Acta Chir Belg, 2008, **108**, 492-502

The Risk of Spinal Cord Ischemia during Thoracic Aorta Endografting

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Key words. Thoracic aortic aneurysm ; stentgraft ; spinal cord ischemia.

Introduction

Spinal cord ischemia (SCI) is a devastating complication of thoracic aortic surgery and its physiopathology is still poorly understood. Endovascular treatment with stentgrafts for the thoracic aorta (TEVAR) has significantly reduced the morbidity associated to thoracotomy and aortic cross clamping, but the incidence of SCI is still not negligible. We believe that TEVAR provides an opportunity to improve the knowledge of this devastating complication, since it removes the background noise of aortic cross-clamping and intercostal artery reimplantation.

Management of thoracic aorta pathology with endovascular aortic repair had reduced in-hospital mortality, post-operative morbidity and recent series have reported encouraging midterm results. However the incidence of immediate and delayed SCI ranges from 0% and 12% (Table I). The results of three multicenter investigational trials for FDA approval of different thoracic endografts have been recently published with rates of SCI ranging from 2.8% to 8.7% (1-3) (Table II). Moreover these trials fail to demonstrate any statistically significant difference in the incidence of SCI between TEVAR and open repair.

Mechanism of spinal cord injury during TEVAR

The physiopathology of SCI is definitely multi-factorial but is still ill-defined, and many concepts, summarized in Table III, are linked to SCI from both clinical and preclinical studies.

Due to its relatively inaccessible location, vascular anatomy of the spinal cord is still not completely clear and relies on a rather limited number of studies that use post-mortem angiography, micro-angiography and dye injection techniques. Most studies are limited to the arteries and refer to subjects without aortic pathology. Moreover, in the literature there is no real agreement upon nomenclature and this brings even more confusion to an already complex topic. Only recently, advances of CT and MR techniques are allowing a better knowledge of the in vivo anatomic pattern of individual patients (4).

The superficial arteries to the spinal cord include two systems (Fig. 1) :

A) The longitudinal arterial trunks (anastomotic channels between ascending – smaller – and descending branches of neighbouring radicular arteries) :
– Anterior spinal artery (single)
– Posterior or Posterolateral spinal arteries (double)
B) The Perimedullary vascular network or Pial Plexus

The inflow to these arteries includes the vertebral arteries, a variable number of segmental vessels originating from the intercostal and lumbar arteries and the hypogastric arteries. Griepp *et al.* (5) has recently described the "collateral network concept" detailing the redundancies in the blood supply to the spinal cord. However this anastomotic circulation has a large anatomic variability and it greatly depend on the integrity of the anterior spinal artery (6). While the "collateral network" may guarantee adequate vascularization in many instances, this may not always be the case. TEVAR could affect at different levels the inflow arteries of the network and this could explain physiopathology of SCI in many circumstances.

Intentional overstenting of the left subclavian artery during TEVAR in order to gain an adequate proximal aortic neck is performed in many cases. Selective indications to left subclavian artery revascularization have been proposed by several authors with few adverse events reported (cerebrovascular accident, subclavian steal syndrome). However the data from the Talent Thoracic Retrospective Registry demonstrated that occlusion of the left subclavian artery without previous revascularization was significantly associated to stroke ($p = .004$) but not to SCI (7). Recently the data from EUROSTAR registry demonstrated an independent correlation with SCI and the left subclavian artery covering without revascularization ($p = .023$, $OR = 3.9$) (8).

Table I

Data of spinal cord ischemia after TEVAR from principal studies published in literature

Author	Year	N° patient	30-day mortality	Spinal cord ischemia		
				Paraparesis	*Paraplegia*	*Total*
Amabile	2008	67	6 (8.9%)	2 (2.9%)	3 (4.4%)	5 (7.5%)
Khoynezhad	2007	184	18 (9.8%)	4	4	8 (4.3%)
Sandroussi	2007	65	3 (4.6%)	0	4 (6.1%)	4 (6.1%)
Tespili	2007	43	4 (9.3%)	0	0	0
Kawaharada	2007	144	3 (4.2%)	–	–	5 (3.6%)
Rodriguez	2007	324	18 (5.5%)	3 (0.9%)	5 (1.5%)	8 (2.46%)
Buth	2007	606	62 (10.2%)	–	–	15 (2.5%)
Wheatley	2006	158	6 (3.8%)	3 (1.8%)	1 (0.6%)	4 (2.5%)
Weigang	2006	36	0	0	0	0
Criado	2005	180	9 (4.7%)	5 (2.7%)	3 (1.6%)	8 (4.3%)
Cheung	2005	75	2 (3%)	3 (4%)	2 (3%)	5 (6.7%)
Chiesa	2005	103	2 (2%)	2 (2%)	2 (2%)	4 (4%)
Demers	2004	15	1 (2.7%)	0	0	0
Leurs	2004	443	41 (9.3%)	–	–	11(2.4%)
Bell	2003	67	5 (7.4%)	–	3 (4%)	3 (4%)
Ellozy	2003	84	5 (6%)	1 (1.2%)	3 (4%)	4 (4.7%)
Criado	2002	47	1 (2.1%)	0	0	0
White	2001	26	1 (4%)	0	1 (4%)	1 (4%)
Greenberg	2000	25	5 (20%)	2 (8%)	1 (4%)	3 (12%)
Dake	1998	103	9 (9%)	–	–	3 (3%)
Total		2872	202 (7.0%)			93 (3.2%)

