁷ In addition, we used no fluoroscopic monitoring during SET deployment. Therefore the SET was apt to be deployed more distally than when done precisely through the endovascular approach. In another alternative, such as delayed (staged) open surgical repair with a conventional elephant trunk technique,¹ one can reattach the intercostal arteries if necessary. The conventional elephant trunk technique does not manipulate the distal aneurysmal neck, which is a potential source of distal embolization when severe atheromatous disease exists. This might be the reason

that the SET technique has a greater risk of SCI than delayed (staged) open surgical or endovascular repair.

Conclusions

In our relatively elderly patients with several comorbidities, the incidence of SCI after SET repair seemed considerably higher than one might expect. The underlying mechanism might be excessive sacrifice of intercostal arteries that jeopardizes collateral blood flow to the spinal cord or thromboembolic event. A history of previous AAA repair was also an increased risk for SCI. Therefore patients with a history of AAA repair who might require extensive deployment of an SET should be managed by other alternatives to avoid postoperative SCI.

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Appendix 1. Variables evaluated for logistic regression analysis to identify predictors for spinal cord injury

Preoperative variables

Age
Sex
Dissection
Emergency
History of aortic surgery
History of thoracic aortic aneurysm–dissection repair
History of infrarenal aortic aneurysm repair
Chronic obstructive pulmonary disease
History of cerebrovascular accident
Hypertension
Ischemic heart disease
Diabetes mellitus
Chronic renal failure
History of cigarette smoking
Maximum diameter of the aneurysm
Presence of severe atherosclerosis

Intraoperative variables

Concomitant total aortic arch replacement
Concomitant operation
Duration of circulatory arrest
Duration of aortic crossclamping
Duration of selective cerebral perfusion
Duration of cardiopulmonary bypass
Duration of operation
Intraoperative blood loss
Intraoperative transfusion
Axillary artery perfusion

Postoperative variables

Respiratory insufficiency
Acute renal failure
Stroke
Re-exploration for bleeding
Late cardiac tamponade
Duration of intensive care unit stay
Vertebral level of distal landing zone
Hospital mortality