Importance of extrasegmental vessels for spinal cord blood supply in a chronic porcine model

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Abstract

Objective: Our purpose was to investigate the interaction of the important components of spinal cord blood supply in the pig model to enable its use for future studies of spinal cord protection.

Methods: Twenty-five juvenile pigs (20–22 kg) underwent serial intercostal (IC) or lumbar artery (LA) ligation until disappearance of motor evoked potentials (MEPs). Pigs underwent sequential craniocaudal IC/LA ligation alone (\(n = 5\)); following clamping of both subclavian arteries (\(n = 4\)), or clamping of the median sacral artery (MSA, \(n = 4\)). Animals also underwent serial caudocranial clamping of LA/IC alone (\(n = 4\)); preceded by clamping of the subclavian arteries (\(n = 4\)), or of the MSA (\(n = 4\)). Results were verified by Tarlov’s scores and perioperative angiography.

Results: All animals with MEP loss suffered postoperative paraplegia. Groups were equivalent with regard to stable arterial pressures (64.6 ± 3.1 \(\text{mmHg}\)) throughout the experiment, temperature (36 ± 1.1 \(^\circ\text{C}\)) and other physiological parameters. Mean number of clamped IC/LA before MEP loss for cranio-caudal clamping direction was 12.8 ± 0.8 for segmental arteries isolated, 9 ± 0.8 if both subclavian arteries were ligated previously and only 4.3 ± 0.5 IC if the median sacral artery was clamped before. Mean number of clamped LA for caudo-cranial clamping direction was 5.8 ± 0.9 for segmental lumbar arteries, 5.5 ± 0.6 LA if both subclavian arteries were ligated previously and 3.5 ± 0.6 if the median sacral artery was clamped before.

Conclusion: This study confirms the importance of lumbar and MSA arteries to cord viability. It documents the interaction of the subclavian and MSA (roughly equivalent to the hypogastric arteries in humans) with segmental vessels in providing spinal cord blood supply. It also provides the physiologic basis for use of the pig model for studies of spinal cord protection in aortic surgery.

Keywords: Thoraco-abdominal aortic replacement; Spinal cord blood supply

1. Introduction

Replacement of the thoracoabdominal aorta for treatment of large aortic aneurysms, often involves the sacrifice of segmental vessels, putting in jeopardy the blood supply to the spinal cord. Mortality and morbidity of even extensive thoracoabdominal replacement has improved markedly in recent years, postoperative paraplegia remains a devastating risk. Current research has focused increasingly on obtaining a better understanding of the physiology of spinal cord blood supply in the hope of reducing the incidence of this dreaded complication.

Although there are a multiplicity of different approaches to the prevention of spinal cord ischemia, re-implantation of sacrificed segmental arteries to restore blood flow is a common approach in trying to avoid permanent dysfunction of the cord. Strategies range from time-consuming re-implantation of all sacrificed segmental vessels, to selective re-implantation of only those arteries from which backflow is observed, or those considered indispensable on the basis of size or location [1]. Although re-implantation of segmental arteries has the appeal of common sense, doubts have been raised about the effectiveness of re-connecting any intercostal or lumbar arteries to the graft, since long-term patency of these reattached vessels has not been documented [2,3]. Re-implantation of segmental arteries...
has also been questioned on theoretical grounds, since it is known that many extra-segmental arteries make major contributions to spinal cord blood supply, permitting cord viability even after extensive resection of segmental vessels.

Adjunctive procedures during surgery—monitoring of somato-sensory-evoked or motor evoked potentials, distal aortic perfusion and use of hypothermia—have reduced the incidence of postoperative cord dysfunction. A significant number of patients still suffer from postoperative paraplegia or paraparesis. Intraoperative recording of motor evoked potentials has been considered the most effective means of monitoring spinal cord function intraoperatively, and therefore the most reliable guide to determining the critical number of segmental vessels that need to be restored. Since the presence of MEPs after restoring blood flow to the lower body indicates preserved spinal cord function, and the patient with intact MEPs usually awakens without immediate neurological impairment, a close correlation between intraoperative monitoring and clinical outcome is observed.

