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Abstract:
Objectives. We adopted the nearinfra-red spectroscopy (NIRS) technology to monitor the spinal oxygen supply through the paraspinal muscles oxygenation in agreement with the concept of “collateral network” circulation. We retrospectively investigated our database of subjects who underwent Thoraco-abdominal aorta open repair assessing for the reliability of this monitoring to predict spinal cord injury.

Methods. Consecutive Patients who underwent elective thoraco-abdominal aorta open repair between March 2019 and September 2021. In addition to standard monitoring, patients received the monitoring of the paraspinal muscles oxygenation by NIRS.

Results. In one patient a significant drop of the mean arterial pressure (49 mmHg) and the spinal-cord perfusion pressure (31 mmHg) occurred after the aortic clamping, with a contemporary lowering of the left-side oxygenation of paraspinal muscles (<40%). Both the blood pressure and the spinal cord perfusion pressure were restored within 10 minutes, but the oxygenation remained at an unsafe level (<55%) until the end of the surgery. This same patient experienced a lower-limbs paralysis post-operatively. It did not happen in the other 11 cases of the sample.

Conclusions. The main finding of our retrospective analysis indicates reliability of this technology to monitor the spinal cord oxygenation during open thoraco-abdominal aortic surgery and possibly predict spinal cord injury. Still, several questions need to be addressed about the suitability of this technology to the anatomic and pathophysiology of the spinal cord circulation.

Key Words: Thoraco-abdominal aortic surgery; spinal cord injury; paraplegia.

INTRODUCTION
Thoraco-abdominal aortic (TAA) open repair is a complex surgical procedure with a relevant impact due to the great “surgical invasiveness” and anesthesiologic issues linked to it. Consequently, the patient is at high risk for a complicated outcome (respiratory failure, acute kidney injury, severe intra-and/or post-operative bleeding, ileus, liver disfunction, cardiac adverse events, spinal cord injury) or even death.

Spinal cord injury (SCI) due to ischemia during aortic surgery still has a significant incidence (5-11%) and is one of the most distressing complications in this surgical setting1,2. It impacts on patients’ quality of life because of the paraplegia perse and the psychological aftermath.

Spinal cord (SC) viability during thoracic aortic surgery can be monitored by motor evoked potentials (MEP) or somato-sensory evoked potentials (SSEP), two systems requiring invasive applications, dedicated personnel, and technical skills3. Therefore, MEP and SSEP are not routinely employed. The most widely adopted estimation of SC perfusion is the Spinal-cord perfusion pressure (SC-PP) resulting from the difference between the mean arterial pressure (MAP) and the sub-archnoid pressure (sAP). In addition, the catheter that permits the monitoring of sAP allows the anesthetist to drain the cerebro-spinal fluid (CSF). This action, causing the sAP reduction, contributes to increase the SC-PP, if MAP does not change or increase.

A decade ago, Etz et al. described the “Collateral Network” , a concept whereby the blood circulation of paraspinal muscles should provide blood supply to the spinal cord too4. Following this assumption and considering the anatomic characteristics of the spinal cord circulation (as also described
by Melissano et al. - Figure 1), we started to monitor the near-infra-red spectroscopy (NIRS) of the paraspinal muscles oxygenation during open thoracic and thoraco-abdominal aortic surgery. The present study reports the results of the retrospective analysis of a small case series.

Figure 1. The spinal cord circulation

METHODS
Between March 2019 and September 2021 we collected the perioperative data of consecutive patients who underwent elective open surgery repair of thoraco-abdominal aorta, at Humanitas Research Hospital in Milan, (Italy). The open approach was indicated and consequently performed upon multidisciplinary consultation.

Emergent operations and endovascular procedures were not included.

This retrospective observational study received the permission of the local Ethical Committee (CE n. 39/21).

STROBE guidelines, and the STROBE checklist were used (http://strobe-statement.org/index.php?id=strobe-home).

The type of TAA in our Hospital is classified according to the Crawford classification6.

