Evaluation of collateral network near-infrared spectroscopy during and after segmental artery occlusion in a chronic large animal model

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ABSTRACT

Objective: Ischemic spinal cord injury remains the most devastating complication after open and endovascular aortic repair. Collateral network near-infrared spectroscopy has been introduced to noninvasively monitor real-time spinal cord oxygenation. In view of recent advancements in endovascular treatment and minimally invasive staged preconditioning before aortic repair, this study sought to evaluate collateral network near-infrared spectroscopy during and after segmental artery occlusion in a chronic porcine model.

Methods: Surgery for segmental artery occlusion was performed in 12 juvenile pigs, and bilateral lumbar collateral network near-infrared spectroscopy was recorded. Two intervention groups were designed: Group 1 received subtotal segmental artery occlusion (mimicking reimplantation of crucial segmental arteries with patent T12/T13, N = 5), and group 2 received total occlusion (T4-L5, N = 7). Pigs were monitored over 3 days.

Results: All animals were paraplegic during the first 24 hours. The subtotal occlusion group completely recovered, whereas 57% of the total occlusion group remained paraplegic (N = 4/7). After segmental artery occlusion, collateral network near-infrared spectroscopy decreased from $92.3\% \pm 8\%$ of baseline to $69.3\% \pm 18\%$ after 10 minutes in the subtotal group ($P = .003-.017$) and from $90.1\% \pm 4\%$ to $58.2\% \pm 9\%$ in the total group ($P < .001-.008$). Throughout the postoperative period, collateral network near-infrared spectroscopy in the total occlusion group remained lower compared with the subtotal group ($<30\%$ baseline threshold, $P < .05$). Lumbar collateral network near-infrared spectroscopy and neurologic outcome were significantly correlated ($R = 0.7$, $P < .001$).

Conclusions: Lumbar collateral network near-infrared spectroscopy reacts to occlusion of segmental arteries and correlates with neurologic outcome. The preliminary data suggest that collateral network near-infrared spectroscopy may be a valuable noninvasive tool for detecting imminent spinal cord ischemia during and after aortic procedures involving segmental artery occlusion. (J Thorac Cardiovasc Surg 2019;158:155-64)

Scatter graph for cnNIRS and neurologic outcome showing significant positive correlation.

Central Message

cnNIRS reacts to SA occlusion. It correlates with neurologic outcome and is lower in total compared with subtotal occlusion.

Perspective

Lumbar cnNIRS may be a valuable noninvasive tool for detecting pending spinal cord ischemia during and after aortic procedures involving SA occlusion. Further in-depth analyses are warranted to determine the exact threshold for imminent SCI with regard to absolute cnNIRS values.

See Commentary on page 165.

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Ischemic spinal cord injury (SCI) remains the most devastating complication after repair of thoracoabdominal aortic aneurysm (TAAA).^{1,2} Despite contemporary perioperative

Scanning this QR code will take you to the article title page to access supplementary information.

Abbreviations and Acronyms

CN	= collateral network
cnNIRS	= collateral network near-infrared spectroscopy
MAP	= mean arterial pressure
MIS ² ACE	= minimally invasive staged segmental artery coil and plug embolization
SA	= segmental artery
SCI	= spinal cord injury
TAAA	= thoracoabdominal aortic aneurysm

and postoperative adjuncts, the incidence of paraplegia and paraparesis due to SCI after extensive open and endovascular aortic repair (Crawford type II) remains up to 18% in large contemporary series.^{1,3} In addition to the individual tragedy for the patient, postoperative paraplegia also represents an immense socioeconomic burden.⁴

MATERIALS AND METHODS**Monitoring the Spinal Cord**

Few modalities exist to monitor the spinal cord. Common invasive methods of intraoperative spinal cord viability monitoring include motor-evoked potential and somatosensory-evoked potential.^{5,6} Although somatosensory-evoked potential monitoring can be implemented during the postoperative period, motor-evoked potential monitoring on the awake, nonsedated patient is limited.^{7,8} Nevertheless, these modalities usually require significant technical and human resources. Ideally, spinal cord monitoring should reflect perfusion and ultimately tissue oxygenation in real-time to allow for rapid response in hemodynamic (mean arterial pressure [MAP]), cardiopulmonary (atrial fibrillation, ventilation), and cerebrospinal fluid management.

Collateral Network Concept

The collateral network (CN) corresponds to an extensive arterial network—largely localized in the paraspinal musculature—fed by branches of the subclavian arteries, hypogastric artery, and directly from aortic segmental arteries interconnected via collaterals both longitudinally and horizontally. These collaterals enable sufficient blood flow to the spinal cord tissue during chronic or acute perfusion loss after extensive segmental artery (SA) sacrifice.^{9,10}

Collateral Network Near-Infrared Spectroscopy

Collateral network near-infrared spectroscopy (cnNIRS) has been experimentally and clinically introduced and evaluated for noninvasive (indirect) real-time monitoring of spinal cord perfusion and oxygenation in open TAAA repair.¹¹⁻¹³ The rationale for cnNIRS is based on the idea that according to the CN concept, blood supply to and oxygenation in the paraspinal vasculature correlate with spinal cord perfusion and oxygenation.