To better understand the pathophysiology and mechanisms responsible for paraplegia, further research is still necessary to investigate the anatomy and dynamics of spinal cord blood supply, and the reaction of the spinal cord to ischemia. There is still controversy about whether there are specific vessels, which make an almost irreplaceable contribution to spinal cord blood supply, or whether the spinal cord depends upon an extensive network of almost interchangeable collaterals. Little is known about the existence and possible duration of a period of increased vulnerability after the ischemia and sudden reduction in blood flow which occur during aneurysm surgery, or whether a short interval of ischemia initiates recruitment of collaterals which help to protect the cord in the event of later reductions in blood flow.

The pig has become a popular and widely accepted model for investigating different strategies to prevent neurological dysfunction after operations on thoracoabdominal vessels [4–6], but not much information is available about the blood supply and vascular anatomy of the pig spinal cord, and how it compares to the human patient. With the intent of devising a chronic animal model for investigating the development of paraplegia, we thought that a thorough knowledge of the blood supply of the spinal cord of the pig would be essential.

In this experimental protocol, adequacy of spinal cord blood supply was assessed using myogenic motor evoked potentials in response to transcranial electrical stimulation of the motor cortex. MEPs selectively reflect transmission in spinal cord motor neuron pathways, and can detect within minutes the interruption of spinal cord blood supply [7]. The aim of this study was to identify the range of critical segmental arteries contributing to perfusion of the spinal cord in the pig using transcranial myogenic motor evoked potentials (MEP) under various circumstances: with and without major extrasegmental vessels thought to be involved in the collateral vascular network of the spinal cord. Observations based on acute intraoperative MEP findings were subsequently confirmed by postoperative neurological outcome in a chronic porcine model.

2. Materials and methods

2.1. Study design

Twenty-five female juvenile Yorkshire pigs (Th. D. Morris, Inc., Reisterstown, NY, USA), 2–3 months of age, weighing 20–23 kg, were used for this experiment. The animals underwent serial intercostal (IC) or lumbar artery (LA) ligation—in either a cranio-caudal (group A) or caudo-cranial (group B) direction—until disappearance of motor evoked potentials (MEPs). Pigs underwent sequential cranio-caudal IC/LA ligation alone \((n = 5)\); following clamping of both subclavian arteries \((n = 4)\), or after clamping of the median sacral artery (MSA, \(n = 4\)). Animals also underwent serial caudocranial clamping of LA/IC alone \((n = 4)\); preceded by clamping of the subclavian arteries \((n = 4)\), or of the MSA \((n = 4)\).

2.2. Perioperative management and anesthesia

All animals received humane care in compliance with the guidelines ‘Principles of Laboratory Animal Care’ formulated by the National Society for Medical Research and the ‘Guide for the Care and Use of Laboratory Animals’ published by the National Institute of Health (NIH Publication No. 88-23, revised 1985). The protocols for all experiments were approved by the Mount Sinai Institutional Animal Care and Use Committee.

After pretreatment with intramuscular ketamine (15 mg/kg), and atropine (0.03 mg/kg) to induce the anesthesia, animals were anesthetized with intravenous sodium thiopenthal (20 mg/kg). After endotracheal intubation, the pigs were ventilated mechanically with a FiO2 of 0.5 and isoflurane 1–2% to induce sufficient anesthesia. Inhalation of isoflurane was discontinued, and anesthesia was maintained with an infusion of ketamine 15 mg/kg per hour and sufentanil 5 μg/kg per hour. This anesthetic regimen has no major effect on MEP responses and has been described previously [8]. Paralysis was achieved with intravenous pancuronium (0.1 mg/kg). The ventilator rate and the tidal volume were adjusted to maintain the arterial carbon dioxide tension at about 35–40 mmHg. End-expiratory carbon dioxide, and inspiratory and expiratory isoflurane were monitored continuously (PPG Biomedical Systems, Model 2010-200 R, Lenexa, KS, USA). Arterial oxygen tension was maintained greater than 100 mmHg.

A bladder catheter (Foley 8–10 F) was inserted for online measurement of urine output and temperature probes were placed in the esophagus and the rectum. Electrocardiographic measurements were recorded continuously. An arterial line was placed in the right brachial artery for monitoring spinal cord function intraoperatively, and clinical outcome is observed.
pressure monitoring during the whole procedure and blood sampling (pH, oxygen tension, carbon dioxide tension, oxygen saturation, base excess, hematocrit, hemoglobin and glucose, lactate, Blood Gas Analyzer, Ciba Corning 865, Chiron Diagnostics, Norwood, MA, USA).

