Identification and Selective Perfusion of the Spinal Cord-Feeding Arteries by Intrathecal pO_2 Monitoring for Spinal Cord Protection

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Objectives: to study whether spinal cord-feeding arteries could be identified by the changes in the intrathecal pO_2 (I-pO_2), and to examine whether selective perfusion of feeding arteries identified by this method could protect the spinal cord against ischaemia.

Design: controlled animal experiments.

Materials and methods: in experiment 1, using 16 mongrel dogs, 18 segmental arteries were cannulated through which oxygenated saline was injected and the I-pO_2 change was observed. When the I-pO_2 increase was more than 0.5 mmHg, the artery was considered to be a spinal cord-feeding artery. In experiment 2, involving 10 dogs, the segmental arteries identified as spinal cord-feeding arteries were perfused with arterial blood and the recovery of I-pO_2 and evoked spinal potentials (ESP) was examined.

Results: of 208 segmental arteries examined, 176 (84.6%) arteries were correctly judged and 32 (15.4%) were not. It was observed that the I-pO_2 recovered from 13.9 to 30.5 mmHg and the ESP recovered from 20.9% and 8.2% to 66.5% and 44.7% of each control for the first negative (N1) and second negative (N2) components, respectively.

Conclusion: spinal cord-feeding arteries were successfully identified using the I-pO_2 monitoring method. Perfusion of these arteries with arterial blood improved the I-pO_2 and ESP, which were significantly depressed by ischaemia.

Key Words: Spinal ischaemia; Aorta; Surgery; Intrathecal pO_2; Evoked spinal potentials; Feeding artery; Selective perfusion.

Introduction

Paraplegia remains one of the most catastrophic complications of thoracic and/or thoracoabdominal aortic surgery. Svensson et al. reported the incidence of ischaemic spinal cord injury to be 16%.¹ Theoretically, it would be beneficial to perfuse the spinal cord-feeding arteries while the thoracic or thoracoabdominal aorta is cross-clamped and/or opened for surgery. However, it is essential to identify the spinal cord-feeding arteries from among the many pairs of segmental arteries (intercostal or lumbar arteries).

When blood supply to the spinal cord decreases, O_2 tension in the spinal cord must consequently decrease.² We have recently developed a monitoring method for intrathecal pO_2 (I-pO_2).³ The purpose of this study was to examine firstly whether the spinal cord-feeding arteries could be identified by measuring the I-pO_2, and secondly to examine whether or not perfusion of these arteries with oxygenated blood could improve the I-pO_2 and evoked spinal potentials (ESP) which decrease during ischaemia.

Materials and Methods

Sixteen mongrel dogs, weighing between 8.5 to 19 kg, and 10 mongrel dogs, weighing between 7 to 13 kg, were anaesthetised initially by ketamine hydrochloride (10 mg/kg) intramuscularly (i.m.) with atropine sulphate (0.25 mg, i.m.). After endotracheal intubation, the animals were mechanically ventilated (oxygen: 41/ min; halothane: 0.5 vol %; tidal volume: 20 ml/kg; respiratory rate: 16 times/min). Pancuronium bromide (total dose: 2-4 mg/dog) was used as a muscle relaxant. Before aortic clamping, heparin sulphate (100 U/kg) was given.
Fig. 1. Placement of the pO₂ probe and the electric stimulation electrode for ESP. After opening dura mater at the L3 level, an intrathecal pO₂ (I-pO₂) probe was placed adjacent to the anterior spinal cord artery. A silver-ball electrode for ESP stimulation was placed at the L4 level in the epidural space. L1, L2, L3, L4: the first, second, third and fourth lumbar vertebrae, respectively.

Experiment 1

Dogs were laid on their abdomen and a laminectomy performed on the third lumbar vertebra (L3). After the dura mater was opened, the pO₂ measuring probe was placed at the level between L1 and L2 in front of the spinal cord and as closely as possible to the anterior spinal cord artery (Fig. 1). The animals were then turned onto their right side and a thoracoabdominal incision made. The aorta was dissected below the left subclavian artery and above the iliac bifurcation to determine the level of intercostal and lumbar arteries between the 10th thoracic vertebra (T10) and L5. The aorta was encircled for clamping with a tape between T11 and T12 and between L5 and L6. The coeliac, superior mesenteric, and bilateral renal arteries were also taped for clamping (Fig. 2).

The I-pO₂ was measured as the control value, the aorta was clamped just below the left subclavian artery and the I-pO₂ observed for 5 min. The aorta was then additionally clamped between T11 and T12 and between L5 and L6. The coeliac, superior mesenteric and bilateral renal arteries were also clamped to eliminate collateral influx into the spinal cord. The abdominal aorta was then opened and each of seven pairs of segmental arteries from T12 to L5 was cannulated using a 4 French size (4F) catheter.

