# The Spinal Cord Collateral Network: Implications for Endovascular Aortic Repair

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## Introduction

Endovascular repair of aortic aneurysms has evolved as the primary treatment strategy for many patients suffering from infrarenal aortic pathologies, and already represents an alternative treatment for patients with aortic aneurysms involving the thoracic and visceral segment of the aorta. With the implementation of fenestrated and branched stent grafts, we are now facing different complications than were usually encountered after open repair, but certain issues remain unsolved. Among these, paraplegia as a consequence of spinal cord ischemic damage has an incidence as high as 30 % in some reports, is the most devastating complication to patients and most dreaded by surgeons. Paraplegia results in dramatic life changes and often in early mortality, encouraging us in the quest for ways to minimize its risk.

## Background

### Anatomy

To understand the anatomy of the spinal cord vasculature and its physiological mechanisms as a reaction to critical changes in spinal cord perfusion is a vital first step toward improved treatment. The spinal cord is nourished by three major arteries: the anterior spinal artery (ASA) feeds the anterior two-thirds of the spinal cord, and two posterior spinal arteries provide blood flow to the posterior third. Arising from the aorta, intercostal and lumbar arteries give off branches to the spinal arteries: the anterior and posterior radicular–medullary arteries (ARMA, Fig. 7.1).

The traditional teaching that there exists one dominant artery which feeds the spinal cord, the artery of Adamkiewicz, has dominated the thinking of surgeons seeking to safeguard spinal cord perfusion, and many attempts have been made to identify and preserve this elusive vessel preoperatively and intraoperatively, recently using high-resolution computed tomographic angiography (CTA). Unfortunately, however, valiant attempts to re-implant SAs associated with prominent radicular arteries have been frustrated by lack of improvement in paraplegia rates. We have shown in a review of hundreds of TAAA resections that there is no unique SA whose interruption results in cord ischemia [1, 2]. Lazorthes et al. were among the first to question the idea of a single dominant artery, and they described the importance of additional inflow into the spinal cord circulation provided by the subclavian and hypogastric arteries [3–5]. The occlusion of a large number of segmental arteries when replacing a long segment of the aorta by open or endovascular means results in immediate loss of blood flow to the cord through intercostal and lumbar arteries, and this immediate ischemia results in recruitment and development of additional sources.

### Pathophysiology

Serial examination of spinal cord blood flow (SCBF) using fluorescent microspheres in experimental pig studies has

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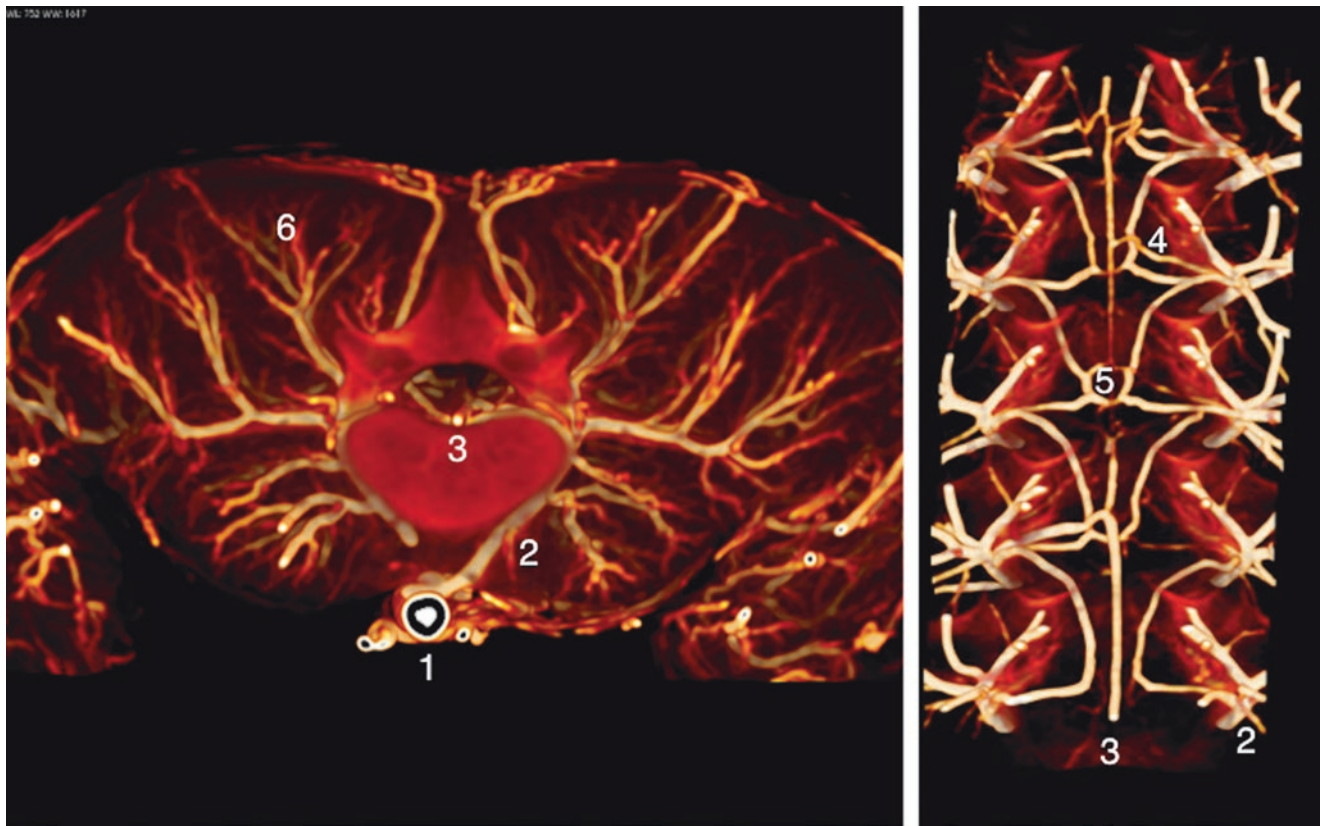e-mail: ebgriepp@aol.com; randallgriepp@msnyuhealth.org