Lower limbs palsy was defined by ASIA classification (American Spinal Injury Association; see https://asia-spinalinjury.org).

Before general anesthesia, we inserted a sub-arachnoid catheter (Hermetic™ Lumbar Catheter Open Tip, 80 cm, Integra NeuroSciences, Plainsboro, NJ, USA) at lumbar level (L3-L4) aimed at monitoring and managing the sub-arachnoid pressure (sAP) and measuring the cerebro-spinal fluid lactate concentration (LacCSF) by a point-of-care machine (GEM Premier 3500-Instrumentation Laboratory Company, Bedford, MA, USA). Then, we placed two NIRS sensors (INVOS™ 5100 Somanetics - Medtronic, Minneapolis, MN, USA) at the thoraco-lumbar region (T9-L2) over paraspinal muscles, (Figure 2).

Figure 2. NIRS sensors placement
NIRS=Near Infra-Red Spectroscopy

An arterial line had been placed into the radial artery to monitor the invasive blood pressure (IBPrad). Moreover, a four-lines central venous catheter was inserted into the left internal jugular vein for drugs and fluids administration, while another 8Fr-central venous catheter was inserted into the right internal jugular vein for fluids and blood products at high-flow rate.

The surgeon provided a second arterial line into the right femoral artery to monitor the blood pressure (IBPfem) supplied by the by-pass pump (Bioconsole560-Medtronic, Minneapolis, MN, USA) draining blood from the left atrium and returning it into the left femoral artery.
The patient is placed in the left lateral decubitus position. Incision, aortic dissection, proximal and distal cross-clamping and anastomosis, and need for arterial reattachment, depend on aneurysm type.

For type 1 and 2 aneurysms, we perform the incision at the 5th intercostal space level, with posterior displacement of the ribs; extension of the incision anteriorly and along the median line of the abdomen is required for type 2 aneurysms. It allows the exposure of the abdominal aorta in the retroperitoneum by mobilizing spleen, left kidney, and left colon to the left side.

For type 3 and 4 aneurysms, we chose the skin incision at the 8th or 9th intercostal space.

For type 2 and 3, the diaphragm is sectioned.

Once the exposure is complete and the aorta is adequately isolated, we perform proximal cross-clamping after the left-bypass pump started.

Regarding the distal clamping, a fixed or a sequential clamp technique can be chosen depending on the level of the distal aneurysmal neck.

Sometimes, we use Fogarty balloon catheters to aid in occluding intercostal, visceral, or renal arteries. Considering ischemic time might be lengthy, we generally provide these arteries with a cooled perfusion solution.

When needed, we adopt a Carrel patch technique for visceral and renal arteries reattachment: most commonly, the celiac trunk, the superior mesenteric artery and the right renal artery are kept on the same patch, while the left renal artery is reimplemented individually. Sometimes, endoarterectomy of the arterial ostia might be required. Typically, the inferior mesenteric artery can be safely ligated after ensuring colonic perfusion is maintained by the arc of Riolan.

Thereafter, we perform the distal anastomosis at a level depending on the extension of the aneurysm. If the abdominal aorta is involved, we prefer to execute it at the level of the iliac bifurcation. Eventually, some previously selected intercostal arteries can be reattached to the aortic graft using a patch - if they are anatomically close enough - or a button technique - if they are too far to be positioned on a unique patch.

Intra-operative monitoring included standard measurements (non-invasive blood pressure, NIBP; Electrocardiogram of D2 and V5 lines; heart rate, HR; end-tidal CO\(_2\), etCO\(_2\); peripheral oxygen saturation, SpO\(_2\)), mean invasive blood pressure from both lines (mIBP\(_\text{rad}\) and mIBP\(_\text{fem}\)), and blood-gas analysis. Further monitoring included cerebro-spinal lactate concentration (Lac\(_\text{CSF}\)), spinal-cord perfusion pressure (i.e., SC-PP=mIBP\(_\text{rad}\) - SAP) and spinal-cord oxygenation derived from the NIRS (rSO\(_2\)) sensors.