Our previous clinical and experimental studies have shown that cnNIRS is technically feasible and that lumbar readings correlate with spinal cord perfusion and oxygenation during and after aortic crossclamping and reperfusion.^{11,12} Contemporary data also suggest that high thoracic cnNIRS (T5-T6/7) does not depict changes in regional oxygenation during distal aortic interventions.^{11,12}

Study Aim

Considering the recent introduction of minimally invasive staged SA coil and plug embolization (MIS²ACE) for CN preconditioning before

TAAA repair for paraplegia prevention,^{6,14,15} real-time spinal cord oxygenation monitoring becomes increasingly important, particularly because clinical observation of the awake patient represents the only monitoring method during these procedures.

The aim of this study was to evaluate cnNIRS during and after SA occlusion, focusing on its capability to differentiate between complete and incomplete SA sacrifice and correlation with postoperative neurologic outcome. For this purpose, a chronic large animal model has been designed.¹⁶

MATERIALS AND METHODS**Ethics Statement**

The chronic experimental animal studies were approved by the Institutional Animal Care and Use Committee in accordance with the local Veterinary Office and the Principles of Laboratory Animal Care.¹⁷ An experienced veterinarian was present throughout the experiments.

Preoperative Preparation and Monitoring Set-up

Twelve juvenile female pigs (German Landrace, 36–45 kg) were lodged in groups for 5 days preoperatively to acclimate. Animals were examined thoroughly with regard to their physical and neurologic condition. Neurologic assessment was performed according to a modified Tarlov score¹⁶ (Table E1).

On the day of the operation, the pigs were sedated before being transferred to the operating room. After preoxygenation, anesthesia was supplemented by fentanyl (0.03–0.05 mg/kg fentanyl; Pfizer, New York, NY), and after endotracheal intubation, inhalative isoflurane (1.5%) was administered. Continuous arterial blood pressure monitoring was established via the left femoral artery. Mechanical ventilation was set to 50% oxygen at 20 breaths per minute with a tidal volume adjusted at 8 mL/kg. Body temperature was maintained at 37°C ± 1.5°C. Central venous catheterization of the left jugular vein was performed using a 7F, 20-cm multilumen catheter for additional infusions and blood sampling. The pig was then placed on its right side.

Near-Infrared Spectroscopy of the Collateral Network

After shaving of the animal, lumbar cnNIRS optodes were cutaneously placed bilaterally at level L2 to L3. Preliminary experiments have shown that in nonpigmented, shaved pigs weighing less than 55 kg, cnNIRS measurements during ischemia–reperfusion and baseline are not significantly different regarding cutaneous versus subcutaneous optode placement ($P = 1.000$). Near-infrared spectroscopy signals were continuously recorded using an interface device for noninvasive monitoring of regional tissue (muscle) oxygen saturation of hemoglobin as the ratio between deoxygenated hemoglobin and the sum of deoxygenated and oxygenated hemoglobin (INVOS Oximeter 5100C; Medtronic, Dublin, Ireland). Baseline lumbar cnNIRS values were acquired after preoxygenation and intubation at standard ventilator settings with fraction of inspired oxygen of 0.5.

Surgical Approach

Through a lateral thoracotomy via the fifth and ninth intercostal space, the descending thoracic aorta was visualized, and the segmental arteries (SAs) T4 to T13 were exposed. A catheter was introduced into the proximal descending aorta for invasive arterial blood pressure monitoring. An additional catheter was placed into the left atrium. For pressure monitoring, blood sampling and medication administration during the postoperative period catheters were channeled through the fifth intercostal space and subcutaneous tissue and fixated between the shoulders. Abdominal access and exposition of the abdominal aorta and lumbar SAs were achieved via a longitudinal incision.

Intervention Groups

Previous studies have demonstrated that the most prominent ischemic spinal cord tissue damage after serial SA occlusion occurs between the lower thoracic (T9/10) and upper lumbar (L2/3) segmental levels.^{16,18} During open TAAA repair, many centers perform reimplantation of crucial segmental arteries located in this area. To explore the influence of patent perfusion in this region on lumbar cnNIRS—via segmental arteries located centrally at level T12/T13—2 intervention groups were designed. Group 1 received consecutive SA closure with complete lumbar occlusion but patent SAs at levels T12/13 (subtotal, N = 5). Group 2 received consecutive occlusion of all SAs (N = 7) (Figure 1). One animal was originally intended for subtotal occlusion; however, because of an aortic tear and bloody oozing, 2 pairs of SAs at the lower thoracic level needed to be ligated in short succession to avoid blood loss and prolonged ventilation. Because this animal ultimately had all SAs occluded, it crossed over to the total occlusion group (verified during autopsy).