Table II

Data of spinal cord ischemia after TEVAR from the three multicenter trials for FDA approval of Gore TAG, Zenith TX2 and Talent endograft

Trial	N° patient	Mortality n (%)	Spinal cord ischemia n (%)		
			Paraparesis	*Paraplegia*	*Total*
Gore TAG	142	2 (1.5%)	3 (2.1%)	1 (0.7%)	4 (2.8%)
Zenith TX2	160	3 (1.9%)	7 (4.4%)	2 (1.3%)	9 (5.6%)
Valor	195	4 (2.1%)	14 (7.2%)	3 (1.5%)	17 (8.7%)
Total	497	9 (1.8%)	24 (4.8%)	6 (1.2%)	30 (6.0%)

Table III

Concepts that are linked to SCI from both clinical and experimental literature

Concept	Authors	Consensus
Influenced by time of aortic cross-clamping	Svensson, Coselli	+++
Influenced by aortic region involved	Crawford, Coselli, Safi,	+++
Influenced by extent of aorta involved	Le Maire, Estera, Svensson	+++
Very rare after chronic thrombosis of intercostal aa.		+++
Distal perfusion	Coselli, Safi	++
Spinal fluid drainage (prevention)	Coselli, Cina, Safi	+++
Spinal fluid drainage (treatment)	Chiesa	++
Avoid steal	Griepp, Kawanishi	++
Reattachment of intercostal arteries	Safi, Wong	++
Preoperative location of ARM (Angio)	Kieffer	+
Evoked potentials	Sandman, Nijenhuis	+

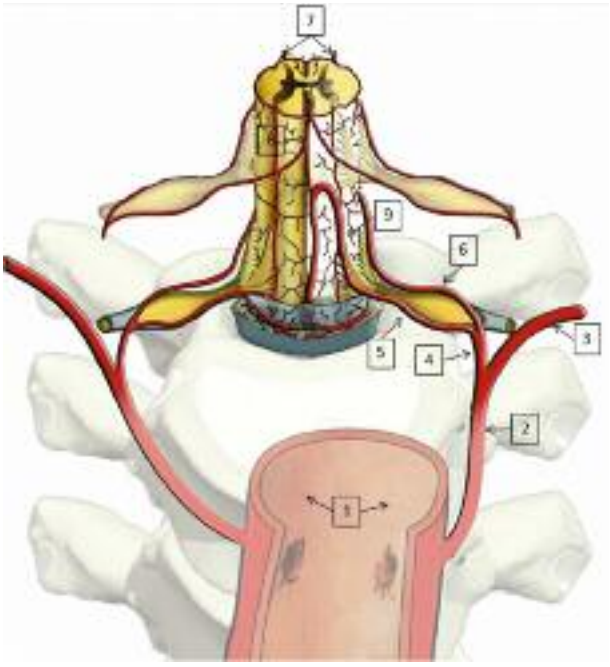

Fig. 1
Schematic view of spinal cord supply. From the aorta arises segmental posterior intercostal arteries (2) that provide a vertebral branch (3) and the nervomedullary artery (4). The nervomedullary arteries (4) divide into constant branches that supply the ventral or dorsolateral surface of the medulla called the anterior (5) and posterior (6) radicular artery respectively. The anterior radicular artery provides one anterior spinal artery (8) and the posterior radicular artery provides two posterolateral spinal arteries (7). One of the anterior radicular artery is always distinctly dominant in calibre nad is therefore termed the great radicular artery of Adamkiewicz (9).

Endoluminal repair avoids aortic cross clamping and its sequelae, however, the intercostal arteries covered by the stent graft cannot be reimplanted. Moreover the extent of segmental artery sacrifice is greater since it includes not only the length of the aneurysm, but also that of the proximal and distal landing zones (Fig. 2). Not surprisingly, the coverage of a thoracic aortic segment longer than 20 cm correlates with SCI (7, 9) as well as the use of longer grafts (10). The EUROSTAR registry revealed that the use of more than three stent grafts correlates with SCI ($p = .041$, $OR = 3.4$) (8).

The segment of aorta covered with endograft could play a role in the pathogenesis of SCI after TEVAR. Univariate analysis of the EUROSTAR registry demonstrated that intercostals arteries at the T_{10} level were more frequently occluded in patients with SCI compared with those without neurologic event ($p = .034$, $OR = 2.98$), but these data have not been confirmed at the multivariate analysis.

The segment of aorta from T_8-L_2 is critical because the intercostal arteries of this tract could feed the Adamkiewicz artery (AKA). The importance of a preoperative identification of the location of the AKA by means of selective angiography before thoracic and thoracoabdominal aortic surgery was demonstrated by Kieffer *et al.* (12). The complexity and invasiveness of the method, however, prevented its widespread diffusion. There is growing evidence that the AKA may, nowadays, be visualized through non invasive methods, such as magnetic resonance angiography or computerized tomography angiography (13, 14). We reviewed a total of 12 relevant studies (13-24) from 2000 to 2008, where the

