Eur J Vasc Endovasc Surg (2009) **37**, 654–660

REVIEW

Prevention of Paraplegia during Thoracoabdominal Aortic Aneurysm Repair

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Submitted 27 October 2008; accepted 21 February 2009
Available online 08 April 2009

KEYWORDS
Aneurysm repair;
Paraplegia;
Prevention of paraplegia;
Hybrid repair;
Aneurysm stenting

Abstract Paraplegia affects up to 22% of patients undergoing thoarcoabdominal aneurysm surgery, producing long-term morbidity and a significant burden to healthcare. This article discusses the mechanisms that may lead to paraplegia during open and endovascular repair from an anatomical and physiological perspective. There are many adjuncts that must be considered to reduce the risk of spinal cord injury, such as revascularisation of intercostal arteries, maintenance of high mean blood pressure, spinal cord drainage and cooling. These adjuncts are discussed, highlighting the evidence available for each method and the practical ways in which they may be used.

Introduction

One of the most feared complications of thoracoabdominal aneurysm repair is paraplegia following seemingly successful surgery. Very few vascular centers around the world have conquered this threat, and neurological injury after conventional open repair occurs in up to 22% of patients after type II repair.[1] Paraplegia rates are often diluted into a wider group of patients – such as thoracic repair[2] and type IV repair[3] – in whom the risk is reduced. Although the anatomy and physiology of the spinal cord are well studied, the complex mechanisms regarding the pathology of this condition remain poorly understood. Paraplegia results not only in severe physical disability, but is also associated with decreased survival rates.[4] There is much debate over the best methods to reduce the rate of paraplegia and this article studies the strategies employed by surgeons.

Anatomy of the Spinal Cord

There is a need to understand the anatomy of the spinal cord in order to get to grips with the fundamental problems encountered when attempting to prevent paraplegia during thoracoabdominal aneurysm surgery. The supply to the cord is via the anterior spinal artery and two posterior spinal arteries. These in turn are supplied by segmental radicular arteries that are small branches of the cervical, thoracic and lumbar vessels. Thus, back bleeding from an intercostal

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1078-5884/$34
doi:10.1016/j.ejvs.2009.02.008

artery into the open aorta implies a patent radicular artery but if this vessel was occluded, back bleeding could still occur from the intercostal supply of the rib rather than the spinal radicular artery.

The largest of the radicular arteries is the artery of Adamkiewicz, often given off from the T10 level but varying in position from T7 to L4. This artery supplies the conus, but has a poor connection with the superior portion of the spinal cord. It is given off by the left intercostal or lumbar artery in over 75% of patients[5] and is recognised by its characteristic hairpin bend. The use of selective arteriography is virtually abandoned as it is cumbersome and carries a non-negligible risk of embolization. With new imaging techniques, this artery may be identified in the majority of patients using computerized tomography and magnetic resonance scanning.[6]

The radicular vessels are of great importance in determining an adequate supply of blood to the cord. From the vertebral arteries, just proximal to the formation of the basilar artery, a longitudinal anterior spinal artery is formed which runs uninterrupted along the cord and anastomoses with all other radicular divisions. The two posterior spinal arteries arise from the posterior inferior cerebellar arteries, that are similar in nature to their anterior counterparts but there is usually a rich networking of smaller arteries that interlink these two posterior vessels. There is very little communication between the anterior and posterior spinal networks so that anterior spinal artery occlusion causes ischaemia of the anterior horns and paralysis.

The segmental blood supply to the longitudinal anterior spinal vessels is supplemented by collaterals: in the caudal segments from the lateral sacral, middle sacral, iliolumbar and lumbar arteries. These radicular arteries are well represented in the cervical spine but poorly represented in the lumbar spine. From an anatomical point of view therefore, the sacrifice of the intercostal arteries during a thoracic aorta repair could be justified. However, if an extended thoracoabdominal aortic repair is planned, preservation of blood flow from the lumbar arteries is important.[7] Lumbar artery ligation during previous infra-renal aneurysm repair is an independent risk factor for the development of paraplegia after thoracic or thoracoabdominal aortic aneurysms repair.[8]