Experimental Sequence and Monitoring Procedure

Consecutive serial occlusion of the exposed SA (pairs) was performed using vessel clips (Titanium Clips, Teleflex Medical, RTP, Morrisville, NC). Starting from SA T4, occlusion was performed in the caudal direction until L5. MAP (aorta + left femoral artery) and lumbar cnNIRS oxygenation were continuously recorded. Regular arterial blood samples were drawn at 10-minute intervals while continuous oxygenation monitoring via pulse oximetry was recorded. The cnNIRS monitoring system stored oxygenation measurements at 5-second intervals. After SA occlusion, the

animals remained sedated in a right-sided position for 2 additional hours at identical ventilator settings to ensure standardized cnNIRS measurements. During this period, drainage tubes (thoracic and abdominal) were placed and wound closure was performed. During the entire procedure, no vasoactive drugs were administered.

Postoperative Monitoring and Neurologic Assessment

After extubation and transportation from the operating room to the animal housing facility, blood samples and measurements of invasive arterial blood pressure, core temperature, peripheral oxygenation, and lumbar cnNIRS were recorded hourly by a physician until 8 hours postoperatively. Afterward, arterial blood pressure and blood samples were recorded at 6-hour intervals. Clinical outcome and neurologic evaluation were assessed every 12 hours. Animals were observed for 72 hours. Neurologic recovery was defined according to previous studies^{18,19} as a modified Tarlov score greater than 5 and permanent paraplegia/paraparesis 5 or less, respectively. After the experiments were completed, the animals were anaesthetized and euthanized in deep sedation. The spinal cord was removed en bloc immediately after euthanasia before correct catheter placement and SA occlusion was confirmed, and the autopsy resumed.

Histopathologic Evaluation

All spinal cords were harvested, and samples from each cord level (identified by nerve root) collected. Evaluation of ischemic cell injury was performed independently and blinded by 2 experienced researchers as previously described and illustrated (Table E2).^{16,18}

FIGURE 1. Subtotal (group 1) = consecutive SA occlusion with patent perfusion of T12 + T13, total (group 2) = complete SA occlusion T4-L5.

Statistical Analysis

Data were imported to SPSS (version 17.0; SPSS, Chicago, Ill) for description and analysis. Continuous variables are expressed as mean $\pm$ standard deviation. Normal distribution of measurements was determined using the Shapiro–Wilk test, and Q–Q plots were created for verification. Group comparison of lumbar *cnNIRS* and spinal cord tissue was performed using analysis of variance or Student *t* test for repeated/correlated measures as appropriate. For correlation analysis, scatter plots were calculated and evaluated using the Spearman's rank correlation coefficient.

RESULTS

Clinical Outcome and Paraplegia Rate

Immediately after the operation all animals—subtotal and total occlusion—presented with severe hind limb motor function loss (modified Tarlov score ≤ 2) for the first 12 hours and 5 or less until 24 hours after surgery. All animals in the subtotal group recovered within 48 hours (median score at 48 hours = 9; range, 8–10), whereas animals in the total occlusion group needed more time for neurologic recovery (median score at 48 hours = 6; range, 1–8; $P = .023$). The rate of permanent paraplegia/paraparesis in group 2 (total) was 57% ($N = 4$). Other adverse events throughout the experiment are listed in Table E3.

Lumbar Near-Infrared Spectroscopy Measurements

Analysis of variance between left and right *cnNIRS* measurements did not show systematic differences ($P = 1.000$); therefore, the 2 results were averaged to provide a mean estimate of changes.

Collateral network near-infrared spectroscopy during subtotal segmental artery occlusion (group 1). During serial SA occlusion of T4 to L5—sparing SA T12/13—*cnNIRS* remained stable throughout thoracic SA occlusion, but rapidly decreased from $92.3\% \pm 8\%$ of baseline to $77.8\% \pm 9\%$, $72.4\% \pm 10\%$, and $69.3\% \pm 14\%$ at 1, 5, and 10 minutes after SA occlusion, respectively ($P = .003$ – $.017$). Within 1 hour after surgery, *cnNIRS* values increased to $76.0\% \pm 10\%$, fluctuating during the first 24 hours—reaching minimum values of $71.2\% \pm 11\%$ at 6 hours and maximum values of $79.5\% \pm 10\%$ at 12 hours postoperatively—before steadily increasing to stable values of $86.0\% \pm 6\%$ and $89.5\% \pm 9\%$ on days 2 and 3, respectively (Figure 2, group 1/black, and Table E4).