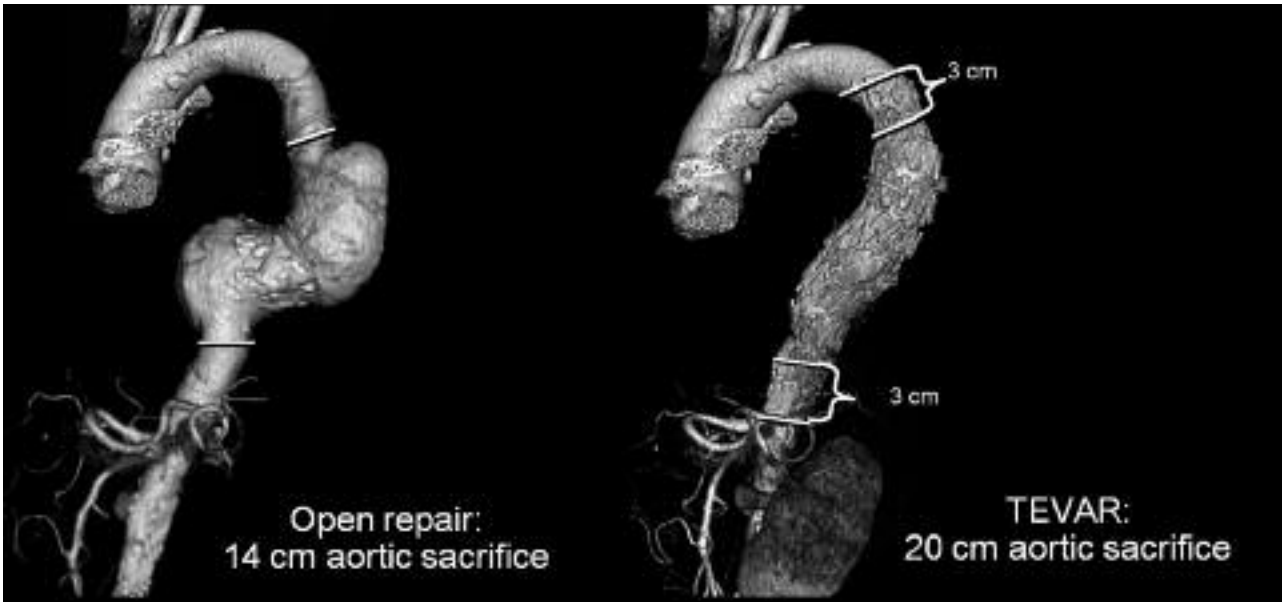

Fig. 2
The extent of segmental aortic sacrifice is greater with TEVAR since it includes not only the length of the aneurysm and but also the proximal and distal landing zones.

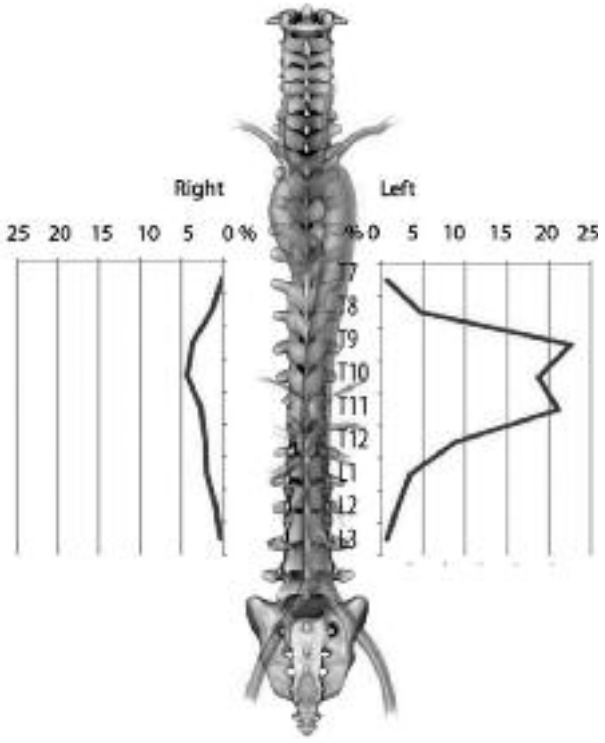

Fig. 3
Percentage of AKA origin level in relation to the intercostal artery, its location and method used. Note the higher left T9 to T12 prevalence.

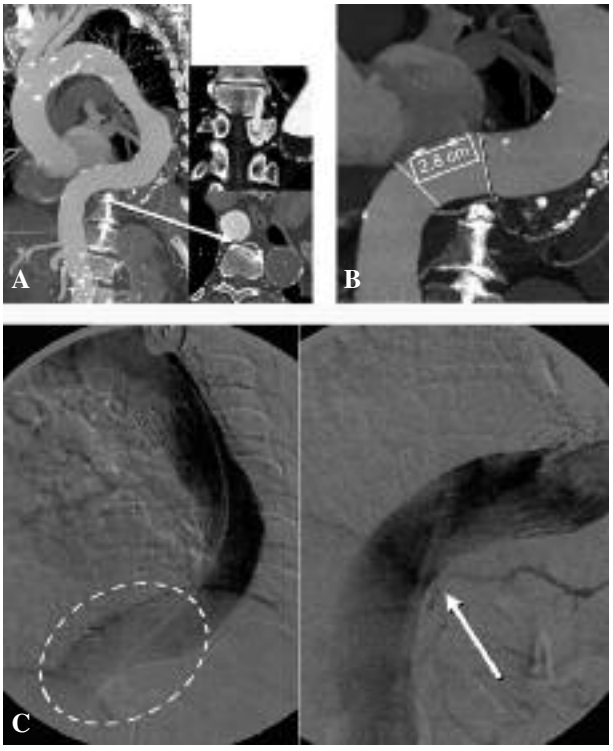

Fig. 4
(A) Preoperative CT scan reconstruction of a descending thoracic aneurysm and identification of an intercostal artery feeder of the Adamkiewicz artery. (B) The critical intercostal artery originates 2.8 cm below the distal end of the aneurysm. (C) Intraoperative angiogram shows successful exclusion of the descending thoracic aneurysm with preservation of the critical intercostal artery.