2.3. Monitoring technique for motor evoked potentials (MEP)

A 5-cm longitudinal incision was made in the scalp overlying the skull, and the periosteum was removed to expose the sagittal and coronal sutures of the calvarium. Four stainless steel screw electrodes with attached wire leads were screwed into the skull 10-mm lateral to the sagittal suture. Two screws were placed on the left side (8 mm anterior and 8 mm posterior to the coronal suture), and two were similarly placed on the right side. The wire leads were connected to an electrical stimulator (Digitimer Stimulator Model D 180A, Welwyn, Garden City, UK). Electromyographic recordings were made from sterile stainless steel needle electrodes placed through the skin over the quadriceps muscle in the hind leg and the muscles in the foreleg. A stimulation train (three pulses, 200–300 V, 100-μs pulse duration, and 2-ms interstimulus interval) delivered to the skull electrodes was used to elicit motor evoked potentials (MEPs). MEPs were amplified (gain = 2000), bandpass filtered (10–1000 Hz), digitized, and stored on a optical disk for subsequent analysis by a Spectrum 32 neurophysiological recording system (Cadwell Laboratories Inc., Kennewick, WA, USA). Sample MEPs are shown in Fig. 1.

MEPs were recorded before clamping, during the period of occlusion, and after clamp release. The baseline value was determined just prior to the start of segmental clamping. A lack of response to the stimulus is consistent with an ischemic spinal cord.

Data acquisition and analysis were performed on a computer with an AD converter and software (LabVIEW, National Instruments, Austin, TX).

2.4. Operative technique for induction of spinal cord ischemia

The chest was opened via a left thoracotomy in the seventh intercostal space. The aortic arch and the supraaortic vessels were dissected to reach both subclavian arteries, which were encircled with a silastic catheter. The descending aorta was mobilized, and all thoracic segmental arteries, with their single origins, were dissected and exposed to the level of the diaphragm. The abdominal aorta, the lumbar segmental arteries, the median sacral artery and the aortic bifurcation were exposed through a left retroperitoneal incision between the lower margin of the 12th rib and the superior iliac crest. The renal arteries, the celiac trunk and the superior and inferior mesenteric arteries were carefully identified and kept untouched.

After all surgical work was done a baseline MEP recording was obtained, and repeated three times while mean arterial blood pressure and anesthesia conditions were stable (Fig. 2a).

Thereafter, prepared segmental arteries were sequentially clamped and ligated from different directions, starting from T2 for cranio-caudal clamping and L6 for caudo-cranial clamping. After placement of each additional segmental artery clamp, an observation period of 5 min was allowed to detect whether ischemic spinal cord dysfunction developed, as evidenced by a MEP amplitude decrease below 50% of baseline. Measurements for MEP response were taken 1 and 5 min after clamping of each segmental artery. When MEPs indicated spinal cord ischemia (Fig. 2b), the clamped segmental artery was considered critical for spinal cord blood flow, and the clamp was released immediately. To avoid producing irreversible spinal cord damage, the observation period to allow MEPs to recover following each unclamping did not exceed a total of 5 min; clamping of each possibly critical segmental artery was repeated to verify the MEP findings. All previous clamped segmental arteries were ligated permanently.

![Fig. 1. Typical motor evoked potential (MEP) response curve for both lower limbs. MEP latency means duration in ms from stimulation to the first progressive negative deflection. MEP amplitude means peak-to-peak amplitude in microvolts (μV).](https://academic.oup.com/ejcts/article-abstract/24/5/817/394362)
A period of 30 min was considered adequate to monitor MEP recovery after clamp release (Fig. 2c).

2.5. Postoperative course

After the last measurement—30 min after clamp release following identification and transient clamping of the critical segmental artery—the thoracotomy and retroperitoneal incision were closed. All animals remained on the operating table with intermittent positive pressure ventilation for a recovery period of 2 h after closing all incisions. Mean arterial pressure was maintained >65 mmHg using 0.9% sodium chloride infusion if required. The animals were then extubated and brought to the recovery room, where food and water were provided starting on POD 1. For continued observation, the pig was placed in a separate pen as soon as it was alert. Analgesic treatment (butorphenol 0.1 mg/kg) was maintained for all 3 postoperative days.