Adjuncts and Ancillary Techniques during Surgical Repair

Revascularistion of spinal cord

Given the delicate nature of the arterial supply to the anterior spinal cord it seems logical to attempt to revascularize dominant supplying arteries. Indeed it has been shown in retrospective series that re-implantation of significant patent arteries is associated with lower paraplegia rates. Revascularization of arteries around the T11/T12 level may well be most important in reducing the risk of cord ischaemia.[9] However, if the radicular branch, arising from the segmental posterolateral aortic branch that is revascularised, is small or occluded then a great deal of time may be spent unintentionally revascularising an intercostal muscle. Some information may be provided on the need for revascularization and risk of cross-clamping by pre-operative imaging of the collateral circulation of the cord. Using magnetic resonance imaging, the presence of a collateral circulation has been shown to be 97% predictive for stable intra-operative spinal cord function when measured by motor evoked potentials.[10]

Although revascularization of prominent thoracic arteries is widely practiced during thoracoabdominal aortic surgery the problem of spinal cord ischaemia still exists. In our experience there are cases where successful revascularization of a dominant intercostal artery with a patent functioning graft none the less results in profound paresis. A view of the pathological cause of spinal cord ischaemia that only takes into account the anatomical arterial supply of the spinal cord is simplistic and other factors need to be taken into account.

Not all surgeons believe that intercostal artery revascularisation is of paramount importance. Some argue that without profound hypothermia of the cord, intercostal re-implantation jeopardizes spinal cord blood flow from back bleeding or balloon obstruction of afferent collateral vessels. Acher[11] describes a technique of thoracoabdominal aneurysm repair with no intercostal artery revascularisation, sewing off the origins of these vessels immediately the aorta is opened. This technique, combined with expedient surgery and cardiovascular stability has produced results that are impressive with regard to spinal cord ischaemia. He believes that by suture ligation of these vessels the flow of blood is directed to the spinal cord by collateral vessels and the need for revascularisation is abolished. Biglioli's approach involves clipping the intercostal arteries from the outside of the thoracic descending aorta before aortic cross-clamping, with no intercostal or lumbar artery reattachment to the graft, again with comparable results to that of Acher.[12] The literature is further confused by including all thoracoabdominal aneurysms when type II aneurysms have a significantly greater risk of paraplegia than types III and IV. In type IV aneurysm repair, for example, the paraplegia rate is close to that of infra-renal repair.[1]

In addition to revascularization of the intercostal vessels, it is also important to consider the superior and inferior supply to the cord via the subclavian arteries and internal iliac network. Revascularisation of the internal iliac arteries should not only be considered in the context of buttock ischaemia but also in an attempt to maintain adequate spinal perfusion. The internal iliac artery should be maintained on at least one side and needs careful consideration in the case of common, and internal, iliac aneurysms as well as in cases where a uni-iliac stent graft is placed. The left subclavian artery has achieved prominence in the case of stent grafting. Often a secure landing zone for a thoracic stent can only be achieved by covering the origin of the left subclavian artery. If this is combined with coverage of a long length of aorta then revascularization of the subclavian artery either by carotid subclavian transposition or bypass should be mandatory.

Reducing spinal cord ischaemic time

Whilst successful revascularisation of the segmental vessels supplying the spinal cord seems important, reduction in ischaemia time is also of great value in reducing paraplegia rates. Large retrospective series have shown that the duration of aortic cross-clamping is intimately related to the risk of neurological complications.[13,14]

This was recognised early on in the history of thoracoabdominal aneurysm repair.[15] Crawford developed the ''clamp and sew'' technique which consisted of three primary principles of aortic surgery: the use of a Dacron tube graft, a simple inlay technique to revascularise visceral and renal arteries and a short cross-clamp time. Reduction of aortic cross-clamp times along with these other methods vastly improved the results of thoracoabdominal aneurysm repair. During this ''clamp and sew'' era in Houston, aortic cross-clamp time was the most important predictor of immediate post-operative neurological deficit along with the extent and type of aortic aneurysm repaired, the presence of aortic rupture, patient age, and renal dysfunction.[13] The incidence of paraplegia was noted to be 27% in those with an aortic cross-clamp time of over 60 min, falling to 8% with those that have expedient surgery and clamp times of less than half an hour.