AKA was visualized through gadolinium-enhanced magnetic resonance or angio computer tomography. These papers studied 514 patients with different thoracic pathology, which underwent a total of 574 exams aimed at the visualization of the AKA. Recognition of the AKA was achieved in 474 out of 574 scans (82.6%,CI 95% 0.795 – 0.857). In particular the origin of the AKA was deemed recognizable in 464 (80.8%) scans. In 385 (82.9%) cases the AKA originated from a left intercostal artery, in 79 (17%) cases it originated from a right intercostal artery. The most frequent level of localization of the intercostal artery feeding the AKA was form T_8 to T_{12} (90.1%) (Fig. 3). If possible, trying to avoid covering the AKA with the stent-graft may have a role in preventing paraplegia. Kawaharada *et al.* (16), among 71 patients with preoperative visualization of the AKA, reported a 9.1% of paraplegia in the subgroup in which the stent-graft covered the intercostal artery feeding the AKA versus a 0% in the subgroup that did not require coverage of the critical intercostal artery. As a consequence of this and his personal experience that focuses on the strong relationship between postoperative SCI and AKA coverage, Kieffer *et al.* (17) indicate open surgery for patients in whom preoperative arteriography revealed the emergency of the AKA from within the aneurysm (Fig. 4).

Open repair of abdominal aortic aneurysm (AAA) requires ligation of lumbar arteries with consequent impairment of the collateral network (10, 27, 28). Previous AAA open repair have been associated with an increased risk of SCI (14.3% vs 1%) (29). Simultaneous open repair of AAA and TEVAR have been associated with an increased risk of SCI in the EUROSTAR registry ($p = .0003$, OR = 7.96) (8).

Recently, Khoynezhad *et al.* (30) demonstrated that the chance of developing SCI was significantly higher in patients with an occluded or excluded hypogastric artery. Similarly, Berg *et al.* (31) observed a significant correlation between emboli ($p < 0.001$) and coil embolisation of hypogastric or lumbar arteries ($p < 0.029$) and the development of SCI in patient with endovascular abdominal aortic repair. Patients requiring an iliac conduit for vascular access for TEVAR have more chance of SCI developing because of possible injury/embolization to the external iliac artery from the stent delivery (30). Rodriguez *et al.* (32) demonstrate that incidence of SCI is statistically associated with retroperitoneal approach for vascular access. They also noted that female gender

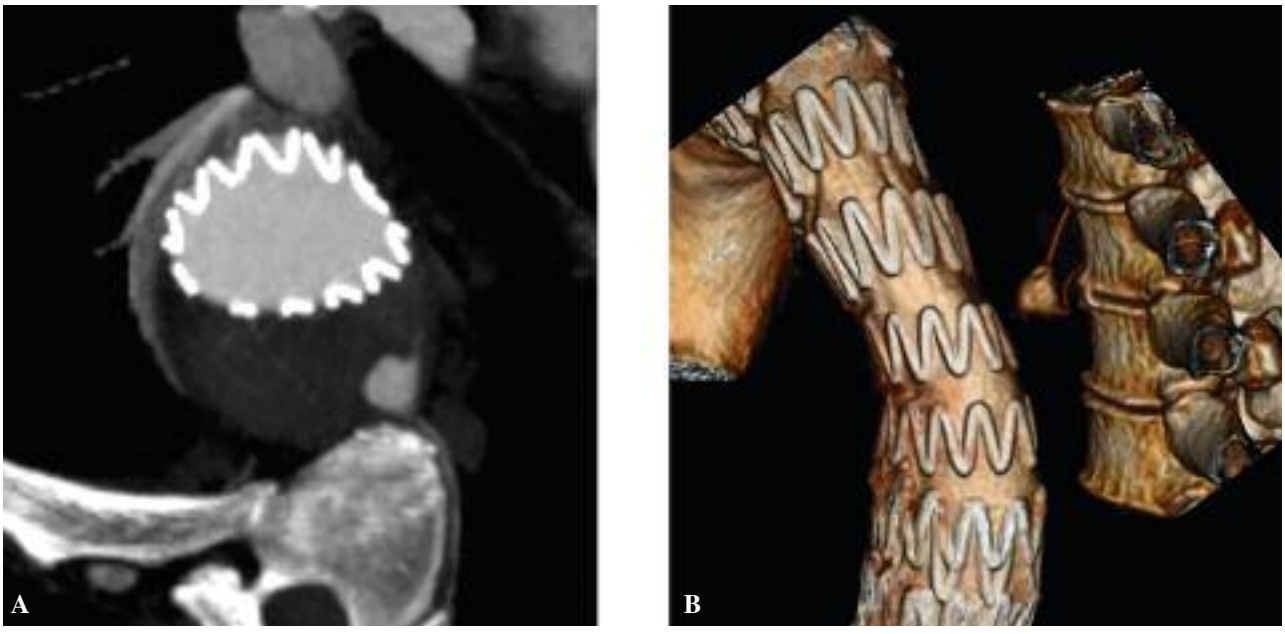

Fig. 5
(A) Postoperative CT scan of a type II entry flow from an intercostal artery. (B) 3D reconstruction showing the inflow and outflow source of the type II entry flow from a pair of intercostals arteries.

had a tendency towards increased risk of SCI possibly because they were more likely to receive a retroperitoneal approach due to small femoral vessels.