**Fig. 7.1** High-resolution CT scan of the vasculature. The aorta (1) gives rise to the segmental arteries (2), which run around the vertebral bodies and connect to the anterior spinal artery (3) through the anterior radicular–medullary arteries (4), and give off branches to the epidural arcades (5). Its connections with the dense vasculature within the para- spinous muscles can also be seen (6). Reprinted from The Journal of Thoracic and Cardiovascular Surgery, 144(6), Geisbusch S, Schray D, Bischoff S, Lin HM, Griepp RB, Di Luozzo G, Imaging of vascular remodeling after simulated thoracoabdominal aneurysm repair, 1471– 8, Copyright 2012, with permission from Elsevier

shown that the lowest flow occurs within 5 h after extensive SA ligation, at a time when sham-operated pigs demonstrate hyperemia. Pigs that recover from SA ligation with normal hind limb function show a return to baseline SCBF at the 5-h time point, whereas those that suffer paraplegia do not reach baseline until 72 h after SA sacrifice (Fig. 7.2) [6].

Monitoring of the actual spinal cord perfusion pressure (SCPP) via a catheter inserted in the stump of a ligated SA confirms that the most severe drop in pressure occurs also at 5 h, with recovery even in paraplegic animals by 72 h (Fig. 7.3). In patients as in pigs, SCPP is a fraction of mean arterial pressure (MAP): in hypertensive patients, MAP must be maintained at preoperative levels during and after operation in order to avoid spinal cord ischemic injury [7, 8].

The explanation for the physiological patterns of spinal cord perfusion after sacrifice of SAs has been provided by several anatomic studies. The blood supply to the spinal cord is part of an extensive network of vessels within and surrounding the cord and the vertebrae, extending into the paraspinous muscles, which is interconnected with major arteries: the subclavian, hypogastric, and internal thoracic. The most surprising finding of our initial anatomic studies—carried out using acrylic casts of the vascular system in the pig—is the dominance of the vasculature of the paraspinal muscles over the much less extensive arterial supply of the spinal cord (Fig. 7.4) [9].

There are multiple longitudinal interconnections between the blood supply of the muscles, an extensive epidural system, and the anterior spinal artery, with numerous anastomoses at every thoracic and lumbar level between these various components of the network. A reconstruction based on several casts of the paraspinal and intrathecal vessels is shown in Fig. 7.5 [9].

Following sacrifice of all SAs from level T4 to S1 through simulated TAAA repair in a pig model, an increase in the diameter of the ASA can be seen already at 24 h after operation. By 48 h and especially 120 h, there is also a significant increase in the volume and diameter of the epidural arteries, and evidence of proliferation of small arterioles within the muscles surrounding the cord as well as enlargement of those which were present before SA ligation [1, 9].