Collateral network near-infrared spectroscopy during total segmental artery occlusion (group 2). Analogous to group 1 (subtotal), complete SA occlusion led to a significant, yet more pronounced reduction in *cnNIRS* with mean

FIGURE 2. Comparison of lumbar *cnNIRS* measurements between subtotal (blue dots) and total (red dots) SA occlusion. Values gradually digress throughout the postoperative period (represented by the regression lines). The regression line of animals from the subtotal group (blue line) remains above the 30% *cnNIRS* threshold. *cnNIRS*, Collateral network near-infrared spectroscopy; SA, segmental artery.

differences between groups ranging from $4.4\% \pm 3.1\%$ to $6.1\% \pm 3.9\%$ during the first 10 minutes. Starting from $89.4\% \pm 4\%$ of baseline prior occlusion, *cnNIRS* in group 2 gradually decreased to $70.5\% \pm 10\%$, $65.9\% \pm 9\%$, and $59.2\% \pm 8\%$ at 1, 5, and 10 minutes, respectively ($P < .02$). After surgery, *cnNIRS* values increased to $64.3\% \pm 10\%$ and $61.8\% \pm 14\%$ from 1 to 24 hours, respectively. At 36 hours postoperatively, lumbar *cnNIRS* demonstrated a decrease to $57.8\% \pm 15\%$ baseline before gradually increasing over the remaining surveillance period reaching stable maximum values between $60.5\% \pm 14\%$ and $63.2\% \pm 15\%$ (Figure 2, group 2/red, and Table E4).

Comparison between subtotal and total segmental artery occlusion. Continuous *cnNIRS* measurements before SA occlusion did not differ significantly between groups. Postocclusion *cnNIRS* measurements for the total occlusion group were lower throughout the entire surveillance period compared with the subtotal group, but they did not reach statistical significance until 10 minutes after SA occlusion ($P < .05$). After 2 days, *cnNIRS* remained stable in both groups at different oxygenation levels between 86.0% and $89.0\% \pm 8\%$ of baseline for the subtotal and 60.0% and $63.0\% \pm 16\%$ of baseline for the total group, respectively ($P < .05$, Figure 2).

Mean Arterial Blood Pressure Measurements

Changes in MAP of the entire cohort ranged from 5% to 7% of baseline. After surgery, MAP did not demonstrate

excessive variations (range, 92%-102% of baseline). Comparison of MAP during and after consecutive SA occlusion reveals no significant difference between subtotal and total occlusion (Figure E1; $P = .314-.899$). Correlation analysis among unaltered MAP, *cnNIRS*, and neurologic outcome was not significantly correlated ($R = 0.1-0.5$, $P = .227-.950$). During the experiment, MAP was not intentionally altered to minimize its influence on *cnNIRS* measurements.

Lumbar Collateral Network Near-Infrared Spectroscopy and Neurologic Outcome

Irrespective of the intervention group, animals that recovered ($N = 8$) returned to *cnNIRS* values above 30% of baseline within the first postoperative hour, whereas animals with permanent paraplegia ($N = 4$, all total occlusion animals) remained below 30% of baseline throughout the entire surveillance period (Figure 3). Immediately after SA clipping until 10 minutes postocclusion, both recovering and paraplegic animals demonstrated comparable lumbar *cnNIRS* dynamics with significantly reduced levels compared with baseline ($P = .001$, Table E5). Within 3 days postoperatively, *cnNIRS* measurements of recovering animals returned to values not significantly different from their individual baseline ($91.4\% \pm 6\%$ vs $88.9\% \pm 9\%$, $P = .429$). However, paraplegic animals' postoperative *cnNIRS* measurements further decreased relative to their baseline values ($88.5\% \pm 4\%$ vs $37.7\% \pm 14\%$, $P = .023$; Table E5).

FIGURE 3. *cnNIRS* is shown throughout the experiment (top) and the postoperative neurologic status (bottom, Tarlov score). Animals that recovered (left, *cnNIRS* in blue) and animals that remained paraplegic (right, *cnNIRS* in green). Recovering animals remain above the 30% *cnNIRS* threshold throughout the postoperative period (black median line), whereas paraplegic animals remain below the 30% threshold. *cnNIRS*, Collateral network near-infrared spectroscopy; SA, segmental artery.

The return of lumbar *cnNIRS* measurements above 30% baseline preceded neurologic recovery by approximately 24 to 30 hours. Analysis demonstrates a significant positive correlation between *cnNIRS* measurements and neurologic outcome as illustrated in Figure 4 ($R = 0.7$, $P < .001$). For clarification, a scatter graph showing individual *cnNIRS* point data with regard to subtotal versus total occlusion and recovering versus paraplegic animals has been generated (Figure E2).