Other reports have also described retroperitoneal hematoma combined with external iliac injury as a cause of SCI after endovascular stent repair (33, 34). In these cases the predominant mechanism of SCI is a blood loss greater than 1000 mL (32). Excessive bleeding could lead to episodes of hypotension that have been associated to SCI in our previous published experience (35). We found at univariate analysis that perioperative hypotension, described as a lowest mean arterial pressure (MAP) of < 70 mm Hg, is a significant risk factor.

Despite the collateral network concept may explain physiopathology of SCI in many circumstances, all the different causes underlying the occurrence of SCI after TEVAR have not been fully understood yet, as SCI appears to be related to a complex interaction of several different mechanisms and its understanding represents a key issue for further development of TEVAR.

Different studies demonstrate that most of the SCI cases after TEVAR have a delayed onset. SCI leading to immediate paraplegia is explained by occlusion of a critical feeding artery of the anterior spinal artery, and this is considered the first mechanism of neurologic impairment (36). Delayed SCI may then develop because of episodes of hypotension or subsequent loss of collaterals (36). In particular loss of collateral due to thrombosis within the excluded sac may not be immediate and some collateral circulation between intercostal arteries could be present (i.e. type II endoleak). We can assume that complete thrombosis of the aneurismal sac could interrupt collateral pathways that are still present in the sac making the collateral network insufficient with delayed onset of SCI (Fig. 5). Kieffer *et al.* (37) reported recently a peculiar case of recurrent episodes of transient SCI in a young patient who underwent TEVAR for traumatic injury of the aortic isthmus, probably due to a steal from the collateral circulation between intercostal arteries. The patient began experiencing transient SCI triggered by anteflexion of the trunk, sexual intercourse, and muscular exertion, such as dancing, involving the lower extremities. A type II endoleak was suggested by visualization of the left T_7 artery originating from the stented portion of the aorta. The authors speculated that a possible explanation for transient spinal cord ischemia is that activity involving the abdomen or legs caused steal from a spinal cord territory to which blood flow had already been reduced owing to coverage of the left T_7 artery by stent graft. Notably all symptoms have been resolved after open conversion and reimplantation of left T_7 artery.

San Raffaele University Experience

Patients and methods

We conducted an analysis of data prospectively collected on a computerized database of 206 consecutive patients (176 men, mean age 68.6 ± 10.8 years) undergoing

TEVAR at our institution between January 1999 and April 2007. Etiology included atherosclerotic aneurysm in 166 cases, type B dissection in 21, penetrating ulcer/intramural haematoma in 7, pseudoaneurysm in 6, trauma in 3 and different causes in another three patients. According to Ishimaru's classification (38), the proximal aortic landing zones involved were : Zone 0 in 15 cases, Zone 1 in 13, Zone 2 in 42, Zone 3 in 67 and Zone 4 in 69. In 17 patients, the distal landing zone was located below the celiac axis and therefore defined as a thoraco-abdominal aortic pathology. Thirty-six patients had previous infrarenal aorta open repair that was performed synchronously to TEVAR in four cases ;17 patients had previous open or endovascular repair of TAA.

We employed several different commercially available stent-grafts : 55 Excluder TAG, old and new device (WL Gore and Associates, Inc, Flagstaff, Ariz), 11 Endofit (Endomed, Phoenix,Ariz), nine Talent and Vailant (Medtronic, Santa Rosa, Calif), 126 Zenith TX1 and TX2 (Cook Inc, Bloomington, Ind) and five Relay (Bolton Medical España S.L.U., Barcellona, Spain).

All the procedures were performed in the operating room, using a portable digital C-arm image intensifier with road-mapping capabilities. The procedures were performed under general anesthesia in 139 cases, epidural or subaracnoid anesthesia in 50, and local anesthesia in 17. Cerebro-spinal fluid drainage (CSFD) was instituted in 27 selected patients ; indications were an aneurysm involving intercostal arteries between T8 and L1, the required coverage of a descending thoracic aortic segment $\geq$ 15 cm and, since 2005, previous AAA repair (29). The drainage was inserted postoperatively in all the 11 patients that developed SCI-related deficits.

In 180 cases (87.4%) the common femoral artery, exposed through an inguinal incision, was used as access vessel. A direct arterial puncture without a conduit for an aorto-iliac approach was used in 21 cases (10.2%) and in five patients (2.4%) the device was inserted through an infra-renal aortic graft during combined surgery for synchronous AAA.

TEVAR for zone 0 and 1 or for thoraco-abdominal aorta cases was accomplished with an associated supra-aortic or visceral vessel debranching as previously reported (39, 40). In case of aortic arch involvement (Zone 0, 1 and 2), intentional overstenting of the left subclavian artery (LSA) was performed in 50 cases. In 20 cases (two cases of Zone 0, four cases of Zone 1, 14 cases of Zone 2), we performed a revascularization of the LSA. The latter was deemed necessary when LSA supplied coronary circulation through a left internal thoracic artery-to-left anterior descending coronary artery bypass grafting, when the controlateral vertebral artery was inadequate, in young patients, left handed professionals or to improve spinal cord collateral circulation (since 2005) in cases of previous abdominal aortic surgery.