Given this necessity for short periods of ischaemia, utilising left heart bypass, to set up retrograde perfusion of the spinal arteries was developed. The left atrium is cannulated through the left inferior pulmonary vein or atrial appendage. If left heart bypass is employed, serial clamping of the aneurysm may be achieved to allow retrograde perfusion of all the vital organs and spinal cord feeding vessels during the proximal anastomosis. Coselli[16] has reported a large group of over 1000 patients who had thoracoabdominal aneurysm repairs, comparing those where left heart bypass was employed with a historical cohort. In patients with type II thoracoabdominal aneurysms, those undergoing surgery with bypass had a incidence of paraplegia or paraparesis of 4.5%. This was significantly lower than the rate of 11.2% in those that did not. Interestingly this holds true even though the aortic clamp times are longer when bypass is utilised. Although this method seems useful for type II aneurysms, it does not appear to be of benefit universally, especially in type I disease.[17,18] Left heart bypass has its own problems, not only from increasing aortic clamp times, but also from the necessary cannulation of the heart and extracorporeal circulation which may cause extensive coagulopathy in patients with an extensive area of surgical dissection. In addition, serial clamping of the aneurysm is not always possible, especially in large type II aneurysms.

In type II and III aneurysms the use of left heart bypass can be supplemented by selective perfusion of the coeliac trunk, superior mesenteric and both renal arteries after cross-clamping and opening of the abdominal aorta. Four Pruitt catheters (9 Fr.) are connected as an ''octopus'' to the extracorporal circulation to provide flow into the visceral vessels whilst the lower anastomoses are fashioned.[19] Initially excellent results were published from series employing the octopus, especially after a second pump was employed in the system to increase flow rates into the visceral segments. However, the rates of spinal cord dysfunction are not abolished by this technique and cannulation of each visceral vessel further complicates the procedure and carries a risk of thrombosis and/or dissection. Nevertheless this technique seems to be associated with greatly improved paraplegia rates.

Spinal cord hypothermia

Further protection of the spinal cord tissue may be gained by cooling of the epidural space during ischaemic periods. Davison et al.[20] demonstrated regional hypothermia of the spinal cord with an infusion of iced (4 °C) saline solution. This was administered into an epidural catheter while monitoring cerebral spinal fluid (CSF) temperature, which reached 25–28° during cross-clamping and returned to near core temperature levels by the end of the procedure. Cambria[14] has reported good results with regional hypothermia. In his series of 334 thoracoabdominal aneurysm repairs, neurological injury to some degree occurred in 11.4%. Epidural cooling reduced the risk in patients with types I-III TAA from 19.8% to 10.6%.

In our experience, cooling of the epidural space alone is hard to achieve quickly and may complicate the procedure unnecessarily. The same effect may possibly be achieved by allowing the patient to cool to 33 °C during the procedure with active warming on completion.

Cerebrospinal fluid drainage

The perfusion pressure of the neurological tissue within the spinal cord is a direct function of the mean arterial pressure and the cerebrospinal fluid pressure (CSF). CSF production rises during ischaemia causing increased pressure immediately after cross-clamping and late spinal cord oedema after an ischaemic insult may also cause a significant pressure increase. If the CSF pressure is allowed to rise, this may well render the neurones relatively ischaemic. Coupled with a fall in spinal perfusion pressure, this mechanism may well be one of the major causes of spinal cord ischaemia. Drainage of CSF to reduce the pressure is a widely practiced technique. This is commonly achieved by placing the patient in the lateral position and insertion of a Tuohy needle into the subarachnoid space, confirmed by free flow of CSF from the needle. Through this a spinal drain may be inserted into this space. The CSF pressure may be monitored and the pressure maintained at 10 mmHg by free drainage in an open system. We maintain patients in the horizontal or 30° head up position; with the spinal drain, set up as an open system, 13 cm (13 cm water equates to 10 mmHg) above the external auditory meatus. This allows the spinal fluid to drain when the pressure rises above 10 mmHg. Clearly the drain must be clamped when moving and sitting and requires regular monitoring to maintain patency. This method avoids the need for pressure monitoring which may be inaccurate and falsely reassuring.