The proliferation of small vessels as well as enlargement of major collateral arteries after SA ligation has been

**Fig. 7.2** Spinal cord blood flow (SCBF) drops after sacrifice of all thoracoabdominal segmental arteries and returns to baseline 5 h after the operation in pigs that recover without impairment of hind limb function. In paraparetic pigs, it takes up to 72 h to return to baseline levels. By permission of Mayo Foundation for Medical Education and Research. All rights reserved
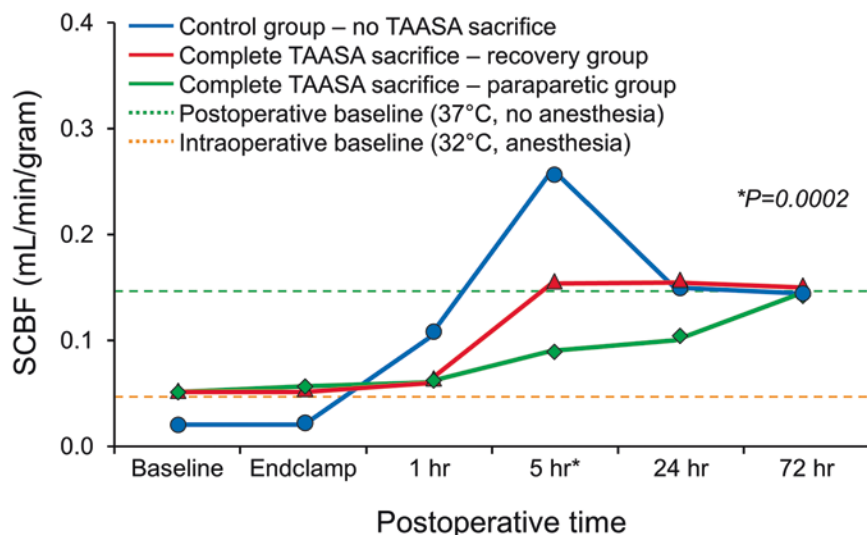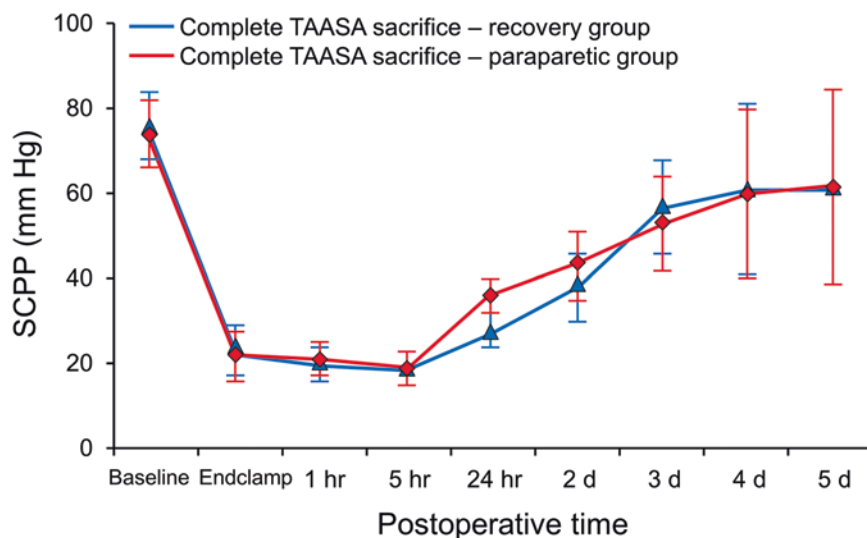
**Fig. 7.3** Spinal cord perfusion pressure (SCPP) drops immediately after sacrifice of all segmental arteries and shows complete recovery even in paraparetic animals. By permission of Mayo Foundation for Medical Education and Research. All rights reserved

confirmed by studies using a barium latex infusion viewed by means of CT scanning [1]. One of the most striking findings is the extensive anterior-posterior collateralization, which develops between the internal thoracic and intercostal arteries. The dramatic proliferation of the network is easily appreciated visually, and can be confirmed by morphometric studies. Figure 7.6 shows a native pig compared with a pig 24 h and 5 days after complete SA ligation. The latex-barium method permits analysis of the vessels in situ, in contrast with the need for digestion of the tissue around the acrylic vascular cast, a process, which destroys many small and fragile vessels.

Histological findings have made it clear that necrosis of the spinal cord neurons is most prominently seen in the lower thoracic region (T9-T13), the part of the cord where input from cranial and caudal sources is limited when direct blood flow through SAs is interrupted (Fig. 7.7) [10].

After simulated TAAA repair in experimental models, there is also a striking reorientation of vessels within the musculature, from a random pattern (top) to one more parallel to the cranio-caudal axis (bottom), suggesting that this is a mechanism to augment flow along the longitudinal axis and provide both cranial and caudal input to the central region of a spinal cord which has been deprived of its direct blood supply (Fig. 7.8) [11].