In cases of involvement of thoraco-abdominal aorta, we performed a visceral aorta debranching as previously described (40).

Patients were stratified and results described according to the reporting standards for endovascular aortic repair (41). Different types of endoleak were classified according to contrast CT scan findings (42).

SCI was assessed by an independent neurologist and graded according to the Modified Tarlov Scale. Paraplegia or paraparesis observed immediately or upon awakening were defined as immediate. Deficit occurring after a period of normal neurologic function were classified as delayed. We investigated the role of the following factors as possible predictors of spinal cord ischemia : demographic factors classified according to Society of Vascular Surgery Suggested Reporting Standards, perioperative cardiac risk index according to the Goldman revised cardiac risk index, previous abdominal or thoracic aorta surgery, etiology, proximal aortic landing zone, intentional coverage of left subclavian artery without revascularization, coverage of critical intercostal arteries (T8 to L1), preoperative CSFD, length and type of device used, intraoperative and postoperative lowest mean arterial pressure < 70 mmHg.

Data are shown as number (%) for categorical variables or as median, 1st quartile and 3rd quartile (Q1-Q3) and mean for continuous variables, as they did not show a gaussian distribution. Comparisons of categorical variables among different classes of patients have been performed by means of the Chi-square test or the Fisher exact test. Continuous variables have been compared by the Mann-Whitney test or Kruskal-Wallis test. Univariate and multivariate analyses were conducted for risks factors associated to spinal cord ischemia and odds ratio and 95% confidence limits (95% C.I.) are shown. Analyses were performed using SAS 8.02 software (SAS Institute Inc, Cary, NC-USA) and SPSS/ PC+ 15.0 statistical software (SPSS, Inc, Chicago, III) for Windows (Microsoft, Redmond, Wash).

Results

Overall, a primary technical success was achieved in 195/206 cases (94.7%). One patient died intraoperatively (43). Ten patients (4.9%) had a residual type IA endoleak that was left untreated because the aortic proximal neck was deemed inadequate for further endovascular procedures.

An initial (30 day) clinical success was obtained in 185/206 cases (89.8%) with a mortality rate of 5.3%. Causes of death included : intraoperative graft migration in one case, stroke in three cases, multiorgan embolization in one case, multiple organ failure in four cases, bleeding and acute respiratory failure in one case each. One patient was electively submitted to a successful

Table IV

Principal characteristics of patients with spinal cord ischemia in "Vita-Salute" University experience

Case	Zone	Previous aortic surgery	Preoperative CSFD	Onset (days)	Tarlov at onset	Tarlov at discharge	Outcome
#1	3	no	no	Immediate	0	4	Discharged
#2	4	no	no	Immediate	0	1	Late death (3 m.)
#3	4	Previous AAA	no	Immediate	0	0	In-hospital death
#4	2	Previous AAA	no	Immediate	0	0	In-hospital death
#5	3	Previous AAA	yes	Immediate	3	4	Discharged
#6	TAAA	Previous TAAA	no	Delayed (3)	3	5	Discharged
#7	4	Pervious AAA	no	Delayed (2)	2	5	Discharged
#8	4	no	no	Delayed (1)	1	5	Discharged
#9	2	no	no	Delayed (4)	4	5	Late death (9 m.)
#10	3	AAA syncronous	no	Delayed (1)	4	5	Discharged
#11	3	Untreated AAA	yes	Delayed (2)	3	3	Discharged
#12	3	no	no	Delayed (41)	0	5	Discharged
#13	4	no	no	Delayed (3)	3	4	Discharged

surgical conversion 2 weeks after the procedure because of a total collapse of the graft.

SCI was recorded in 13/206 cases (6.3%) : four cases were immediate and more severe and nine cases had a delayed onset (up to 35 days after the procedure). Among patients with immediate SCI, 2 died in-hospital, 1 had a partial recovery and 1 did not improve. Among those with delayed SCI, after CSFD, steroids administration and arterial pressure pharmacologic adjustment, six patients recovered completely, 2 had a partial improvement and one case did not improve (Table IV).

At a mean follow-up of 11 ± 8 months, one patient who had had a delayed moderate SCI that completely resolved, died of pneumonia 9 months after the procedure and one patient with immediate severe and improved SCI, died three months later of sepsis following urinary infection.

Patients demographics and risks factors, cardiac risk index, etiology, proximal aortic landing zone, intentional coverage of left subclavian artery without revascularization, coverage of critical intercostals arteries (T8 to L1), preoperative CSFD and length and type of device used were not found to be related to SCI.

Univariate analyses showed perioperative lowest mean arterial pressure < 70 mmHg (p = .002) and previous AAA surgery (p = .004) to significantly predict the occurrence of paraplegia. Multivariate analysis also identified perioperative lowest mean arterial pressure < 70 mmHg (p < 0.0001) (odds ratio = 39.038 ; 95% CI : 8.907 – 171.107) and previous AAA surgery (p = 0.0380) (odds ratio = 4.894 ; 95% CI : 1.092 – 21.940) as independent risk factors (Table V).

Strategy of diagnosis, treatment and prevention

Early diagnosis of SCI is crucial to improve the outcome. In several cases, SCI was reversed with prompt and aggressive treatment.