Histologic Results

The cervical spinal cord tissue showed no relevant ischemic damage, independent of the intervention group and postoperative neurologic status (Figure 5).

Animals with subtotal occlusion ($N = 5$) had less severe tissue damage compared with the total occlusion group ($N = 7$; Figure 5, top). Although differences are evident starting from level T3 downward to level L5, statistical significance is reached only for T5 and T8 ($P = .030$ and $.045$).

Accordingly, because all paraplegic animals were from the total occlusion group ($N = 4$), mean spinal cord tissue damage was significantly more severe for paraplegic

animals compared with animals that recovered (0-4.3, range, 0-8 vs 0-1.9, range, 0-5; $P < .001$; Figure 5, bottom).

DISCUSSION

The presented experiment showed for the first time that lumbar *cnNIRS* reacts to selective SA occlusion and is capable of differentiating between a subtotal and a total occlusion pattern. Furthermore, evaluation of *cnNIRS* and neurologic outcome revealed significant positive correlation. Although an exact cutoff value for *cnNIRS* regarding SCI could not be determined, animals that remained paraplegic had consistent mean *cnNIRS* values lower than 30% of baseline, whereas animals that recovered returned to levels above 30% of baseline within the first postoperative hour. A short synoptic perspective statement is provided in Video 1.

Demand for Noninvasive Monitoring

With the recently introduced endovascular procedure for paraplegia prevention by means of staged CN preconditioning through MIS²ACE,^{14,18} and a general trend toward more extensive endovascular aortic procedures, noninvasive

FIGURE 4. Correlation graph for *cnNIRS* and neurologic outcome. Values are depicted for each animal at each postoperative time point ($N = 12$, starting 1 hour postoperatively) showing a significant positive correlation. Different time points are color coded demonstrating the association between recovering animals and higher *cnNIRS* ratios after 24 hours. High *cnNIRS* values associated with low Tarlov scores are exclusively measurements within the first 24 postoperative hours, when “temporary” paraplegia was present in all animals. It is demonstrated that high Tarlov scores (>5) are not associated with low *cnNIRS* measurements ($<30\%$ of baseline). *cnNIRS*, Collateral network near-infrared spectroscopy.

FIGURE 5. Degree of histopathologic spinal cord damage; (left) comparing recovering (N = 8, blue) and paraplegic (N = 4, red) animals; (right) comparison between subtotal (N = 5, blue) and total (N = 7, green) SA occlusion. Each colored dot represents a spinal cord tissue sample (cervical = C; thoracic = T, and lumbar = L) with a horizontal line showing the median value according to a tissue damage scoring system from 0 (no damage) to 8 (severe damage). It is noticeable that cord damage of the lower thoracic and lumbar region is more severe in paraplegic animals (left, red) and after total SA occlusion (right, green) compared with recovering animals and those receiving subtotal occlusion, respectively.

monitoring methods depicting real-time spinal cord perfusion/oxygenation become all the more essential.

Previous Experience With Collateral Network Near-Infrared Spectroscopy

Previous experimental and clinical studies on *cnNIRS* have shown that although in heterogeneous setups and study protocols, it reflects oxygenation changes after aortic cross-clamping and distal aortic perfusion in real-time.^{7,8,11-13,20}

On the basis of these and other studies, *cnNIRS* emerged as a promising new and economic method, potentially guiding extensive aortic procedures by giving real-time feedback on spinal cord perfusion.²¹

Sensitivity of Collateral Network Near-Infrared Spectroscopy to Segmental Artery Occlusion

Lumbar *cnNIRS* reacted to acute interruption of proximal SA perfusion; however, lumbar *cnNIRS* first started

VIDEO 1. Short background, conclusion, and perspective statement by the senior author. Video available at: [https://www.jtcvs.org/article/S0022-5223\(18\)33255-0/fulltext](https://www.jtcvs.org/article/S0022-5223(18)33255-0/fulltext).

to decrease once the lower thoracic/lumbar SA inflow was occluded, demonstrating a less severe decrease in measurements with patent lower thoracic SAs. Whether SA occlusion by means of stent-graft implantation or MIS²ACE of only a limited number of arteries can be depicted by lumbar cnNIRS remains to be evaluated. After serial SA occlusion, cnNIRS signals of recovering animals consistently increased throughout the surveillance period, which is in accordance with previous clinical reports and experiments.^{2,10,16,22} Moerman and colleagues²² demonstrated an immediate linear correlation of cnNIRS and arterial blood pressure after regional SA inflow interruption. However, this linear cnNIRS dependency on arterial blood pressure was not demonstrated in the present study, because no animal experienced relevant blood pressure alterations.