Neurological examination using the Tarlov score was carried out daily at the same time by an investigator blinded to the grouping. The Tarlov score is as follows: 0 = spastic paraplegia, no movements; 1 = paraparesis, slight movements; 2 = paraparesis, powerful movements in hindlimbs, but not able to stand; 3 = able to stand but unable to walk; 4 = full recovery, normal walking function [9]. After assessment of the Tarlov scores on POD 3, the animals were killed with intravenous pentobarbital.

2.6. Statistical methods

Animals were randomized to one of the groups after induction of the anesthesia by an independent party who announced membership in the selected group immediately after the baseline timepoint.

Groups were compared separately at baseline, during before segmental clamping, after segmental clamping and after incision closure. The t-test or the Mann–Whitney test, as appropriate, were used for comparisons at baseline. When the data were consistent with normality and equal variance assumptions, the measurements at the various timepoints were compared using repeated measures ANOVA, with tests for average differences between groups and for group–time interactions (change in the difference between groups over time). Otherwise the groups were compared separately at each time point using the Mann–Whitney or Fisher exact tests. We report P values unadjusted for multiple testing: their purpose is not for an exact global assessment but rather as a guide to help interpret the pattern of differences between groups at different times. The Bonferroni correction was not utilized because we expect these tests at successive time points to be highly correlated. Analyses were implemented with SAS software on a VAX computer and StatXact 4 for Windows.
3. Results

3.1. Mortality

All animals survived the operative procedure and completed the full observation period of 3 postoperative days (POD). No animal required inotropic support during the procedure.

3.2. Comparability of experimental groups

A comparison of preoperative animal weights (cranio-caudal group: 21.6 ± 1.7 kg vs. caudo-cranial group: 21.2 ± 1.5 kg) and age (cranio-caudal group: 12.1 ± 0.6 vs. caudo-cranial group: 11.8 ± 0.6) showed no differences between the groups.

As intended by the design of the study, basic hemodynamic data showed no significant differences between groups in heart rate, mean arterial pressure or central venous pressure. There were also no significant differences in rectal or esophageal temperatures between the groups; the mean esophageal temperature ranged from 35.8 to 36.5 °C in the different groups, and the mean rectal temperature from 36.1 to 36.7 °C. No clear hemodynamic, metabolic changes, or blood gas changes were noted during the procedure, with the exception of rising lactate levels. The mean arterial pressure was stable during the procedure under continuous anesthesia, and did not show an increase during segmental or extrasegmental clamping. Arterial lactate levels went up throughout the procedure, but failed to reach significant differences for the different clamping directions (see Table 1).

3.3. Results of motor evoked potentials (MEP)

Reproducible MEPs could be recorded in all study animals. Stimuli were obtained in each animal by the use of a 200–280-V stimulation intensity.