Coselli[21] has performed a randomised controlled trial of cerebrospinal fluid drainage in 145 patients who underwent type I or II thoracoabdominal aneurysm repair. The protocol for the control group included heparinization, left heart bypass, and reattachment of patent critical intercostal arteries. A second group received this standard protocol as well as CSF drainage, with a target pressure of 10 mmHg, which began at anaesthetic induction, continued for 48 h after surgery. The two groups had broadly similar risk factors and a comparable aortic clamp time and left heart bypass time as well as a similar number of intercostal arteries that were grafted. There was a significant difference in paraplegia rates; 13% in the control group and 2.6% in the CSF drainage group. This is an 80% reduction in the relative risk of post-operative deficit.

Safi[22] provide useful information of this subject in a study of patients who develop late onset spinal dysfunction. All patients in his study who developed spinal cord paralysis showed an acute rise in cerebrospinal fluid pressure before the onset of symptoms. Interestingly half of the patients who developed spinal symptoms had a period of blood pressure instability immediately beforehand. There are also reports of immediate reversal of neurological deficit with spinal catheter insertion following thoracic aortic repair which adds to the argument that this method is important in reducing the incidence of spinal cord ischaemia.

However, this useful adjunct is not without risks as highlighted by a recent study of 486 patients undergoing thoracoabdominal aneurysm repair. Neurological deficits attributable to the spinal drain itself including intracranial haemorrhage occurred in 1% of patients and patients with cerebral atrophy were found to be at increased risk.[23]

Cardiovascular stability

The importance of patient stability cannot be overstated. The surgeon plays a major role in ensuring control of haemorrhage is achieved at all times. Clearly hypotension will decrease the spinal cord perfusion substantially and long periods may precipitate immediate neurological injury. The volume of blood lost is significantly related to spinal cord injury[21] presumably as a result of decreased spinal cord perfusion. Anaesthetic staff need to be well trained in the field of major thoracoabdominal aneurysm surgery to prevent large fluxes of blood pressure and end organ perfusion during the procedure. Equally an intensive care unit that is familiar with all aspects of post-operative care is invaluable in maintaining stability. As mentioned above[22] many patients who develop late onset paraplegia have a documented period of cardiovascular instability prior to symptoms. This is also our experience.

Monitoring spinal cord function

Motor evoked potential (MEP) and somatosensory evoked potential (SSEP) monitoring are established methods of spinal cord monitoring during the procedure. MEPs are elicited by placing electrodes on the scalp to produce transcranial electrical stimulation which is recorded either via the epidural space or from peripheral limb muscles. Jacobs has shown that successful MEP monitoring can be achieved in all patients.[24] Maintaining a mean distal aortic pressure of 60 mmHg with left heart bypass, MEPs are adequate in 82% of patients. In those that have evidence of impaired spinal cord function increasing distal aortic pressure is successful in restoring MEPs. Study of MEPs during surgery may also guide the physician in determining the optimum post-operative blood pressure post-operatively. In patients who are at significant risk of spinal cord ischaemia, serial cross-clamping of the aorta may identify the critical segments of the aorta that supply important blood supply to the spinal cord. MEPs may therefore be used to guide the need and position of intercostal and lumbar artery graft placement. In some patients (less than 20% of cases), MEPs decrease significantly during aortic cross-clamping because of critical spinal cord ischaemia but usually return after spinal cord blood flow is restored. If the MEPs remain attenuated it is likely that the patient will be left with a permanent neurological deficit.

Whilst this method of monitoring spinal cord function may be useful in studying the effectiveness of adjuncts to improve the risk of paraplegia, it sometimes provides false positive results. Particularly since the neurological function of the spinal cord may be affected by anaesthetic agents which may depress the synaptic function of the cerebral cortex and spinal grey matter.

SSEP monitoring may also be useful in detecting spinal cord ischaemia. However, SSEPs only reflect conduction of sensory information in the posterior column, which has a different blood supply from that supplying the motor system located in the anterolateral part of the spinal cord. Since this neurological pathway is thought to be the last to become ischaemic, this method has limited clinical use. However, recently Safi has directly compared MEPs and SSEPs in a large cohort of patients[25] and shown that these two methods for detection of spinal cord dysfunction are well correlated when intra-operative changes are irreversible and that each method has a strong negative predictive value. He concluded that the more complex measurements do not add further information to that obtained by SSEPs.

