Transcutaneous near-infrared spectroscopy for detection of regional spinal ischemia during intercostal artery ligation: Preliminary experimental results

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Objective: Real-time information about regional spinal cord ischemia can guide intraoperative management and reduce the risk of paraplegia after thoracic aortic surgery. We hypothesized that near-infrared spectroscopy could provide such information during intercostal and lumbar artery ligation in pigs.

Methods: Transcutaneous near-infrared spectroscopic sensors were placed in the midline over the upper and lower thoracic vertebrae of 4 progressively larger pigs (weight range 21-70 kg). After the entire aorta was exposed, segmental arteries from T6 through L1 were sequentially ligated while regional oxygen saturation was monitored. Decreases in regional oxygen saturation were calculated as percentage changes from baseline. The degrees of ischemia in the upper and lower spinal cord were compared histopathologically.

Results: Baseline regional oxygen saturations were similar in the upper (68.8% ± 9.0%) and lower (68.0% ± 11.5%, $P = .82$) cord. After ligation, however, regional oxygen saturation levels were significantly lower in the lower cord (41.3% ± 10.1%) than in the upper cord (64.8% ± 9.3%, $P = .037$). The regional oxygen saturation had decreased by 39.0% ± 11.5% in the lower cord but only by 6.3% ± 7.6% in the upper cord ($P = .026$). This difference was confirmed microscopically: upper-cord sections had fewer ischemic neurons (8.8 ± 9.4) than did lower-cord sections (21.3 ± 13.6, $P = .002$).

Conclusion: Intraoperative spinal cord ischemia was detectable with near-infrared spectroscopy in pigs weighing as much as 70 kg. The potential utility of this technique in patients undergoing thoracic aortic surgery warrants investigation.

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The inability to directly measure spinal cord blood flow and oxygenation intraoperatively is a major obstacle to preventing paraplegia after thoracic aortic surgery. Real-time information about spinal cord ischemia can guide the adjustment of distal aortic perfusion pressure and the reattachment of intercostal arteries.[1]

Current spinal cord monitoring techniques rely on somatosensory-evoked potentials (SSEPs) or motor-evoked potentials (MEPs). Monitoring SSEPs has several disadvantages, including slow response time (caused by delays between the onset of ischemia and the disappearance of potentials) and poor overall sensitivity and specificity.[2-4] Although MEP monitoring has been successfully used to detect spinal cord ischemia, guide surgical strategy, and prevent postoperative neurologic deficits, it has limitations that have prevented it from being widely adopted.[1,5-7]

Transcutaneous near-infrared spectroscopy (NIRS), which exploits the unique near-infrared absorption profiles of hemoglobin, oxyhemoglobin, and cytochrome aa3, is currently widely used for cerebral oximetry during cardiovascular sur-

Abbreviations and Acronyms
MEP = motor-evoked potential
NIRS = near-infrared spectroscopy
Sro_2 = regional spinal oxygen saturation
SSEP = somatosensory-evoked potential
TAAA = thoracoabdominal aortic aneurysm

gery.[8-12] This technique assesses the oxyhemoglobin fraction within a focal area of underlying tissue by measuring the differential absorption of two wavelengths of near-infrared light (730 and 810 nm) that reflect deoxyhemoglobin and total hemoglobin concentration. The purpose of this pilot study was to assess the feasibility of using NIRS to detect spinal cord ischemia during intercostal artery ligation in the pig.

Materials and Methods

The protocol for this study was approved by the institutional animal care and use committees of both Baylor College of Medicine and the Texas Heart Institute. The animals received humane care and handling in compliance with the "Principles of Laboratory Animal Care" formulated by the National Society for Medical Research and with the "Guide for the Care and Use of Laboratory Animals" (http://www.nap.edu/catalog/5140.html).