## The Impact of the Collateral Network on Endovascular Repair

Although its incidence is gradually diminishing, paraplegia following repair of aortic aneurysms is a formidable complication and continues to be disturbingly high even in the hands of experts, especially in cases where the aneurysm
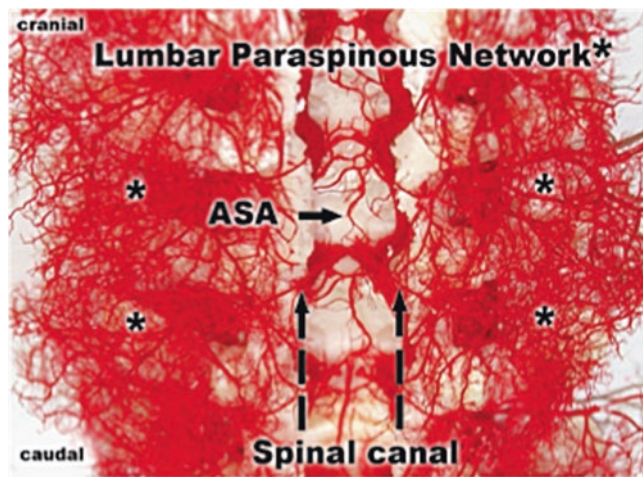
**Fig. 7.4** Casting of the vasculature using acrylic resin revealed a dense network within the paraspinous muscles. Reprinted from The Journal of Thoracic and Cardiovascular Surgery, 141(4), Etz CD, Kari FA, Mueller CS, Silovitz D, Brenner RM, Lin HM, et al., The collateral network concept: a reassessment of the anatomy of spinal cord perfusion, 1020–8, Copyright 2011, with permission from Elsevier

spans most of the thoracic and thoracoabdominal aorta. The number of SAs to be sacrificed during an operation—equivalent to the extent of the aneurysm—and the presence of additional compromise of input resulting from previous or concomitant occlusion of the subclavian or hypogastric arteries are the major factors in assessing the risk of paraplegia or paraparesis [12–14]. Current surgical strategies to reduce the risk of cord ischemia include reimplantation of SAs and use of cardiopulmonary bypass to increase intraoperative flow, and deep hypothermia to decrease the nutritional demand of the spinal cord, but these techniques are of limited relevance in endovascular repair, where intraoperative cord ischemia is much less of a problem. Other surgical adjuncts, such as drainage of cerebrospinal fluid (CSF) and maintenance of mean arterial pressure (MAP) at high normal levels, are part of the routine perioperative management in both surgical and endovascular repair to assure adequate SCPP. In addition, monitoring tools such as motor-evoked potentials (MEPs) or somatosensory-evoked potentials (SSEPs) help to immediately detect changes and adjust treatment in anaesthetized patients, but are not feasible once they awaken, making us rely on clinical assessments of spinal cord function.

The impact of the collateral network on recovery from endovascular aortic repair becomes apparent when we look at results of clinical as well as experimental studies in which extensive aortic replacement has been carried out in two stages. There is an undeniable decrease in the incidence of postoperative paraplegia after staged repair [15–17], notwithstanding the ongoing controversy over the impact of previous aortic repair as a risk factor for paraplegia: the detrimental effect of previous surgery may well be a consequence of hypogastric or subclavian artery sacrifice. Experiments in which various numbers of SAs T4–S1 were sacrificed have shown that the incidence of spinal cord ischemia corresponds to the number of sacrificed vessels. Further studies have shown that pigs in which the subclavian and/or the hypogastric arteries had been ligated prior to SA sacrifice had a worse outcome than those in which these other sources of blood flow were intact: in the absence of an intact subclavian or hypogastric blood supply, fewer SAs could be sacrificed without spinal cord injury [18].

Taking into account what we have learned about spinal cord anatomy and physiology, it is likely that the first step of a two-stage procedure provides an ischemic stimulus which stimulates the collateral network to develop small new vessels (angiogenesis) and to transform existing small vessels into larger ones (arteriogenesis) and to reorient them. All of these changes serve to augment spinal cord blood flow to compensate for diminished direct SA input. Patients in whom recruitment of collateral input sources is compromised by previous occlusion of subclavian or hypogastric vessels are therefore at higher risk of spinal cord ischemia following SA sacrifice during aneurysm repair.

With constant improvement of endovascular strategies including fenestrated and branched stent grafts, innovative concepts to prevent spinal cord ischemia after complete endovascular repair have been developed, with the idea of promoting enhancement of the collateral network before occlusion of all segmental vessels. First published in 2010, temporary aneurysm sac perfusion (TASP) after branched thoracic endovascular aortic repair (bEVAR) is a technique which involves leaving two or more branches open at the time of initial repair, and performing side branch completion in a second stage procedure days to weeks later. TASP has shown promising results in a case report and two series of 10 and 40 patients [19–22]. Although spinal cord perfusion is dramatically reduced by implanting a thoracoabdominal stent graft, leaving some branches open seems to assure sufficient cord perfusion until the collaterals have had time to develop, while placing the stent graft immediately reduces the risk of rupture by minimizing flow into the aneurysm sac.