The advantage of spinal cord drainage with increased pressures can be seen when the spinal cord is monitored by methods described above. With drainage of CSF there may be a dramatic reversal in spinal cord function as monitored by motor evoked potentials. Indeed this monitoring method may be used to guide the need for spinal fluid aspiration.

Management and Prevention of paraplegia during and after Thoracic Aortic Stenting and Hybrid Repair

Thoracic aortic stenting

Thoracic aortic stent grafting has made us rethink the pathophysiology of cord ischaemia. Coverage of the thoracic aorta without revascularisation of intercostals that feed reticular vessels of the spinal cord was expected to produce higher rates of spinal cord ischaemia than are seen. Stenting may be performed with cerebrospinal fluid drainage but other adjuncts believed to be necessary in avoiding spinal ischaemia such as revascularisation of important intercostal branches cannot be employed. Yet the paraplegia rates are low in a number of large series[1,2,26,27] which have confirmed the findings of Dake[28] after he published his original series of 13 thoracic stent grafts in 1994, with encouraging results. There was no paraplegia in this group.

The absence of aortic cross-clamping and cardiovascular stability may account for the encouraging results. Some experimental animal work suggests that covering of the thoracic aorta using stent grafts in sheep causes little in the way of spinal cord ischaemia, whereas cross-clamping of the aorta for an extended period produces a profound neurological deficit.[29] Animal studies however have their limitations, especially in sheep that derive a great deal of spinal cord blood supply from the lumbar and sacral vessels.

The low risk of paraplegia in thoracic stent grafting compared with open surgery may be due to a difference in case mix. For example, Dake's series, although impressive, contained largely localised aneurysms and the length of aorta covered was small in many cases. When considering the success of thoracic stent grafting it must be remembered that the extent of repair and stent coverage is vitally important in determining the risk of significant spinal cord ischaemia.[1,4,30] If series contain patients with a shorter length of covered aorta they will inevitably show improved rates of spinal cord ischaemia. Likewise, when a dissected aorta is stented there is often backwash into the lower end of the false lumen of the dissected portion and this may maintain necessary supply to intercostal vessels. This is clearly not a phenomenon that occurs after surgical repair and complete exclusion of the aneurysm. Comparing similar case series when discussing surgical and endovascular treatment options are important. The length of aorta covered is also relevant when the case of synchronous or dumbbell shaped aneurysms is considered, where a staged approach is sensible to allow vital formation of collaterals to the spinal cord.

Chiesa[31] has reviewed a large case series of over 100 patients undergoing thoracic stent grafting and found a delayed-onset paraplegia rate of 4%. These neurological deficits resolved completely after the institution of CSF drainage, steroids administration, and arterial pressure adjustment. A number of studies have reported similar results. Of note, a perioperative mean arterial pressure (MAP) of less than 70 mmHg and CSF drain complications have been shown to be independent risk factors for the development of delayed-onset paraplegia.[31–34] Other variables that have been reported as significant predictors of paraplegia in patients undergoing thoracic stenting included those with a previous abdominal aortic aneurysm repair and those with significant pre-operative renal insufficiency.[8] A thorough understanding, therefore, of the risk profile in patients requiring TEVAR is essential. Careful haemodynamic monitoring is vital and prophylactic measures for spinal cord protection should be considered in patients whose thoracic aortas require extensive coverage and those with other independent risk factors. The use of somatosensory evoked potentials has also been advocated in TEVAR.[35,36] However, the occurrence of ischaemic changes during these tests may jeopardize the completion of the procedure, and the risk of embolization remains considerable.[37]

Recent study of the EUROSTAR multicenter registry of thoracic stent grafting[38] has demonstrated that perioperative paraplegia or paraparesis is significantly associated with blockage of the left subclavian artery without revascularization. In this series of 606 patients with variable aneurysm pathology, paraplegia or paraparesis developed in 15 patients (2.5%). In a multivariate analysis of this data, spinal cord ischaemia was independently correlated with left subclavian artery coverage without revascularization, the presence of renal failure, concomitant open abdominal aortic surgery and the use of three or more stent grafts. Coverage of the left subclavian without surgical revascularisation increases the risk of paraplegia nearly fourfold.