All patients received general anesthesia (Propofol+Fentanyl for the induction; O\(_2\)+Air+Sevoflurane for maintenance; Rocuronium for neuromuscular blockade).

Our monitoring targets consisted of mIBP\(_\text{rad}\) >65 mmHg, sAP <15 mmHg, SC-PP ≥50 mmHg and mIBP\(_\text{fem}\) 60-80 mmHg. Despite Literature suggests a mIBP\(_\text{fem}\) >80 mmHg, in agreement with surgeons, we adopted a little lower level as a safe compromise between providing the spinal cord perfusion and the limitation of intraoperative blood loss.

In case of mIBP\(_\text{rad}\) <65 mmHg, Norepinephrine was the first-choice drug. When inotropic support needed, we administered Dobutamine. To reach the target SC-PP we increased mIBP\(_\text{rad}\) and/or reduced sAP by CSF drainage as appropriate: 5-10 ml of CSF within 1-2 minutes.

Alongside spinal-cord perfusion pressure, Lac\(_\text{CSF}\) and rSO\(_2\) were used as warnings of SC hypoperfusion/ischemia. Particularly, CSF lactate concentration >4 mmol/L was the cutoff value, since Lac\(_\text{CSF}\) >3 mmol/L had been described to be associated with SCI.

All the patients were actively warmed. Nevertheless, mild intra-operative hypothermia (34.5-35.5 °C) was tolerated.

After the operation, patients were admitted to intensive care unit (ICU) sedated and mechanically ventilated. When normal body temperature had been reached (36°C), the intensivist performed a basic neurological assessment (awareness and legs’ motility and sensitivity) during a free-of-sedation time–window. Then, sedation restarted along with respiratory support ventilation. The weaning from mechanical ventilation was generally achieved within the following 12 hours if no complications occurred.

In case of lower limbs paralysis, after the provisional diagnosis of SCI, patients would have received a magnetic resonance imaging (MRI).

Upon discharge from our hospital, all the patients were sent to a specialized rehabilitation center.

**Statistics**

Data are reported as either mean ± standard deviation, median and range, or number and percentage, as appropriate.

The Pearson correlation test was used to explore linear association between parameters. Pearson’s coefficient (r) between variables has been reported as value within the Confidence Interval 95%.

We assumed p<0.05 for statistical significance.

Analysis was performed with Prism 8.2.1 Software - GraphPad 2356 Northside Dr. Suite 560 - San Diego, CA 92108 United States.

**RESULTS**

We retrospectively analyzed 12 cases admitted to our hospital for open repair of thoraco-abdominal aorta (TAA).

The sample age was 67 ± 9.5 yrs (median 68 yrs; range 49
÷ 82 yrs) and according to the Crawford classification⁶, their aneurysm resulted as follows: 4 type-1, 6 type-2, 1 type-3 and 1 type-4. Preoperative ASA (American Society of Anesthesiology physical status classification) score resulted as follows: six subjects in class 2 and six in class 3. Nine of them were males, (Table 1).

The mean total duration of the aortic clamping was 101 ± 46 min. The average intraoperative CSF drainage was 73 ± 29 ml.

Before the aortic clamping, the baseline data (T0) are summarized in Table 2.

The type-4 case that had not been considered at a risk for SCI and then the surgeon did not perform any intercostal artery reimplantation to the prosthesis. Conversely, 6 patients received at least two paired intercostal arterial branches reimplantation, and 2 patients received a single pair of intercostal arteries reattached to the aortic graft (one of these two patients experienced SCI).

Out of the 12 patients, one case (Crawford type 2), indicated as Pt2, showed a reduction of rSO₂ to <40% on the left side at T1 and only at T6 it reached a value >50%. In this case a significant hypotensive event (mIBP₉₀ = 49 mmHg; duration 5-10 minutes) occurred at T1 and was promptly and successfully treated by fluids and NE administration.