In an early experiment on spinal cord NIRS monitoring by LeMaire and colleagues,⁷ sequential ligation of segmental arteries from T6-L1 led to a prominent decrease at the lower thoracic level (T9-T11). These were significantly lower than measurements from the upper cord (T6-T7), showing a decrease of only 6.3% of baseline (upper cord) compared with 39% (lower cord, $P = .026$). These findings are consistent with recent studies^{11,12} attributing the measurement stability of the upper thoracic region to the collateralization via the subclavian/internal thoracic arteries. Whether in addition to lumbar cnNIRS optodes, mid and especially lower thoracic cnNIRS measurements also are necessary for a complete and consistent oxygenation mapping of the CN is yet unclear and is the focus of ongoing research. The limitation of optode placement directly above the vertebrae has been acknowledged by their respective authors, who suggested that measuring surrounding tissue may enable indirect cord monitoring via the paraspinal CN,^{7,20,23} a concept that represents the rationale for current cnNIRS monitoring practice.^{11,12,23}

Although sensitivity of cnNIRS after stent deployment during endovascular aortic repair was recently published in 2 reports (total of 3 patients),^{21,22} available data from

previous case series and ongoing clinical investigations suggest that lumbar cnNIRS does not reliably pick up relevant changes in oxygenation during endovascular procedures in humans (not experiencing procedure-related SCI).^{11,24} It is important to note that optode positioning in the aforementioned case reports was at the lower thoracic level (T9-T11), whereas optodes in current clinical investigations are placed bilaterally at the lumbar level (L1-L3).

The presented study demonstrates that cnNIRS is capable of reflecting CN oxygenation in real-time after selective SA occlusion, also differentiating between complete SA interruption and patency of 2 SA pairs. Nevertheless, the threshold of critical SA sacrifice necessary to be detected by cnNIRS in humans remains unclear. Whether patients exhibiting stable cnNIRS signals also have sufficient perfusion to maintain adequate spinal cord tissue oxygenation, directly via intraspinal collaterals or indirectly via the paraspinal CN,^{10,25} needs to be further investigated.

The Conundrum of Segmental Artery Patency

Patency of 2 pairs of segmental arteries led to higher cnNIRS signals and expectably less spinal cord tissue damage with accelerated neurologic recovery. The rationale of maintaining perfusion via the lowest thoracic segmental arteries was mainly chosen on the basis of previous studies, demonstrating that this region exhibits the most distinct spinal cord tissue damage after consecutive SA sacrifice.^{16,18} These findings are consistent with the results of the presented study (most pronounced SCI between thoracic level 8 and lumbar level 2).^{16,18} This boundary zone—ranging from T9/10 to L2/3—seems to represent the most vulnerable region for ischemic tissue damage. The favorable clinical outcome and less severe spinal cord tissue damage of animals with patent CN inflow to this region underscore this theory, also emphasizing the clinical potential of real-time cnNIRS.

During recent years, clinical studies have divided the aortic community.²⁶⁻²⁸ Although it becomes more and more apparent that SA reimplantation during open aortic repair does not provide absolute safety, it may offer some protection against postoperative hemodynamic instabilities. With regard to SCI protection, however, this topic remains highly debated among experts.

At first glance, it may seem that the presented results are in favor of surgical SA reimplantation. However, it is important to emphasize the fundamental differences in clinical SA reimplantation. In this experiment, no aortic cross-clamping, SA ostia opening, or time-consuming surgical reimplantation was performed. Therefore, disadvantageous effects of reimplantation that may potentially mitigate adequate preconditioning, such as back-bleeding with steal from the CN or subsequent thrombotic SA occlusion after reimplantation, did not occur. Rather than SA reimplantation, the presented experimental set-up corresponds to a

lopsided, open-staged procedure for CN preconditioning. On the basis of these observations, 2 different future experimental and clinical approaches may be considered. Either (1) SAs of the lower thoracic/upper lumbar region should be spared during a first MIS²ACE session to ensure potential superior neurologic integrity or (2) exclusively this region should be occluded first, thereby potentially facilitating a more pronounced stimulus for CN preconditioning and adequate spinal cord ischemia prophylaxis.

Clinical Implications and Future Perspectives

The presented findings underscore the potential of lumbar cnNIRS to be a clinically applicable and easy-to-use real-time monitoring modality particularly during the early postoperative period. Of note, all animals that recovered neurologically managed to reestablish cnNIRS oxygenation values above 30% of baseline within 1 hour postoperatively. Whether the predictive value of cnNIRS for neurologic recovery depends on such an oxygenation threshold (eg, 30% of baseline) or is time-dependent (eg, oxygenation recovery within 1 hour postocclusion) cannot be answered conclusively at this point. For clinical practice, however, the demonstrated correlation with neurologic recovery is encouraging, because it is especially important for sedated patients with prolonged ventilation, for whom the risk of delayed paraplegia during the postoperative period seems the greatest.²⁹ The fact that lumbar cnNIRS depicted oxygenation changes in the CN over a course of 3 days, potentially reflecting the CN collateralization process, also warrants further clinical and experimental investigation.