Endovascular occlusion of a number of SAs prior to simulated TAAA repair has shown excellent results in an experimental study: no paraplegia in pigs that had coil occlusion of two or more SAs 1 week prior to sacrifice of all SAs, in contrast to a 60 % rate of spinal cord injury in controls without pretreatment [10]. The first clinical cases report successful application in patients at high risk [23]. Coiling of a few SAs seems to stimulate collateral development prior to subsequent simulated TAAA endovascular repair in healthy pigs without being harmful to spinal cord integrity: histologic
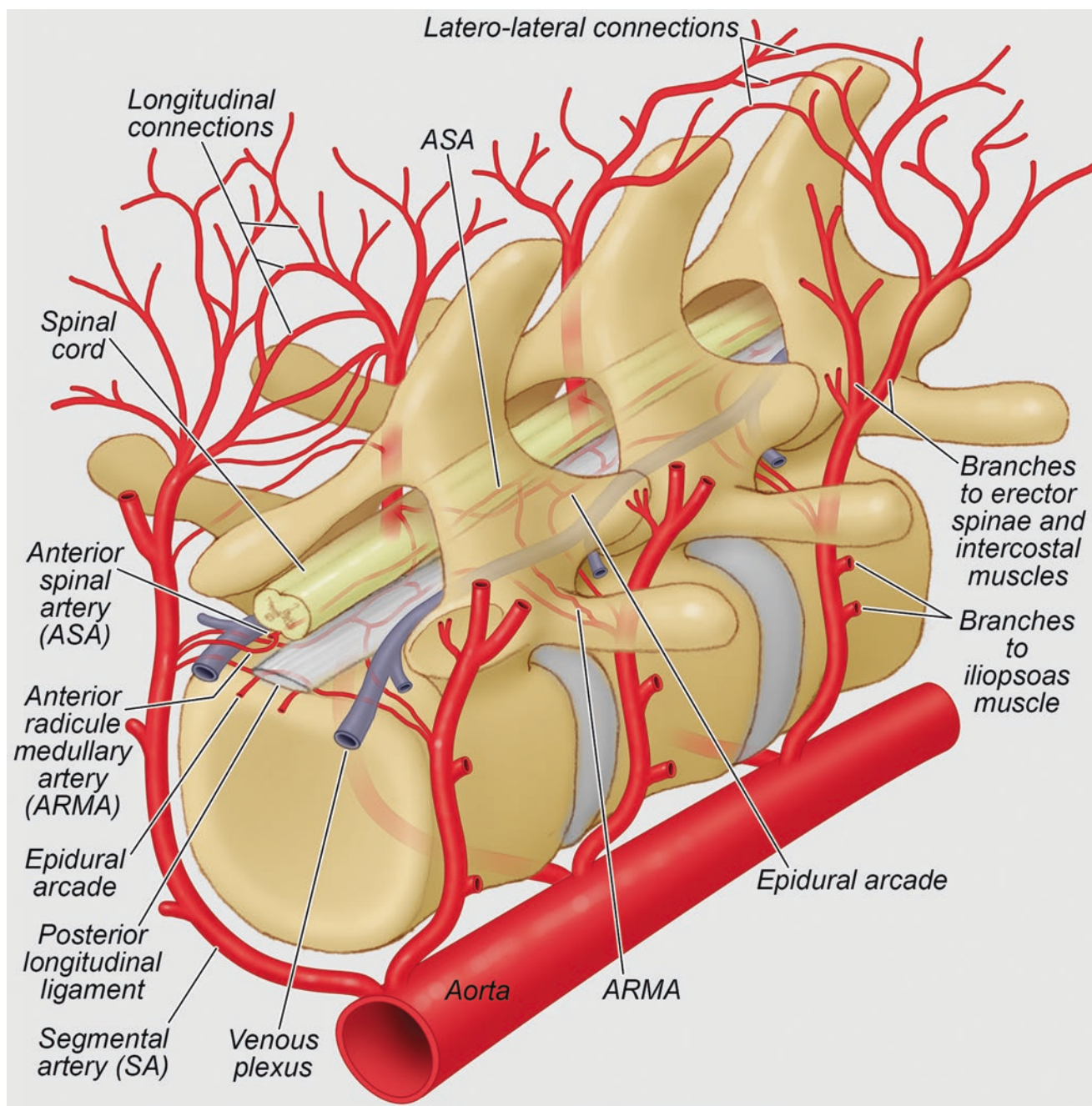
**Fig. 7.5** Spinal cord anatomy with longitudinal interconnections at every thoracic and lumbar level between various components of the network. By permission of Mayo Foundation for Medical Education and Research. All rights reserved

ischemic damage, quantified as necrosis of grey and white matter, was significantly reduced after preparatory coiling ($p=0.001$) (Fig. 7.9).

