Preservation of Spinal Cord Function After Extensive Segmental Artery Sacrifice: Regional Variations in Perfusion

James C. Halstead, MA, MRCS, Michael Wurm, MD, Christian Etz, MD, Ning Zhang, MD, Carol Bodian, DrPH, Donald Weisz, PhD, and Randall B. Griepp, MD

Departments of Cardiothoracic Surgery, Neurosurgery, and Anesthesiology, Division of Biostatistics, Mount Sinai School of Medicine, New York, New York

Background. **Sacrifice of intercostal and lumbar arteries simplifies thoracoabdominal aneurysm surgery and enables endovascular stenting. Little is known about alterations in cord perfusion after extensive segmental artery sacrifice. We explored this question using hypothermia to reduce metabolism.**

Methods. **Twelve juvenile Yorkshire pigs (mean weight, 22.3 kg) were randomized to segmental artery sacrifice at 32°C or 37°C. Cord integrity was assessed with myogenic-evoked potential (MEP) monitoring. Stepwise craniocaudal sacrifice of segmental arteries was continued until MEP diminution occurred; the last segmental artery was then reopened. Fluorescent microspheres were used to measure spinal cord blood flow (SCBF) at baseline, 5 minutes, 1 hour, and 3 hours after segmental artery sacrifice. Hind limb function was monitored for 5 days.**

Results. **All animals recovered normal hind limb function. At 32°C, more segmental arteries, 16.5 versus 15 ($p = 0.03$), could be sacrificed without MEP loss. Baseline SCBF at 32°C was 50% that at 37°C ($p = 0.003$) and remained fairly stable throughout. At 37°C, SCBF to the craniocaudal extremes of the cord (C1 to T3 and L2 to L6) increased markedly ($p = 0.01$) at 1 hour and returned toward normal at 3 hours. Concomitantly, SCBF fell in the middle portion of the cord (T9 to T13) at 1 hour before returning to normal at 3 hours.**

Conclusions. **Almost all segmental arteries can be sacrificed with preservation of spinal cord function. No major change occurs in the central cord in normothermic animals, but there is significant transient hyperemia in segments adjacent to extrasegmental vessels. Hypothermia reduces SCBF and abolishes this possible steal phenomenon. Metabolic and hemodynamic manipulation should enable routine sacrifice of all segmental arteries without spinal cord injury.**

(Ann Thorac Surg 2007;84:789–94)

Spinal cord injury remains the *bête noire* of thoracoabdominal aneurysm surgery. Historical series reported appreciable morbidity and mortality rates, underlining the inherently dangerous nature of this operation [1, 2]. More contemporary series have quoted improved results [3, 4], certainly in part due to an increasing body of experience. Various operative strategies have also been cited as key determinants of the improved outcomes, including systemic hypothermia, distal perfusion, cerebrospinal fluid drainage, and segmental spinal artery reimplantation amongst others. Given that many of these changes arose concurrently and that problems with neurologic injury do still occur, it is important that these factors are carefully and independently assessed.

At Mount Sinai School of Medicine, the clinical approach to thoracoabdominal aneurysm resection has been dictated by the hypothesis that spinal cord perfusion depends on an integrated collateral network rather than the presence of single important major spinal arteries. The use of motor and somatosensory evoked potential monitoring (MEP/SSEP) has led to a technique that avoids reimplantation of segmental vessels altogether, protecting the spinal cord intraoperatively through the use of hypothermia [5] and a variety of bypass techniques (partial cardiopulmonary, left heart, deep hypothermic circulatory arrest) that are usually determined by anatomic factors [4]. Others, reporting a similarly low incidence of neurologic injury, have espoused the importance of critical vessel reimplantation in response to diminution in MEP signals [6].

We sought to examine the changes in spinal cord perfusion during MEP-monitored serial segmental artery sacrifice in a porcine model, with a focus on the impact of mild hypothermia on spinal cord blood flow (SCBF).

Material and Methods

Study Design

Twelve female juvenile (about 3 months old; weight, 24 ± 0.1 kg) Yorkshire pigs (Animal Biotech Industries Inc,

Accepted for publication April 16, 2007.

Presented at the Basic Science Forum of the Fifty-third Annual Meeting of the Southern Thoracic Surgical Association, Tucson, AZ, Nov 8–11, 2006.

Address correspondence to Dr Halstead, Department of Cardiothoracic Surgery, Mount Sinai School of Medicine, One Gustave L. Levy Pl, New York, NY 10029; e-mail: jameschalstead@yahoo.co.uk.

Published by Elsevier Inc

0003-4975/07/$32.00
doi:10.1016/j.athoracsur.2007.04.073

Danboro, PA) were randomly allocated (CB) into two groups of 6 animals: Group A underwent the investigative procedure at 32°C and group B at 37°C. The animals were allowed to reach their target temperature in accordance with group allocation, and fluorescent microspheres were then used to make the baseline SCBF measurements. After this, MEP-monitored segmental vessel sacrifice was undertaken and the blood flow measurements were repeated at specified intervals after the completion of vessel sacrifice.