Ten ml of oxygenated saline (pO₂ approximately 300 mmHg) was manually (approximately 1 ml/s) injected into the segmental arteries each via a catheter and the I-pO₂ measured. As shown in Fig. 3, when a spike-like increase in I-pO₂ of more than 0.5 mmHg was observed, the artery was regarded as a spinal cord-feeding artery. When no I-pO₂ increase or an I-pO₂ increase of equal to or less than 0.5 mmHg was seen, the artery was considered not to be a feeder. The animals were then killed under deep anaesthesia and indigo carmine solution was injected into one or two segmental arteries which were considered as feeders based on the I-pO₂ change. The posterior part of the vertebrae was removed using a Striker saw and the spinal cord carefully exposed without cutting radiculae of the spinal cord. After the thoracic and/or lumbar level of each radicula was examined, the spinal cord was removed. The dura was carefully opened on the ventral side and the anterior spinal artery and radicular arteries which ran into the spinal cord were examined anatomically (Fig. 4). The result was compared with that judged by the I-pO₂ response to the oxygenated saline injection.

Experiment 2

An I-pO₂ measuring probe was placed as in experiment 1, and an ESP-stimulating electrode was inserted into the epidural space at the L4–L5 level through the L3 laminectomy (Fig. 1). After this, a left thoracotomy was done in the 4th intercostal space, the thoracic aorta was taped for aortic clamping and an ESP-sensing electrode placed in the 4th thoracic vertebral disc. Using a thoracoabdominal incision, the entire aorta was exposed and the segmental arteries were
Intrathecal pO₂ Monitoring

Fig. 3. Patterns of the I-pO₂ changes after oxygenated saline injection. (1): Significant, spike-like increases in the I-pO₂ of more than 0.5 mmHg. (2): A change in the I-pO₂ equal to or less than 0.5 mmHg. Three arrows indicate the time of oxygenated saline injection into a segmental artery.

dissected from the 12th intercostal to the 5th lumbar vertebra levels and taped for cannulation. A 4-mm diameter tube was inserted into the thoracic aorta through the left carotid artery and connected to a roller pump for perfusion of segmental arteries with arterial blood (pO₂ 119.9 ± 24.5 mmHg) (Fig. 5).

The thoracic aorta was clamped just below the left subclavian artery for 10 min. After placing another aortic clamp between T13 and L1 segmental arteries, the I-pO₂ and ESP were observed for another 10 min. Following this, the abdominal aorta was clamped between L3 and L4 and between L5 and L6 and longitudinally incised between these two clamps. For the following 20 min, four segmental arteries (two pairs) were examined, as in experiment 1, to determine whether they were spinal cord-feeding arteries. One of the arteries judged as feeders was perfused for the next 20 min (flow volume of 60 ml/min) using a roller pump with arterial blood drawn through the left carotid artery. Recovery of the I-pO₂ and ESP was examined at the time points 5, 10, 15, and 20 min of perfusion. After a 10-min ischaemic interval, one of the arteries judged as non-feeders was perfused in the same manner and the changes in I-pO₂ and ESP were similarly examined.

The I-pO₂ was measured every 5 min and was presented in mmHg, compared between the values of control, before perfusion, and with perfusion of feeders and non-feeders. For ESP measurement, stimulation was given with an amplitude of 10 mA, a pulse width of 0.1 ms, and a frequency of 7 Hz. The 20 responses emitted from the chest electrode were averaged. The ESP change was evaluated as a percentage change in the amplitudes of the first negative component (N1) and the second negative component (N2) as compared to the control wave. The N1 component is considered to represent the conductive potentials in the dorsal and dorsolateral funiculi. The N2 component is considered to represent the activity of the neurons in the posterior horn and the action potentials of the slow conductive dorsal column fibres. In both experiments a 20-gauge catheter was inserted into each of the right brachial and right femoral arteries.
to measure mean proximal aortic pressure (PAP) and mean distal aortic pressure (DAP). Body temperature was measured every 5 min in the paravertebral muscle near the vertebra with a needle electric thermometer. The I-pO₂ was measured with a medical mass spectrometer (Medspect II; Chemetron Corp., St Louis, MO, U.S.A.) using a PhysioProbe (Salt Lake City, UT, U.S.A.) and the values were corrected for body temperature.³

The control PAP and DAP were 104.2±22.4 and 92.8±20.4 mmHg, respectively. After placing the proximal aortic clamp, the PAP promptly increased to 152.1±19.3 mmHg (p<0.01 vs. control), and the DAP promptly decreased to 19.3±4.9 mmHg (p<0.01 vs. control). After the second and third distal clamps, the PAP and DAP showed little change (Fig. 6). The I-pO₂ was 33.5±4.5 mmHg before aortic clamping. After the first clamp below the left subclavian artery, the I-pO₂ suddenly decreased to 20.9±3.4 mmHg (p<0.01). After the second and third distal clamps, the I-pO₂ showed no further changes (Fig. 6)

Statistics/Ethics

Data are expressed as means ± s.d. Statistical analysis was done using Student’s t-test to compare the variable (Statview J4.0.2, Abacus Concepts Inc., U.S.A.). When a p value was <0.05, the difference was considered to be statistically significant.