Table 1
Hemodynamic variables and blood gases

<table>
<thead>
<tr>
<th>Variable</th>
<th>Baseline</th>
<th>Before segmental clamping</th>
<th>After segmental clamping</th>
<th>After incision closure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MAP (mmHg)</strong></td>
<td></td>
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<tr>
<td>Craniocaudal ligation</td>
<td></td>
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</tr>
<tr>
<td>Alone</td>
<td>68 ± 7</td>
<td>65 ± 8</td>
<td>70 ± 14</td>
<td>69 ± 6</td>
</tr>
<tr>
<td>With subclavian ligation</td>
<td>65 ± 9</td>
<td>64 ± 6</td>
<td>64 ± 10</td>
<td>66 ± 9</td>
</tr>
<tr>
<td>With MSA ligation</td>
<td>64 ± 10</td>
<td>64 ± 8</td>
<td>74 ± 8</td>
<td>74 ± 9</td>
</tr>
<tr>
<td>Caudocephal ligation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alone</td>
<td>70 ± 11</td>
<td>65 ± 8</td>
<td>65 ± 6</td>
<td>65 ± 8</td>
</tr>
<tr>
<td>With subclavian ligation</td>
<td>63 ± 8</td>
<td>64 ± 5</td>
<td>65 ± 5</td>
<td>63 ± 5</td>
</tr>
<tr>
<td>With MSA ligation</td>
<td>67 ± 8</td>
<td>64 ± 9</td>
<td>70 ± 7</td>
<td>71 ± 6</td>
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<tr>
<td><strong>pH</strong></td>
<td></td>
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<tr>
<td>Craniocaudal ligation</td>
<td></td>
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</tr>
<tr>
<td>Alone</td>
<td>7.47 ± 0.07</td>
<td>7.51 ± 0.08</td>
<td>7.50 ± 0.03</td>
<td>7.44 ± 0.07</td>
</tr>
<tr>
<td>With subclavian ligation</td>
<td>7.48 ± 0.05</td>
<td>7.39 ± 0.11</td>
<td>7.38 ± 0.08</td>
<td>7.35 ± 0.05</td>
</tr>
<tr>
<td>With MSA ligation</td>
<td>7.51 ± 0.04</td>
<td>7.50 ± 0.05</td>
<td>7.46 ± 0.10</td>
<td>7.43 ± 0.08</td>
</tr>
<tr>
<td>Caudocephal ligation</td>
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<tr>
<td>Alone</td>
<td>7.50 ± 0.03</td>
<td>7.48 ± 0.03</td>
<td>7.41 ± 0.07</td>
<td>7.41 ± 0.05</td>
</tr>
<tr>
<td>With subclavian ligation</td>
<td>7.53 ± 0.05</td>
<td>7.50 ± 0.05</td>
<td>7.43 ± 0.05</td>
<td>7.39 ± 0.08</td>
</tr>
<tr>
<td>With MSA ligation</td>
<td>7.51 ± 0.04</td>
<td>7.52 ± 0.06</td>
<td>7.46 ± 0.08</td>
<td>7.38 ± 0.14</td>
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<tr>
<td><strong>O₂ sat. (%)</strong></td>
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<tr>
<td>Craniocaudal ligation</td>
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<tr>
<td>Alone</td>
<td>99.8 ± 0.08</td>
<td>99.8 ± 0.08</td>
<td>99.7 ± 0.12</td>
<td>99.6 ± 0.14</td>
</tr>
<tr>
<td>With subclavian ligation</td>
<td>99.7 ± 0.14</td>
<td>99.7 ± 0.14</td>
<td>99.6 ± 0.11</td>
<td>99.6 ± 0.08</td>
</tr>
<tr>
<td>With MSA ligation</td>
<td>99.7 ± 0.14</td>
<td>99.7 ± 0.14</td>
<td>99.7 ± 0.14</td>
<td>99.7 ± 0.14</td>
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<tr>
<td>Caudocephal ligation</td>
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<tr>
<td>Alone</td>
<td>99.7 ± 0.14</td>
<td>99.7 ± 0.14</td>
<td>99.7 ± 0.14</td>
<td>99.7 ± 0.14</td>
</tr>
<tr>
<td>With subclavian ligation</td>
<td>99.8 ± 0.08</td>
<td>99.7 ± 0.12</td>
<td>99.7 ± 0.12</td>
<td>99.6 ± 0.14</td>
</tr>
<tr>
<td>With MSA ligation</td>
<td>99.7 ± 0.14</td>
<td>99.6 ± 0.11</td>
<td>99.6 ± 0.11</td>
<td>99.6 ± 0.08</td>
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<tr>
<td><strong>Lactate (mg/dl)</strong></td>
<td></td>
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<tr>
<td>Craniocaudal ligation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alone</td>
<td>1.31 ± 0.34</td>
<td>2.38 ± 1.22</td>
<td>3.89 ± 1.49</td>
<td>5.17 ± 1.89</td>
</tr>
<tr>
<td>With subclavian ligation</td>
<td>1.19 ± 0.62</td>
<td>2.72 ± 0.96</td>
<td>3.26 ± 0.98</td>
<td>4.64 ± 1.45</td>
</tr>
<tr>
<td>With MSA ligation</td>
<td>1.35 ± 0.55</td>
<td>1.99 ± 0.64</td>
<td>4.31 ± 1.14</td>
<td>6.57 ± 2.34</td>
</tr>
<tr>
<td>Caudocephal ligation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alone</td>
<td>1.09 ± 0.54</td>
<td>2.33 ± 0.67</td>
<td>3.18 ± 1.54</td>
<td>2.93 ± 0.44</td>
</tr>
<tr>
<td>With subclavian ligation</td>
<td>1.03 ± 0.44</td>
<td>2.56 ± 1.02</td>
<td>2.27 ± 1.69</td>
<td>4.17 ± 1.39</td>
</tr>
<tr>
<td>With MSA ligation</td>
<td>1.14 ± 0.47</td>
<td>2.31 ± 0.96</td>
<td>2.49 ± 0.94</td>
<td>5.62 ± 1.75</td>
</tr>
</tbody>
</table>