TASP and coiling of SAs seem to have real potential clinical utility, although some issues pose concerns. In patients with degenerative aneurysms, some of the SAs may already be occluded by thrombus, and so the coiling of additional arteries could then itself lead to spinal cord ischemia [19].

Test balloon occlusion in the awake patient may be a way of dealing with this problem: in the absence of neurological symptoms, permanent coils could be placed, or implantation of the branch to complete bEVAR could be performed. In addition, catheter manipulation during the coiling procedure carries a risk of atheroembolization from plaque and mural thrombus and should be performed by an experienced interventionalist or surgeon. The imaging of patent intercostal
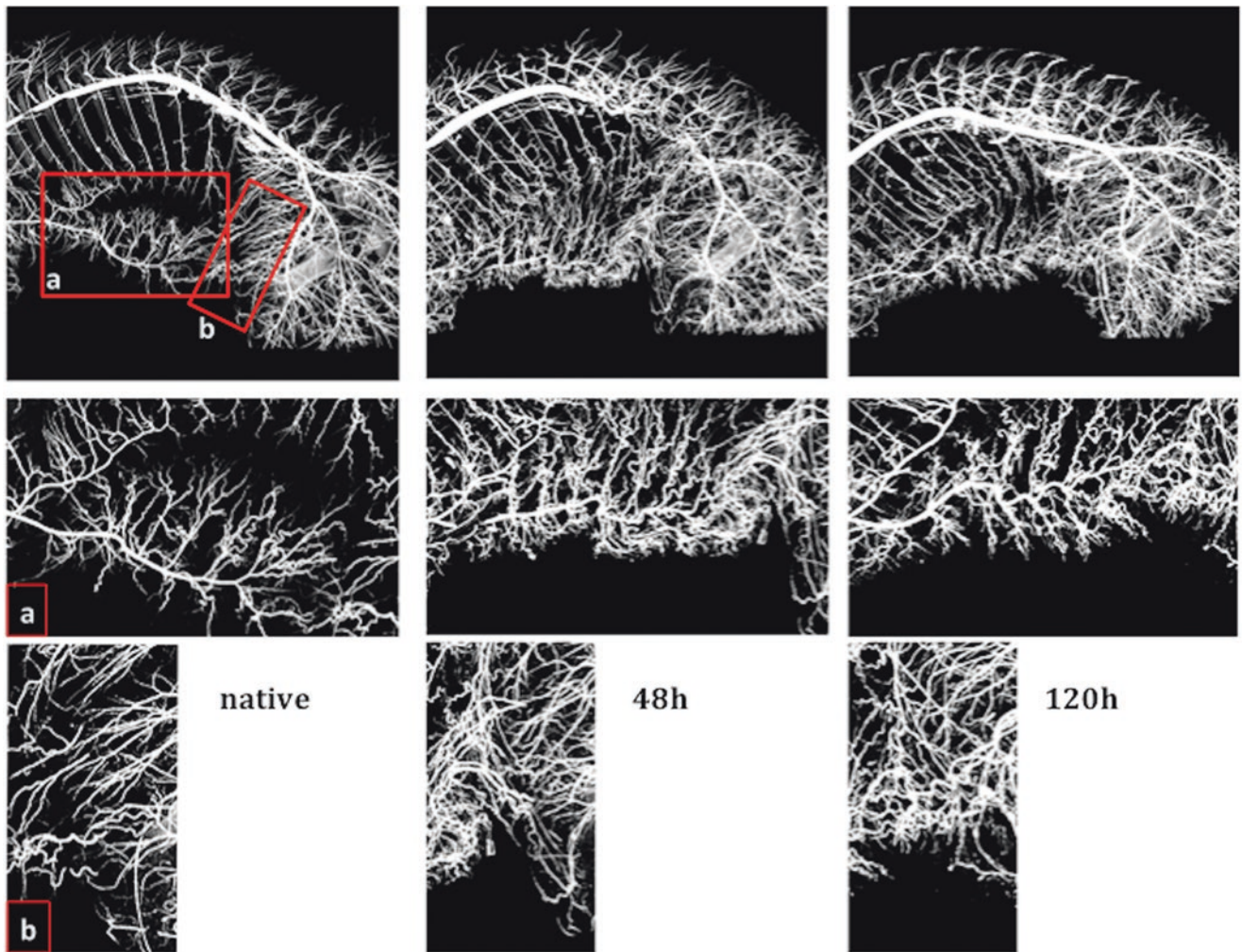
**Fig. 7.6** High-resolution CT scans of a native pig, and pigs 48 and 120 h after complete SA sacrifice (simulated TAAA repair). It can easily be appreciated that a dense network of collaterals develops, and that an increase in vessel diameter occurs as early as 48 h after the operation. Reprinted from The Journal of Thoracic and Cardiovascular Surgery, 144(6), Geisbusch S, Schray D, Bischoff S, Lin HM, Griepp RB, Di Luozzo G, Imaging of vascular remodeling after simulated thoracoabdominal aneurysm repair, 1471–8, Copyright 2012, with permission from Elsevier
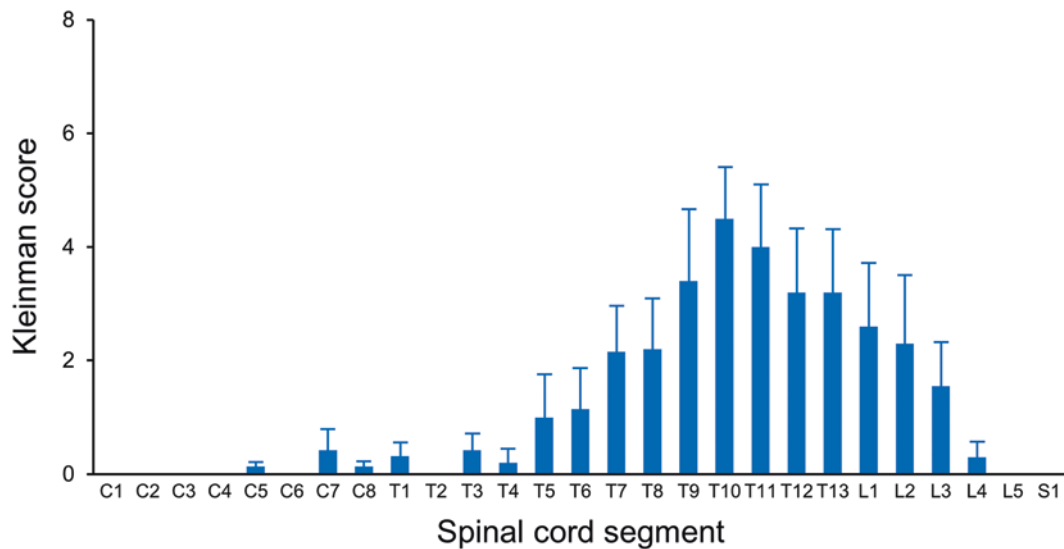