Except for Pt2 case, the whole-sample average of mIBP₉₀ was always >70mmHg and the SC-PP had been maintained >50mmHg. Pt2 showed a SC-PP = 31 mmHg at T1, with both mIBP₉₀ and SC-PP restored during the interval T2-T3 (mIBP₉₀ >80 mmHg and SC-PP >60 mmHg).

In Pt2 we observed a high serum concentration of lactate (sLac). Specifically, at T6, sLac = 7.2 mmol/L and Lac₉₀ = 2.4 mmol/L. At the same time-point the average sLac and Lac₉₀ in the whole sample were 2.7 ± 1.8 mmol/L and 2.1 ± 0.3 mmol/L, respectively.

Figure 3 shows the trends of NIRS, blood pressure and lactatemia both in the serum and CSF, of each single patient. In Pt2, the trends showed some differences. Specifically, at T1 mIBP₉₀ decreased below 65 mmHg, the left-side NIRS dropped with a nadir at around 30% of oxygenation. Then we ruled out the sensor displacement since the right-side oxygenation was stable.

### Table 1. The sample characteristics and general perioperative results

<table>
<thead>
<tr>
<th>Sex</th>
<th>9 Male, 3 Female</th>
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<tbody>
<tr>
<td>Age (years)</td>
<td>67 ± 9.5</td>
</tr>
<tr>
<td>ASA</td>
<td>2-3</td>
</tr>
<tr>
<td>Crawford classification (n, %)</td>
<td></td>
</tr>
<tr>
<td>Type 1</td>
<td>4 (33.3)</td>
</tr>
<tr>
<td>Type 2</td>
<td>6 (50.0)</td>
</tr>
<tr>
<td>Type 3</td>
<td>1 (8.3)</td>
</tr>
<tr>
<td>Type 4</td>
<td>1 (8.3)</td>
</tr>
<tr>
<td>Aortic clamping duration (minutes)</td>
<td>101 ± 46</td>
</tr>
<tr>
<td>Total intra-operative CSF drainage (ml)</td>
<td>73 ± 29</td>
</tr>
<tr>
<td>Hospital length-of-stay (days)</td>
<td>15 ± 11</td>
</tr>
<tr>
<td>ICU length-of-stay (days)</td>
<td>7 ± 8</td>
</tr>
<tr>
<td>Duration of mechanical ventilation (hours)</td>
<td>26 ± 27</td>
</tr>
<tr>
<td>Patients who experienced post-operative complications (n,%)</td>
<td>9 (75.0)</td>
</tr>
<tr>
<td>Deaths during hospitalization (n,%)</td>
<td>0 (0.0)</td>
</tr>
<tr>
<td>Deaths during rehabilitation program (n,%)</td>
<td>1 (8.3)</td>
</tr>
</tbody>
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### Table 2. Baseline values

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<table>
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<tr>
<td>Mean radial arterial pressure (mmHg)</td>
<td>78 ± 14</td>
</tr>
<tr>
<td>Sub-Arachnoid pressure (mmHg)</td>
<td>17 ± 5</td>
</tr>
<tr>
<td>Spinal-Cord Perfusion Pressure (mmHg)</td>
<td>61 ± 13</td>
</tr>
<tr>
<td>Serum Lactate (mmol/L)</td>
<td>0.9 ± 0.3</td>
</tr>
<tr>
<td>CSF - Lactate (mmol/L)</td>
<td>1.5 ± 0.2</td>
</tr>
<tr>
<td>NIRS right side (%)</td>
<td>75 ± 7</td>
</tr>
<tr>
<td>NIRS left side (%)</td>
<td>77 ± 8</td>
</tr>
<tr>
<td>Cardiac Index (L/min/m² body surface area)</td>
<td>2.1 ± 0.5</td>
</tr>
<tr>
<td>Serum Hemoglobin (g/dL)</td>
<td>10 ± 2</td>
</tr>
</tbody>
</table>


In addition, when the Pt2’s blood pressure dropped (T1: 49 mmHg), the spinal-cord perfusion pressure reduced accordingly (31 mmHg) and returned to normal value as blood pressure was restored (T2: mIBP\text{rad} = 80 mmHg; SC-PP = 61 mmHg).