Visceral hybrid repair

Exclusion of complex thoracoabdominal aneurysms that involve the visceral vessels with stent grafting and retrograde revascularisation from the distal aortic or iliac segments is an alternative method of treating this condition. Clearly using this method, revascularisation of the important intercostal and lumbar supply to the spinal cord is impossible. Profound paraplegia may be expected given the considerable length of excluded aorta. Despite this, our initial results with regard to spinal cord ischaemia were exceptional.[39] In the first 29 consecutive patients treated there was no spinal cord ischaemia documented following the procedure. This group included 3 Crawford type I, 18 type II, 7 type III in 7 and 1 type IV thoracoabdominal aortic aneurysms. Exclusion of the full thoracoabdominal aorta was achieved in all 26 completed procedures and extended to include the iliac arteries in four, with revascularization of coeliac in 26, superior mesenteric artery in 26, left renal artery in 21, and right renal artery in 21. Elective and urgent cases had a mortality of 13%.

Although these results, showing no paraplegia, are remarkable perhaps the lack of aortic clamp and patient stability during the procedure are more important than is currently thought. Also, visceral ischaemia times are short and staggered. The median ischaemia time was 15 min (range, 13–27 min) for the superior mesenteric and coeliac arteries and 15 min for the renal arteries (range, 13–21 min). Each of these vessels is anastomosed sequentially so that the liver and gut are not ischaemic.

Our initial results of 29 consecutive patients formed the majority of cases in a systematic review by Donas et al. in 2007.[40] In a total of 13 studies, 58 patients were identified, all unfit for open surgery. The overall early and long-term mortality was 15.5% and no procedure-related neurological deficits were reported. More recent significant series of hybrid repair include Bockler et al. who report a paraplegia rate of 11% in 28 cases,[41] and Siegenthaler et al. who report no spinal cord injury in a series of 21 consecutive patients.[42]

As time has progressed and our experience has grown, we have experienced a more expected paraplegia rate.[43] The only three substantial series of hybrid thoracoabdominal aneurysm repairs in Europe have been collated and presented. A consecutive series of 89 urgent and elective high-risk patients have been studied. This series demonstrated a paraplegia risk of 8%. We believe that the excellent paraplegia rates within our earlier series of hybrid patients were due to a small sample size rather than a change in technique or patient selection.

Summary

Methods thought to decrease the rate of spinal cord ischaemia include reducing aortic cross-clamp times, intercostal revascularisation, retrograde perfusion techniques,

Table 1 This table documents the approaches used for spinal cord protection at St. Mary's Hospital, Imperial College London for open repair (each aneurysm type documented), hybrid endovascular/surgical repair and thoracic stent grafting (TEVAR)

	Type I	Type II	Type III	Type IV	TEVAR	Hybrid
Revascularisation of intercostal arteries	√	√	√	No	No	No
Left heart bypass	√	√	√	No	No	No
Spinal Cord cooling	No, but allow patient temperature to fall to 33°	No, but allow patient temperature to fall to 33°	No, but allow patient temperature to fall to 33°	No	No	No
CSF drainage	√	√	√	No	√	√
Ensure MAP > 80 mmHg	√	√	√	√	After stent deployment	√

We do not routinely measure spinal cord function at St Mary's.
Abbreviations: CSF — Cerebrospinal fluid; MAP — Mean arterial pressure; TEVAR — Thoracic endovascular aortic repair.

cerebrospinal fluid drainage and stability during anaesthesia. It is difficult to separate the effectiveness of each of these methods as the use of various techniques is employed by most. Randomised trials on this subject are sparse. Another major problem is variation in reporting methods between centers. A standardised method of reporting the type of aneurysm repair and severity of paraplegia would greatly benefit the literature on this subject.

A multimodal approach to decrease the risk of spinal cord ischaemia is advocated by most. The combination of various methods seems to be effective in reducing the risk of spinal cord ischaemia (Table 1). However, these techniques do not abolish the problem. The practice of stenting the thoracic aorta and excluding the important spinal cord arteries with relatively low rates of paraplegia suggests that an anatomical basis alone for spinal cord ischaemia is over simplistic and anaesthetic stability and duration of ischaemia may play a major role.

Conflict of Interest

None.

Funding

The authors acknowledge support from the Imperial College Biomedical Research Centre.

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