All values are shown as mean ± standard deviation. * with P < 0.05 significant in changes from baseline in the same group. MAP, mean arterial pressure; O₂ sat., arterial oxygen saturation; Lactate, arterial lactate levels.
Eleven thoracic segmental arteries and six lumbar segmental arteries were identified in each animal. During sequential clamping in the cranio-caudal direction, starting from the highest level at T2, the animals showed an MEP decrease after clamping (see Fig. 3) of a mean of 12.8 segmental arteries. When both subclavian arteries of the animal were ligated prior to the segmental clamping, MEPs detected spinal cord ischemia after clamping of a mean of nine segmental arteries. When the medial sacral artery was clamped prior to segmental artery interruption, MEPs decreased in the animals after clamping a mean of 4.3 segmental arteries in the cranio-caudal direction.

Clamping of segmental arteries in caudo-cranial direction, starting at L6, revealed onset of MEP disappearance after fewer segmental arteries than cranio-caudal ligation.

MEPs decreased after clamping a mean of 5.8 segmental arteries. Prior to clamping of both subclavian arteries resulted in MEP-amplitude diminution of >50% after a mean of 5.5 clamped lumbar arteries in the caudo-cranial direction. MEP amplitudes decreased >50% after a mean of only 3.5 segmental lumbar arteries had been sacrificed, if the median sacral artery was ligated prior to segmental clamping in the caudo-cranial direction (see Fig. 4).

All transiently clamped segmental arteries that showed an MEP decrease >50% after 5 min were immediately released. MEPs returned to baseline within 10 min.

3.4. Functional evaluation

Nineteen animals emerged from the protocol neurological normal, with a Tarlov score of 4 (full recovery, normal walking function) on the morning after surgery. Only two animals presented with a Tarlov score of 3 (able to stand but unable to walk) on POD 1. Both animals were from the protocol where the median sacral artery and four lumbar segmental arteries were clamped in a caudo-cranial direction. Both pigs made an uneventful recovery and reached a Tarlov score of 4 during POD 1 following intensive training. There were no animals with a Tarlov score less than 3 during the observation period of 3 days.

4. Discussion and conclusions

Because paraplegia is such a devastating complication following thoracoabdominal surgery, and seems to occur even with stent placement, there is enormous incentive to try to reduce its incidence even though the numbers of patients with postoperative spinal cord injury is continuing to decline. A better understanding of spinal cord anatomy and physiology are essential to any further reductions in spinal cord injury. Large animal research using the pig model seems essential for investigation of the dynamics of blood supply to the spinal cord and the reaction of the spinal cord to transient and permanent ischemia [5,6,10]. Studies in the pig model will also be important to verify safety and refine protective measures designed for clinical use in preventing paraplegia.

The pig, with its rich collateral blood supply to the spinal cord, has become a popular and widely accepted model for investigating different strategies for preventing neurological dysfunction during operations on the thoracoabdominal aorta [7,11]. Nevertheless, despite its popularity as an experimental model [5], little information is available about the blood supply and vascular anatomy of the spinal cord and its comparability to the human patient. With the intent to devise a chronic animal model for investigating aortic cross-clamping, segmental perfusion, and the occurrence of delayed as well as immediate postoperative paraplegia, we feel this knowledge is essential.
Overall, there are 16–17 segmental arteries in pigs; usually nine to 11 thoracic and six lumbar arteries. In accordance with its body weight and surface area, the pig shows much larger internal thoracic and sub-scapular arteries than are present in humans, providing extensive collateral flow to the lower body, including additional blood supply to the spinal cord via chest and abdominal wall connections. Furthermore, huge bilateral vertebral arteries feed the circulus arteriosus cerebri (circle of Willis) in pigs, with a large number of small branches. The first two branches on each side are major vessels, which arise at a right angle from the vertebral artery, turning toward the spinal cord in the cervical area, and have a major input in this area above the segmental arteries [12]. The median sacral artery in pigs (roughly equivalent to the hypogastric arteries in humans) is a large caliber vessel, with a size comparable to the common iliac artery, and an isolated dorsal single side branch leading to the spinal cord. One centimeter after its origin from the aortic bifurcation, the median sacral artery also bifurcates, with big branches going in a dorsal and dorso-caudal direction to supply blood to the spinal cord and to the muscles of the hindquarters. We think that there is a significant amount of flow going from these vessels to the lower spinal cord, and that this artery has to be considered important in future spinal cord studies (see Fig. 5).