All animals received humane care in accordance with the guidelines from *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 Institutes of Health (NIH publication No. 86–23, revised in 1985). The Mount Sinai Institutional Animal Care and Use Committee approved the protocol for this experiment.

Perioperative Management and Anesthesia

After premedication with intramuscular ketamine (15 mg/kg) and atropine (0.03 mg/kg) to sedate the animals and dry oropharyngeal secretions, an endotracheal tube was inserted, and a 20-gauge catheter was placed in a suitable ear vein. The animals were then transferred to the operating room and were mechanically ventilated with a fraction of inspired oxygen of 0.7, and a minute volume adequate for maintenance of a normal P_{CO_2} (30 to 40 mm Hg). A crystalloid infusion was started to maintain hydration (12 mL/[kg · hour]). Anesthesia was induced by the bolus intravenous administration of propofol (1 mg/kg) and fentanyl (50 μg/kg) and was maintained with infusions of ketamine (15 mg/[kg · hour]), propofol (7 mg/[kg · hour]), and fentanyl (5 μg/[kg · hour]).

An 8F Foley catheter was placed in the bladder for continuous monitoring of urine output, and temperature probes were placed in the rectum and esophagus. Electrocardiographic monitoring was continuous. Systemic arterial pressure was monitored by using a 14-gauge right brachial artery catheter, through which blood gas analyses were also regularly monitored (Ciba Corning 865, Chiron Diagnostics, Norwood, MA) and reference samples for regional blood flow determinations were withdrawn.

Monitoring for Motor-Evoked Potentials

A 3-cm midline scalp incision was made, through which the periosteum was elevated to reveal the sagittal and coronal skull sutures. Four stainless steel electrodes were screwed into the skull: 2 were placed 1 cm to the left and 2 1 cm to the right of the sagittal suture; the anterior one of each pair was sited 0.8 cm in front of the coronal suture, the other 0.8 cm behind the suture. The electrodes were connected to an electrical stimulator (Digitimer Stimulator Model D 180A, Welwyn Garden City, UK).

Electromyographic recordings were made from stainless steel needle electrodes placed into the anterior and posterior muscle compartments of both fore and hind limbs. A stimulation train (3 pulses: 200 to 300 V, 100-μs pulse duration with a 2-millisecond interstimulus pause) was delivered to the skull electrodes, and the MEPs were recorded in the limbs. The MEP signal was amplified (×2000), bandpass filtered (10 to 1000 Hz), and displayed using a Spectrum 32 neurophysiologic recording system (Cadwell Laboratories Inc, Kennewick, WA).

Operative Technique for Motor-Evoked Potentials–Monitored Segmental Artery Sacrifice

A left posterolateral thoracotomy was made through the seventh intercostal space. The thoracic aorta was mobilized, from the left brachiocephalic artery (the pig has 2 brachiocephalic vessels) proximally down to the aortic opening behind the diaphragm distally, to expose its segmental vessels at their origins. These vessels arise on the left side dorsolaterally as a single vessel that later divides into right and left branches.

A linear left flank incision was made from the costovertebral angle cranially to the posterior aspect of the iliac crest caudally. Through this incision, the abdominal aorta was exposed from the distal extent of the thoracic dissection down to the vessel's trifurcation (the pig has a median sacral artery of similar calibre to its common iliac arteries), without entering the peritoneum, to expose its segmental vessels at their origins.

During the above preparations, we allowed the temperature of group A pigs to drift down to 32°C by keeping a normal ambient room temperature (active cooling was not used). Heating blankets were used to maintain a temperature of 37°C in the group B pigs.

Once the target temperature had been attained, heparin (300 IU/kg) was administered into the ear vein catheter. A tiny opening was made into the pericardium over the left atrial appendage and an 8F catheter was placed through this into the body of the left atrium for microsphere delivery. Baseline MEPs were assessed, and a baseline SCBF measurement was obtained.

The segmental vessels were then sacrificed, one at a time, in the craniocaudal direction. The vessels were clamped for 5 minutes, with MEPs taken at 1, 3, and 5 minutes to assess whether each vessel was critical. If there was no MEP diminution (>75%), the vessel was clipped, divided, and its caudal neighbor clamped, and the MEPs repeated. This process was repeated down the aorta until a critical vessel was identified by a MEP diminution exceeding 75%. Once identified, this vessel was promptly reopened. MEP return occurred within 5 minutes in all animals. Once the critical vessel had been identified, microsphere SCBF measurements were taken at 5 minutes, 1 hour, and 3 hours after it had been reopened. The Yorkshire pig has 17 segmental vessels (11 thoracic and 6 lumbar) that arise directly off the aorta.

After the final microsphere injection, the left atrial catheter was removed, the scalp electrodes were detached, and the incisions were closed. Anesthesia was discontinued, the remaining catheters were removed, and the pig was weaned from the ventilator.