Study Limitations

Because of anatomic and physiologic differences between species (pigs and humans), conclusions drawn from any translational experimental research should be interpreted with caution. When assessing regional tissue oxygenation via cnNIRS, the emitted light penetrates through the paraspinal vasculature/muscles, averaging measurements over the entire area in its optical path. In pigs, the deep paraspinal muscles are arranged in a mainly sagittal, rather than transversal manner; thus, a longitudinally placed optode on a 45-kg pig always measures a larger portion of the CN compared with an average human adult. Yet, this difference may be solved by using larger animals or measuring/averaging values of an equally large portion of the human CN (eg, by placement of additional optodes).

CONCLUSIONS

Lumbar cnNIRS reacts to occlusion of segmental arteries in real time and correlates with neurologic outcome. Patency of 2—nonreimplanted—pairs of segmental arteries of the lower thoracic region results in a less pronounced lumbar cnNIRS decrease, potentially facilitating

maintenance of sufficient spinal cord perfusion. This preliminary data suggests that cnNIRS may be a valuable noninvasive tool for detecting imminent spinal cord ischemia during and after aortic procedures involving segmental artery occlusion. Further in-depth analyses are warranted to determine the exact threshold for imminent spinal cord injury with regard to absolute cnNIRS values.

Conflict of Interest Statement

Authors have nothing to disclose with regard to commercial support.

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Key Words: collateral network near-infrared spectroscopy, minimally invasive segmental artery coil and plug embolization, spinal cord protection, thoracoabdominal aortic aneurysm repair

FIGURE E1. The invasive mean arterial blood pressures throughout the experiment are shown (subtotal, N = 5 in blue, versus total, N = 7 in red). No significant differences throughout the experiment and in-between groups can be shown. SA, Segmental artery.

FIGURE E2. Individual data points for lumbar cnNIRS. Left: Scatter plot showing cnNIRS throughout the experiment comparing subtotal occlusion (blue dots and blue regression line) and total occlusion (red dots and red regression line). Right: Comparison between cnNIRS measurements for recovering animals (blue dots and blue regression line) and paraplegic animals (green dots and green regression line). Recovering and paraplegic animals seem to have substantial overlap intraoperatively. Values gradually digress throughout the postoperative period (represented by the regression lines). cnNIRS, Collateral network near-infrared spectroscopy; SA, segmental artery.

TABLE E1. Neurologic assessment (modified Tarlov score)

Modified Tarlov score	
Score	Description
0	No voluntary movements
1	Perceptible movements at joints
2	Good movements at joints but inability to stand
3	Ability to get up with assistance but no ability to stand
4	Ability to get up with assistance and stand with assistance
5	Ability to get up with assistance and stand unassisted
6	Ability to get up and stand unassisted <1 min
7	Ability to get up and stand unassisted >1 min
8	Ability to walk <1 min
9	Ability to walk >1 min
10	Complete recovery

TABLE E2. Ischemic spinal cord damage score with example images

Score	Definition	Image
0	No apparent necrosis
1	Necrosis of single (motor) neurons only	
2	Necrosis of 1 posterior horn only	
3	Necrosis of both posterior horns only
4	Necrosis of both posterior horns/surrounding white matter	
5	Necrosis of both anterior horns only	
6	Central necrosis (posterior/anterior horns/parts of white matter)
7	Complete necrosis of grey matter only	
8	Complete necrosis of the whole section	

TABLE E3. Adverse events other than paraplegia

Adverse events during the experiment	
Postoperative day	Description
0	Intraoperative aortic laceration located in between 2 SAs with need for subsequent ligation (N = 1)
0-1	Temporary difficulties in micturition (N = 3)
0-3	Neurogenic bladder syndrome with overflow incontinence (N = 2, paraplegic animals only)
3	Mild to moderate pleuritis (incidental autopsy finding), normal oxygenation and behavior (N = 2)
3	Pleural effusion not affecting breathing or general health condition (incidental autopsy finding, N = 4)

SA, Segmental artery.