Three more patients experienced a transient hypotensive event during aortic clamping along with SC-PP dropping, but none of them showed a corresponding reduction in rSO$_2$.

We did not find any correlation between SC-PP and Lac$_{Csf}$, SC-PP and rSO$_2$, Lac$_{Csf}$ and rSO$_2$, and slac from T0 to T6, except for rSO$_2$ and slac from T3 to T6. Table 3 lists the Pearson coefficients and statistical significance of these correlations. Conversely, we observed a significant correlation between NIRS and sLac, (Figure 4).

Out of the 12 cases, three cases (25%) had an uneventful outcome. The most frequent complication was respiratory impairment: three cases of post-operative pneumonia (25%) and two cases of atelectasis were also diagnosed (16.6%). All of these had tested positive to a Covid-19 swab more than one month before and underwent surgery after two consecutive negative swabs along with a pre-operative negative chest X-ray.

One case of pneumonia needed ICU admission for 30 days and received a tracheostomy too. He died of a septic shock due to urinary tract infection during the rehabilitation phase.

Other complications consisted of one case (8.3%) of acute kidney injury (AKI) recovered after temporary continuous renal replacement therapy (CRRT), one case of acute pancreatitis (8.3%), one case of transient sub-arachnoid fistula (8.3%), and one case of hematemesis due to stress-related gastric ulcer (8.3%) and finally one case (Pt2) of post-operative paraplegia (8.3%). In addition, two patients experienced two simultaneous adverse events post-operatively (one pneumonia+AKI and the other pneumonia+stress-related gastric ulcer).

The other three patients with transient intraoperative hy-
potension did not show spinal cord injury post-operatively. None of the twelve patients had any complication associated with the insertion of the CSF drainage.

**DISCUSSION**

The main finding of our retrospective analysis indicates a possible reliability of NIRS to monitor the spinal cord oxygenation during open thoraco-abdominal aortic surgery. To corroborate this assumption, we can consider that only the patient who experienced postoperative lower limbs paralysis showed an even unilateral reduction of rSO$_2$ for most of the intraoperative time. Conversely, when rSO$_2$ drop was transient it resulted harmless.

Spinal Cord Injury in TAA repair may occur in a percentage that reach 11% or even more depending on the type of procedure (endovascular or open surgery), the extension of the

<table>
<thead>
<tr>
<th>Time</th>
<th>r</th>
<th>p</th>
<th>r</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>T0</td>
<td>0.2098</td>
<td>0.5127</td>
<td>0.1882</td>
<td>0.5580</td>
</tr>
<tr>
<td>T1</td>
<td>0.4170</td>
<td>0.1774</td>
<td>0.1658</td>
<td>0.6065</td>
</tr>
<tr>
<td>T2</td>
<td>0.1055</td>
<td>0.7717</td>
<td>-0.4357</td>
<td>0.2081</td>
</tr>
<tr>
<td>T3</td>
<td>-0.2271</td>
<td>0.5281</td>
<td>-0.7219</td>
<td>0.0184</td>
</tr>
<tr>
<td>T4</td>
<td>-0.1666</td>
<td>0.6684</td>
<td>-0.7373</td>
<td>0.0234</td>
</tr>
<tr>
<td>T5</td>
<td>-0.6020</td>
<td>0.0384</td>
<td>-0.7785</td>
<td>0.0029</td>
</tr>
<tr>
<td>T6</td>
<td>-0.7444</td>
<td>0.0055</td>
<td>-0.7640</td>
<td>0.0038</td>
</tr>
</tbody>
</table>

**Table 3. Correlation between rSO$_2$ and serum Lactate**

**Figure 4.** Correlation between NIRS and sLac and LacCSF

NIRS=Near Infra-Red Spectroscopy; LacCSF = Cerebro-Spinal Fluid lactate concentration.