**Fig. 7.7** In experimental studies, the ischemic damage within the spinal cord was graded on an 8-point scale after complete SA sacrifice from T4–S1. Necrosis was most prominently seen from T9 to T13, the region farthest away from supportive cranial and caudal input when direct inflow is interrupted.
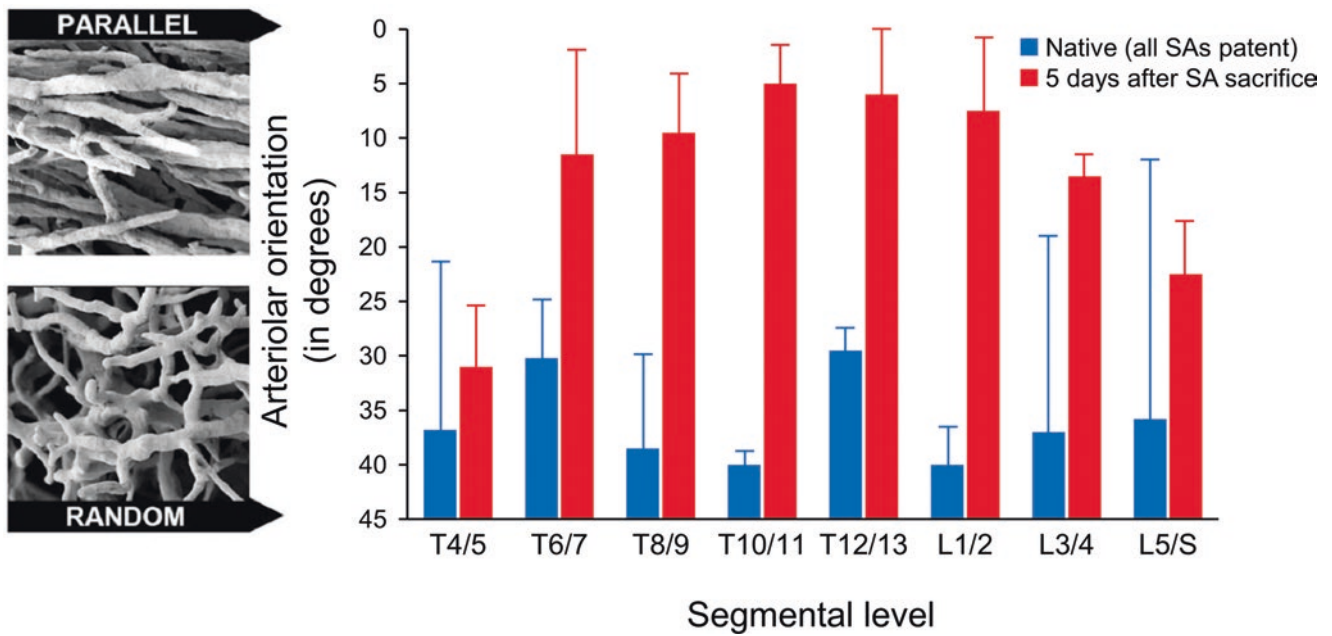
**Fig. 7.8** The reorientation of the smallest vessels within the collateral network, most likely to direct flow to the central region of the cord. Reprinted from The Journal of Thoracic and Cardiovascular Surgery, 141(4), Etz CD, Kari FA, Mueller CS, Brenner RM, Lin HM, Griepp RB, The collateral network concept: remodeling of the arterial collateral network after experimental segmental artery sacrifice, 1029–36, Copyright 2011, with permission from Elsevier
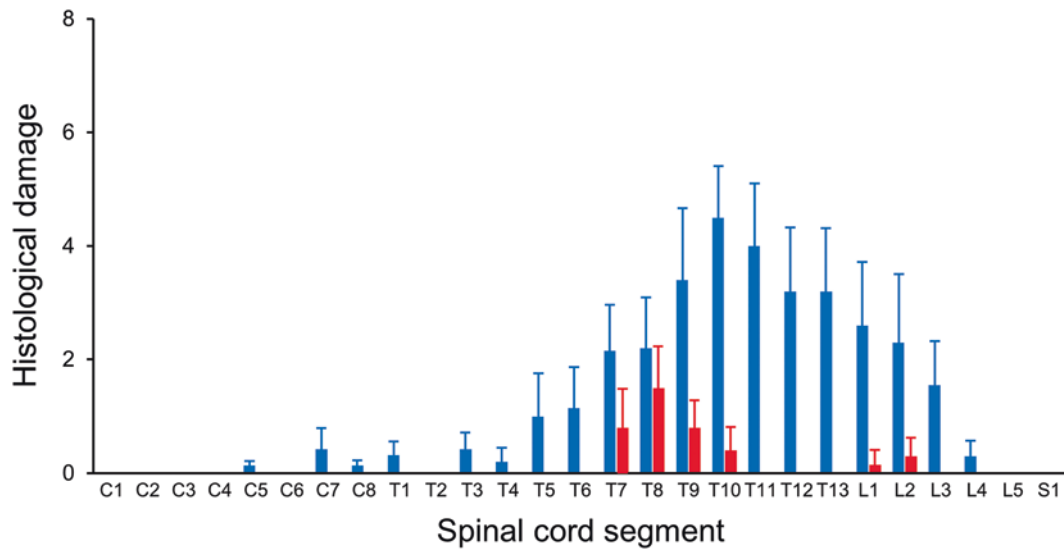