TABLE E4. Lumbar collateral network near-infrared spectroscopy measurements for intervention groups (subtotal and total occlusion)

Procedural step	Group 1 (subtotal, N = 5)			Group 2 (total, N = 7)		
	cnNIRS	cnNIRS (%)	MAP	cnNIRS	cnNIRS (%)	MAP
Preoperative baseline	62.4 ± 5	100	70.8 ± 7	62.5 ± 4	100	67.2 ± 4
Prior SA occlusion	57.3 ± 4	92.3 ± 8	67.0 ± 4	55.5 ± 2	89.4 ± 4	67.6 ± 4
Thoracic SA occlusion	54.7 ± 4	88.1 ± 7	63.2 ± 4	53.9 ± 3	86.3 ± 5	64.0 ± 6
Lumbar SA occlusion	48.6 ± 9	78.3 ± 11	63.6 ± 4	45.3 ± 5	72.7 ± 10	65.0 ± 3
1 min postocclusion	48.3 ± 9	77.8 ± 11	62.0 ± 4	43.9 ± 6	70.5 ± 10	65.4 ± 2
5 min postocclusion	44.9 ± 9	72.4 ± 11	60.8 ± 4	41.1 ± 6	65.9 ± 9	64.4 ± 3
10 min postocclusion	43.0 ± 10	69.3 ± 14	61.2 ± 3	36.9 ± 5	59.2 ± 8	64.6 ± 3
60 min postocclusion	47.2 ± 8	76.0 ± 10	63.0 ± 5	39.8 ± 5	64.3 ± 10	67.8 ± 4
12 h postocclusion	49.4 ± 5	79.5 ± 10	66.4 ± 3	39.3 ± 6	63.6 ± 13	68.4 ± 3
24 h postocclusion	47.7 ± 5	76.8 ± 9	67.8 ± 2	38.1 ± 6	61.8 ± 13	69.4 ± 2
48 h postocclusion	53.4 ± 4	86.0 ± 6	65.2 ± 2	39.5 ± 9	63.2 ± 15	68.7 ± 1
72 h postocclusion	55.6 ± 7	89.5 ± 9	65.0 ± 3	37.7 ± 9	60.5 ± 16	72.4 ± 3

cnNIRS, Collateral network near-infrared spectroscopy; MAP, mean arterial pressure; SA, segmental artery.

TABLE E5. Lumbar collateral network near-infrared spectroscopy measurements for recovering and paraplegic and group comparisons

Procedural step	Recovery group (N = 8)			Paraplegic group (N = 4)		
	cnNIRS	cnNIRS (%)	MAP	cnNIRS	cnNIRS (%)	MAP
Preoperative baseline	62.1 ± 5	100	70.5 ± 5	63.1 ± 3	100	63 ± 2
Prior SA occlusion	56.5 ± 3	91.4 ± 6	66.6 ± 4	55.7 ± 1	88.5 ± 4	70 ± 4
Thoracic SA occlusion	53.9 ± 3	87.1 ± 6	62.2 ± 4	54.7 ± 1	86.9 ± 4	69.5 ± 4
Lumbar SA occlusion	46.2 ± 6	75.0 ± 12	63.5 ± 3	47.2 ± 5	75.1 ± 11	67.2 ± 3
1 min postocclusion	45.0 ± 7	73.1 ± 13	62.8 ± 3	46.3 ± 6	73.6 ± 11	67.3 ± 2
5 min postocclusion	41.3 ± 6	63.2 ± 15	61.8 ± 4	44.2 ± 5	70.2 ± 10	66.2 ± 3
10 min postocclusion	38.8 ± 9	71.3 ± 15	62.3 ± 4	39.5 ± 4	62.8 ± 9	65.6 ± 2
60 min postocclusion	43.8 ± 7	76.5 ± 14	64.8 ± 6	40.6 ± 6	64.7 ± 11	67.5 ± 3
12 h postocclusion	46.9 ± 6	73.7 ± 14	67.5 ± 4	37.0 ± 6	59.0 ± 11	65.5 ± 2
24 h postocclusion	45.2 ± 7	73.7 ± 14	67.6 ± 3	36.4 ± 4	58.0 ± 9	66.5 ± 4
48 h postocclusion	52.8 ± 5	85.1 ± 6	66.6 ± 3	28.0 ± 5	43.0 ± 9	70 ± 3
72 h postocclusion	55.2 ± 8	88.9 ± 9	69.6 ± 5	24.5 ± 9	37.7 ± 14	68 ± 3
Procedural step	cnNIRS (%)		Mean difference	95% CI		P value
Comparison: Recovery group						
Prior SA occlusion	91.4 ± 6					
10 min postocclusion	71.3 ± 15		28.2 ± 11	16.3-38.1		.001
72 h postocclusion	88.9 ± 9		4.2 ± 9	−7.2-14.2		.429
Comparison: Paraplegic group						
Prior SA occlusion	88.5 ± 4					
10 min postocclusion	62.8 ± 9		25.5 ± 5	18.8-29.9		.001
72 h postocclusion	37.7 ± 14		47.9 ± 9	9.2-79.5		.023

cnNIRS, Collateral network near-infrared spectroscopy; CI, confidence interval; SA, segmental artery.