Why did rSO2 desaturation explains the hypoxia of the spinal cord? Second, First, why would only unilateral rather than bilateral oxygen progressively but reached a similar level of other cases.

ly restored, the CSF-Lactate concentration started to rise pro-

- rSO2 and LacCSF may be due to the fact that dead cells (neurons in this case) do not have any metabolism and then

Moreover, Rojas et al., in a study including 32 cadavers, found asymmetry of the spinal cord arterial circulation both in terms of anatomic disposition and caliber of the vessels, in up to 81.25% of the cases.

In few words, the single pair of arterial branches reattached to the aortic graft might have not been sufficient to sustain the spinal cord circulation.

Depending on several vascular and metabolic factors, a safe pressure level does not always ensure an adequate flow. Indeed, in animal models, spinal cord autoregulation is less robust than cerebral autoregulation and more pressure-dependent, hence SC is more sensitive to hypotension.

Noteworthy, Vanpeteghem et al., found different effects of phenylephrine and ephedrine on cerebral oxygen saturation and paraspinous oxygen saturation. Following vasoactive drug administration resulted in a steal phenomenon: an increased blood flow to the spinal muscles, masking the spinal cord hypoxia. The authors concluded that the application of the “Collateral network” concept in case of vasoconstrictive drug use remains to be confirmed.

In our case, NE was able to restore blood pressure promptly, but left side rSO2 remained at low levels. Then, we might assume that the phenomena observed by Luher and Vanpeteghem’s could explain our findings.

With regards to the Lactate concentration, we know that if the Blood-Brain Barrier (BBB) is intact, there is no mixing of blood and CSF. The LacCSF is a marker of the central nervous system anaerobic metabolism, like during an ischemic injury. When the BBB is disrupted (as in the case of prolonged ischemia) a mix of blood and CSF should occur. In Pt2 case LacCSF increased more than in CSF, possibly because lactatemia was also depending on the paraspinous muscles ischemia.

When spinal cord ischemia occurred due to a transient hypotension, rSO2 reduced, marking the hypoxic state on the left side. Even when blood pressure was restored on the left-side, spinal ischemia persisted. The late normalization of rSO2 was only due to the muscles restored oxygenation through any collateral circulation.

In our experience, we already found a significant increase of LacCSF in a patient submitted to open TAA repair who experienced SCI post-operatively. Unfortunately, at that time we did not monitor rSO2 and consequently we cannot compare the two cases.

Experimental evidence about NIRS as an index of spinal cord circulation is conflicting. Suehiro et al., reported that NIRS may be used to detect changes in spinal cord circulation following aortic clamping and de-clamping in animal model, whereas it may not reflect changes in spinal cord circulation due to cerebrospinal fluid drainage.

If both rSO2 and LacCSF are markers of spinal cord ischemia, the inconsistency between the drop of the former and the hampered rise of CSF-lactate concentration in the Pt2 patient is unexpected and difficult to explain. The lacking correlation between rSO2 and LacCSF may be due to the fact that dead cells (neurons in this case) do not have any metabolism and then
do not produce lactic acid.

Our case series has several limitations. First, its retrospective nature along with the small sample size do not permit definite conclusions and consequently these findings should be considered mostly speculative. Moreover, a single case of deoxygenation observed may have been accidental. Finally, as discussed above, our results leave some important open questions.

In conclusion, Near Infra-Red Spectroscopy application at the thoraco-lumbar region over paraspinous muscles may be helpful to indirectly monitor the spinal cord oxygenation during open repair of thoraco-abdominal aorta. Anyway, we are aware that further specific investigations are desirable to better understand how to interpret and integrate paraspinous muscles $rS_O_2$ in the setting of thoraco-abdominal aorta open surgery.

Assessing the reliability NIRS in this field, could provide a helpful and non-invasive tool to monitor the spinal cord oxygen supply. The surgeon might use it as a tool to decide for further collateral branches re-implantation to the prosthesis. The anesthetist might use it to guide the strategies to prevent spinal cord injury.

ACKNOWLEDGEMENTS

Acknowledgement to Prof. Paul A. Kelly (www.profesor-in-ingles-online.com) for the English language support and revision of the paper.

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