Anesthetic Management

Four domestic swine (weighing 21, 37, 48, and 70 kg) were premedicated with intramuscular atropine sulfate (0.5 mg/kg), acepromazine maleate (0.1 mg/kg), and ketamine hydrochloride (20 mg/kg). Isoflurane (0.5%-3.0%) was given by mask for induction. Crystalloid fluid was infused throughout the procedure, and boluses of hetastarch were given when needed. Monitors included a pulse oximeter placed on the ear, electrocardiographic leads, and a rectal temperature probe. The animals were orally intubated with a cuffed endotracheal tube through direct laryngoscopy and connected to a volume ventilator that delivered 100% oxygen at a tidal volume of 10 mL/kg. General anesthesia was maintained with inhaled isoflurane (0.5%-3.0%) and pancuronium bromide (0.1 mg/kg). A warming blanket was placed underneath the pigs to maintain normothermia. A carotid artery catheter was used for blood pressure monitoring and arterial blood gas sampling.

Operative Procedure

The dorsal area was shaved and cleaned, and 5100SAF SomaSensors (Somanetics Corporation, Troy, Mich) were placed in the midline over the upper (T6-T7) and lower (T9-T11) thoracic vertebrae. These sensors were connected to an INVOS 5100 Cerebral Oximeter (Somanetics Corporation). A pediatric spinal drainage catheter was inserted into the subarachnoid space through either a laminectomy or direct puncture between the third and fourth lumbar vertebrae.

A left thoracoabdominal incision was made through the sixth intercostal space. The diaphragm was divided, and the entire thoracoabdominal aorta was exposed. Regional spinal oxygen saturation (Sro_2) was monitored continuously by both upper and lower sensors. Raw optical data from the sensors were stored in a computer at 4-second intervals. After baseline Sro_2 levels were recorded, segmental intercostal and lumbar arteries from T6 through L1 were sequentially occluded at approximately 10-minute intervals. Each artery was initially occluded with a bulldog clamp; after approximately 10 minutes of clamping, Sro_2 was recorded, and the artery was ligated with metallic clips and divided.

After all segmental arteries were ligated, 1 mL indocyanine green dye (2.5 mg/mL; Akorn, Inc, Buffalo Grove, Ill) was injected into the subarachnoid space through the spinal catheter. This dye absorbs near-infrared light in a band centered at 805 nm. The catheter was flushed twice with 1 mL saline solution to distribute the dye evenly within the space surrounding the spinal cord. Optical density (the log of the ratio of measured intensity to incident intensity) at 810 nm was recorded with the oximeter to determine changes in light absorption. After ligation of the L1 segmental arteries in each of the 3 largest pigs, the animals were briefly awakened and examined for hind limb paralysis. After this examination, the animals were reanesthetized and humanely killed with intravenous potassium chloride.

Histopathology

The entire spinal column was removed from each of the 3 largest pigs and placed in formalin after the upper and lower segments monitored by the sensors were marked. Identification of the arteria radicularis magna (Adamkiewicz artery) was not attempted. The cords were sectioned, and representative portions of both regions were stained with either hematoxylin and eosin or luxol fast blue dye. A pathologist (F.J.C.) who was blind to the origin of each section (upper or lower cord) examined the sections and quantified ischemic change by counting the number of normal neurons and the number of ischemic neurons per section.

Statistical Analysis

The statistical analyses were performed with SPSS version 12.0 for Windows (SPSS Inc, Chicago, Ill). The following intraoperative variables were compared: mean upper- and lower-cord Sro_2 values at baseline and after ligation of the segmental spinal arteries T6 through L1; absolute percentage Sro_2 decline from baseline after each vessel was ligated; and mean heart rate, temperature, and mean arterial pressure. The upper and lower cords were compared in terms of the number of ischemic neurons and the ratio of ischemic to normal neurons. Continuous variables are reported as mean ± SD and were analyzed with the Student *t* test for between-group differences. We used analysis of variance for comparisons among three or more groups. The Bonferroni correction was used for multiple comparisons.

Results

Clinical

Mean physiologic parameters at baseline included heart rate of 99.0 ± 3.6 beats/min, mean arterial pressure of 55.3 ± 4.3 mm Hg, and rectal temperature of 36.1°C ± 1.9°C. These parameters remained stable throughout the procedures. Baseline Sro_2 values were similar in the upper

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