Monitorization of motor-evoked and somatosensory-evoked potentials can detect intraoperatively cases of SCI (44). Cheung *et al.* (44) reported resolution of SCI early detected with somatosensory-evoked potentials after treatment with systemic pressure augmentation and CSFD. Bafort *et al.* (45) proposed to perform before stent-graft deployment an aortic occlusion test to detect SCI using multilevel somatosensory evoked potentials in order to identify patients at high risk of SCI. Ishimaru *et al.* (46) proposed to perform a predeployment testing with a retrievable stent-graft under evoked spinal cord potentional monitoring in order to identify patients suitable for TEVAR with reduced risk of SCI. However their results have not been reproduced by others.

Biochemical markers in blood and cerebro-spinal fluid could be useful to detect SCI early. Increase of C-lactate and C-S100 in cerebro-spinal fluid have been demonstrated in case of SCI with acceptable sensibility and specifity (47). Particularly C-lactate seems to increase earlier than S-100 (47). However widespread

Table V

Analysis of risk factors for spinal cord ischemia in "Vita-Salute" University experience

Risks Factors	No Paraplegia (%)	Paraplegia (%)	P*
Overall	193	13	
Male	164 (85%)	12 (92.3%)	
Age (years)	69,0 ± 10,2	72,4 ± 5,5	NS
Cardiac risk index			
I	131 (67.9%)	7 (53.8%)	NS
II	37 (19.2%)	2 (15.4%)	NS
III	23 (11.9%)	3 (23.1%)	NS
IV	2 (1.0%)	1 (7.7%)	NS
Hypertension			
0 (diastolic < 90 mmHg)	75 (38.9%)	4 (30.8%)	NS
1 (easily controlled, single drugs)	52 (26.9%)	4 (30.8%)	NS
2 (requires 2 drugs)	42 (21.8%)	3 (23.1%)	NS
3 (> 2 drugs or uncontrolled)	25 (13%)	2 (15.4%)	NS
Diabetes			
0 (none)	130 (67.4%)	5 (38.5%)	NS
1 (adult onset, diet controlled)	45 (23.3%)	8 (61.5%)	NS
2 (adult onset, oral medication-controled)	8 (4.1%)	0	NS
3 (adult onset, insulin controlled)	6 (3.1%)	0	NS
4 (juvenile onset)	4 (2.1%)	0	NS
Smoking			
0 (none ; abstinence > 10 yrs)	91 (47.2%)	7 (53.8%)	NS
1 (none ; abstinence 1-10 yrs)	65 (33.7%)	3 (23.1%)	NS
2 (< 1 pack/day or abstinence > 1 yrs)	26 (13.5%)	3 (23.1%)	NS
3 (current 1 ≥ pack / day)	11 (5.7%)	0	NS
Hyperlipemia			
0 (within normal limits for age)	127 (65.8%)	5 (38.5%)	NS
1 (mild elevation, diet controlled)	16 (8.3%)	3 (23.1%)	NS
2 (types II, III, or IV, strict diet control)	27 (14.0%)	3 (23.1%)	NS
3 (requires drug control)	23 (11.9%)	2 (15.4%)	NS
*Pulmonary status**			
0	110 (57%)	4 (30.8%)	NS
1	39 (20.2%)	6 (46.2%)	NS
2	31 (16.1%)	3 (23.1%)	NS
3	13 (6.7%)	0	NS
ASA score			
1	0	0	NS
2	20 (10.4%)	0	NS
3	130 (67.4%)	10 (76.9%)	NS
4	43 (22.3%)	3 (23.1%)	NS
5	0	0	NS
*Renal status***			
0	145 (75.1%)	8 (61.5%)	
1	37 (19.2%)	4 (30.8%)	
2	9 (4.7%)	1 (7.7%)	
3	2 (1.0%)	0	
Thoracic pathology			
atherosclerotic aneurysm	154 (79.8%)	12 (92.3%)	NS
post-traumatic aortic rupture,	3 (1.6%)	0	NS
aortic type B dissection	20 (10.4%)	1 (7.7%)	NS
penetrating ulcer/intramural haematoma	7 (3.6%)	0	NS
pseudoaneurysm	6 (3.1%)	0	NS
others	3 (1.6%)	0	NS
Previous AAA surgery	31 (16.1%)	5 (38.5%)	= .0036
Previous TAA surgery	16 (8.3%)	1 (7.7%)	NS
Proximal landing zone			
zone 0	15 (7.8%)	0	NS
zone 1	13 (6.7%)	0	NS
zone 2	40 (20.7%)	2 (15.4%)	NS
zone 3	59 (30.6%)	5 (38.5%)	NS
zone 4	50 (25.9%)	5 (38.5%)	NS
TAAA	16 (8.3%)	1 (7.7%)	NS
Intentional coverage of LSA without revascularization	49 (25.4%)	1 (7.7%)	NS
Coverage of critical intercostals arteries (T8 to L1)	68 (35.2%)	4 (30.8%)	NS
Preoperative CSFD	25 (13.0%)	2 (15.4%)	NS
Device used			
Excluder TAG	54 (28%)	1 (7.7%)	NS
Endofit	11 (5.7%)	0	NS
Talent and Vailant	8 (4.1%)	1 (7.7%)	NS
Zenith TX1 and TX2	116 (60.1%)	10 (76.9%)	NS
Relay	4 (2.1%)	1 (7.7%)	NS
Length of thoracic coverage	165 ± 38 mm	170 ± 30 mm	NS
Intraoperative and postoperative lowest MAP < 70 mmHg	12 (6.2%)	9 (69.2%)	<.0001

* Pulmonary status : 0 = asymptomatic, normal chest X-ray, pulmonary function test (PFT)20% of predicted ; 1 = asymptomatic or mild dyspnea on exertion, mild X-ray parenchymal changes, PFT65 to 80% of predicted ; 2 = between 1 and 3 ; 3 = vital capacity less than 1.85 L, FEV less than 35% of predicted, maximal voluntary ventilation less than 28 l/min or less than 50% of predicted, PCO greater than 45 mmHg, supplemental oxygen use necessary or pulmonary hypertension.