Monitoring of motor evoked potentials (MEPs) is a now a frequently employed adjunct in thoracoabdominal aneurysm operations to assess anterior and lateral motor column function. As has been previously described, MEPs are highly sensitive when recorded from the lower extremity muscles even in pigs [13–16]. The use of MEPs offers the promise of being able to avert neurological compromise through early detection of abnormal signal transmission from the motor cortex to the distal extremities; whether there is a significant diminution in MEP response will establish whether the borderline contribution of a small segmental vessel is critical to cord viability. The routine monitoring of MEPs under stable anesthesia and analgesia conditions is easy to accomplish [8]. All our findings during MEP monitoring were borne out by postoperative clinical observations, with recovery of motor function in all animals that had return of MEP during operation. There were borderline findings initially in some animals that eventually recovered full function, however, probably reflecting a tenuous blood supply.

Our results during the serial clamping of segmental arteries from different directions, with ligation of a given number of vessels providing blood supply to the cord via collateral pathways, were very reproducible. We were able to determine at which segmental level the decrease of spinal cord blood flow to the cord reaches critical levels. Our study confirmed the work of others, showing that an average of 9 ± 3 arteries is the critical number of intercostal vessels that can be sacrificed without signs of ischemic spinal cord dysfunction [7].

We have demonstrated a major influence of flow coming from the median sacral artery. Clamping of the median sacral artery reduced the number of ligated segmental arteries almost in half regardless of the direction of serial clamping. Clamping of both subclavian arteries also reduced the number of ligated segmental vessels tolerated by the spinal cord before MEP decrease. The reduction in the number of intersegmental vessels which could be sacrificed in the absence of these large sources of collateral blood supply demonstrates dramatically the importance of the median sacral and of the subclavian arteries on spinal cord blood supply in the pig [17]. Our findings suggest that there is no real critical zone of spinal cord blood supply [18], but rather a continuous network fed by large arteries both proximally and distally, as well as by segmental vessels [19,20].

On the basis of clinical experience, we think that the basic anatomy and physiology governing spinal cord blood supply are probably the same in humans, although the proportion of blood flow contributed to the spinal cord collateral network by specific extrasegmental arteries may be different in the pig. We would speculate, for example, that the hypogastric vessels might play somewhat less of a role in humans than the median sacral artery in the pig, given the differences in anatomy and function in the two species. Nevertheless, one must take into account the contribution of the extrasegmental arterial vessels when assessing a patient’s risk of spinal cord injury following thoracoabdominal aneurysm repair [21]. A patient who has had previous replacement of the thoracic or abdominal aorta—or other surgery which might disrupt portions of the collateral network feeding the spinal cord—may be at a high risk of spinal cord injury even with a limited thoracoabdominal resection—or stent, which might not otherwise be a cause for apprehension. And, in fact, some studies reporting use of stents in the thoracoabdominal aorta have identified previous abdominal aneurysm repair as a risk factor for paraplegia following subsequent stent placement.
In summary, a given number of segmental vessels in the pig could be clamped serially without critical ischemia to the cord, as evidenced by MEPs and subsequent functional recovery. As has been described by others [1,7,22], these segmental arteries can become critical to spinal cord viability not only under circumstances in which spinal cord perfusion pressure is compromised, but also if extrasegmental vessels in the chest and abdomen have previously been sacrificed.

The results of this spinal cord study also suggest that MEPs can be recorded reliably in the pig, and can detect segmental arteries and collateral vessels critical to spinal cord blood supply pathways under normothermic conditions. Detection of acute and transient spinal cord ischemia with MEPs occurs without a time delay: MEPs react promptly during disappearance and reappearance. This study provides the physiologic basis for use of the pig model for studies of spinal cord protection in aortic surgery.

References