**Fig. 7.9** As opposed to the pattern of spinal cord necrosis after simulated TAAA repair (*blue bars*), the extent of ischemic cell damage is marginal in the T9-T13 region after coiling of two or more SAs in this region of the cord (*red bars*), p = 0.001. The ischemic stimulus likely activates the dilatation of existing vessels and the development of small new vessels that compensate for the loss of inflow after subsequent TAAA repair [10]. By permission of Mayo Foundation for Medical Education and Research. All rights reserved

arteries and thrombus formation by angiography, CT or MRI is a helpful tool in planning the procedure [24, 25].

Revascularization of the left subclavian artery via a bypass graft should be considered in each patient in whom coverage of the artery with a stent graft is inevitable, and when additional risk factors—such as previous aortic repair with sacrifice of the hypogastric artery—are present.

Finally, it should be pointed out that some patients are not eligible for a two-stage procedure, TASP or coiling: those with symptoms or imminent rupture, rapid aneurysm

progression over a short period of time, or large aneurysm diameters. For these patients, the risk of paraplegia with extensive aneurysm repair remains high, and should be minimized using careful monitoring and supportive adjuncts during the first few days following the endovascular procedure.

In summary, minimally invasive endovascular repair of complex extensive aortic pathologies still carries a high risk of postoperative paraplegia, but innovative endovascular strategies in combination with currently accepted management may improve outcome and reduce paraplegia to a rare complication.

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