** Renal status : 0 = no known renal disease, serum creatinine < 1.5 mg/dl, creatinine clearance greater than 50 ml/min ; 1 = creatinine 1.5-3.0 mg/dl, clearance 30-50 ml/min ; 2 = creatinine 3.0-6.0 mg/dl, clearance 15-30 ml/min ; 3 = creatinine > 6.0 mg/dl, clearance < 15 ml/min or on dialysis or with transplant.

use of this marker in clinical practice is limited because the time to obtain results from the laboratory are still too long.

As discussed in the previous section different risk factors could affect the spinal cord blood supply and some of them are clearly modifiable.

The use of intentional coverage of the left subclavian artery without revascularization should be limited at emergency cases (i.e. isthmic rupture) and routine revascularization of the left subclavian artery should be performed in high percentage (up to 80%) of elective cases.

The extent of thoracic aortic pathology and consequent extent of aortic coverage can not be modified, however preoperative identification of critical intercostals arteries feeding the AKA could help accurate planning in order to avoid unnecessary coverage of critical intercostals, especially at the level of the aortic neck (Fig. 4).

Synchronous thoracic and abdominal aortic pathology should be treated in a staged fashion, avoiding simultaneous repair, in order to allow the development of collaterals for spinal cord blood supply (10, 35). During staged procedures, the infrarenal AAA repair, either with open or endovascular treatment, should be carried out with preservation of hypogastric arteries with selective bypass or branched endograft if needed.

Many patients eligible for TEVAR may present contraindications to a peripheral vascular access for iliofemoral occlusive disease, small size or excessive tortuosity of the vessels. Despite evolution of stent-grafts, the delivery systems remain large (20 to 25 F). In the multicenter investigational trials 9.4% to 21.1% of patients required access proximal to the common femoral artery to gain an adequate access site (1-3). Notably in these trials, higher rates of morbidities are related to access inadequacy, with consequent risk of aorto-iliac injury, hypotension and retroperitoneal haematoma that may increase the risk of SCI. Different surgical techniques (48) have been reported to gain an appropriate access site and improve technical success with an associated low morbidity/mortality rate.

Perioperative hypotension with consequent spinal cord hypoperfusion appears in different studies to be a major determinant of immediate and delayed-onset SCI. For this reason maintaining an adequate intra and postoperative systemic pressure is crucial to prevent paraplegia. Thoracic endografts, and particularly those of the earlier generation, are associated with specific technical complications. Older stent-grafts were not firmly anchored to the delivery systems and the wind-socket or parachute effect during deployment of the stent graft mandated a period of asystole or profound hypotension to allow safe and precise deployment. Nowadays technical improvements in the stent-graft and delivery systems allow safe and precise deployment at normal systemic blood pressure. An errant deployment may result in a period of aortic occlusion comparable to surgical cross-clamping , and restoration of aortic patency after deployment completion may cause a spinal cord reperfusion injury (34).

We demonstrated that a mean arterial blood pressure > 70 mmHg should be maintained during the postoperative course in order to avoid SCI. Although no complications were associated with arterial pressure augmentation, the risk of haemorrhage as a consequence of arterial pressure augmentation is presumably lower after TEVAR, where no major vascular anastomoses are present. In cases of SCI, Cheung *et al.* (44) suggested to employ volume expansion and vasopressor therapy in order to obtain and increase of mean arterial pressure ($\geq$ 85-100 mmHg). Arterial pressure augmentation may also be particularly important for the treatment of autonomic dysfunction or neurogenic shock associated with SCI.

CSFD has been demonstrated to reduce the incidence of SCI during open thoracic and thoracoabdominal aortic repair (49). Routine preoperative insertion of CSFD during TEVAR has not been used in most centers, including ours, due to the risks related to its use, the requirement of postoperative care, monitorization and horizontal bed rest, and the discomfort associated with its insertion in patients treated under loco-regional anesthesia. When the CSFD is inserted, it is advisable to maintain spinal cord pressure below 10 cm H_20, with cerebral spinal fluid CSFD for at least 48 hours for patients whose lesions require extensive coverage of the descending thoracic aorta or those with previous abdominal aortic repair (9, 10, 35, 36). While there is not enough evidence to suggest a routine use of CSFD during TEVAR, it is absolutely clear that its timely use together with systemic blood pressure optimization and steroid medication have the potential to improve or even cure SCI symptoms after TEVAR (10, 35).

Conclusions

Despite the employment of endovascular techniques, the rate of SCI after treatment of thoracic aortic pathology remained unchanged over the time. In our experience most cases of SCI are delayed and related to hypotension or previous AAA repair. They are clearly treatable by different means that concur to improve indirect spinal perfusion through collateral circulation. SCI should be managed promptly and aggressively due to its reversibility. Ongoing technical improvements of non-invasive diagnostic modalities will allow hopefully a preoperative assessment of the spinal cord vascular network and a better planning of thoracic aorta stent-graft repair.

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