All animals received care in accordance with the Principles of Laboratory Animal Care formulated by the National Society of Medical Research and the Guide for the Care and Use of the Laboratory Animals prepared by the National Academy of the Sciences and published by the National Institute of Health (NIH Publication no. 80-23, revised in 1978).

Results

Experiment 1

The control PAP and DAP were 104.2±22.4 and 92.8±20.4 mmHg, respectively. After placing the proximal aortic clamp, the PAP promptly increased to 152.1±19.3 mmHg (p<0.01 vs. control), and the DAP promptly decreased to 19.3±4.9 mmHg (p<0.01 vs. control). After the second and third distal clamps, the PAP and DAP showed little change (Fig. 6). The I-pO₂ was 33.5±4.5 mmHg before aortic clamping. After the first clamp below the left subclavian artery, the I-pO₂ suddenly decreased to 20.9±3.4 mmHg (p<0.01). After the second and third distal clamps, the I-pO₂ showed no further changes (Fig. 6)
Table 1. Result of identification of feeder and non-feeder by I-pO₂.

<table>
<thead>
<tr>
<th>Dog no.</th>
<th>n</th>
<th>True (P,N)</th>
<th>False (P,N)</th>
<th>Accuracy (%)</th>
</tr>
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<td>3</td>
<td>12</td>
<td>9 (4,5)</td>
<td>3 (3,0)</td>
<td>75.0</td>
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<tr>
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<td>5</td>
<td>12</td>
<td>10 (4,6)</td>
<td>2 (0,2)</td>
<td>83.3</td>
</tr>
<tr>
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</tr>
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<tr>
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</tr>
<tr>
<td>16</td>
<td>14</td>
<td>11 (5,6)</td>
<td>3 (2,1)</td>
<td>78.6</td>
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<tr>
<td>Total</td>
<td>208</td>
<td>176 (77,99)</td>
<td>32 (19,13)</td>
<td>84.6</td>
</tr>
</tbody>
</table>

pO₂, intrathecal oxygen tension; n, numbers of segmental arteries examined; P, positive; N, negative.

The results with 208 segmental arteries examined (10–14 segmental arteries per dog) are presented in Table 1. Ninety-six arteries were considered as feeding arteries and 112 arteries were judged not to be feeders. The height of the spike-like I-pO₂ increase ranged from 0.7 to 15.0 mmHg (mean 1.7). Anatomical observations revealed that 176 (84.6%) out of 208 segmental arteries examined were correctly assessed using I-pO₂ changes (Table 1). Of these arteries, 77 were judged to be feeders and 99 were not. Thirty-two segmental arteries (15.4%) were erroneously judged by I-pO₂ changes. Of these, 13 segmental arteries were incorrectly assessed as not being feeders (false-negative) and 19 as being feeders when they were not (false-positive). The accuracy in individual dogs ranged from 60% to 100% (mean 84.6%, sensitivity 85.6%, specificity 83.9%).

Experiment 2

The control PAP and DAP were 113.5±16.7 and 103.1±16.3 mmHg, respectively. After the clamp on the proximal thoracic aorta, PAP rapidly increased to 174.1±13.9 mmHg while DAP decreased to 15.5±2.6 mmHg. Both these changes were statistically significant. After the second and third aortic clamps, no further significant changes in PAP and DAP were observed throughout the experiment (Fig. 7). The I-pO₂ was 36.9±6.3 mmHg before aortic clamping. After the first clamp below the left subclavian artery, the I-pO₂ suddenly decreased to 16.7±6.5 mmHg (p<0.01). After the second distal clamp the I-pO₂ further decreased to 13.8±6.1 mmHg. The I-pO₂ then showed little change until the segmental arteries were perfused (Fig. 7). The N1 and N2 components decreased significantly following the first proximal aortic clamp to 77.5±30.6 and 73.4±29.2% of respective control values (15.4%) were erroneously judged by I-pO₂ changes. Of these, 13 segmental arteries were incorrectly assessed as not being feeders (false-negative) and 19 as being feeders when they were not (false-positive). The accuracy in individual dogs ranged from 60% to 100% (mean 84.6%, sensitivity 85.6%, specificity 83.9%).

As in experiment 1, it was anatomically confirmed that all of the 40 segmental arteries at the levels of L4 and L5 examined were successfully identified as being either spinal cord-feeding or non-feeding arteries with the exception of one false negative case. Twelve feeders and eight non-feeders were perfused with arterial blood. After 5-min perfusion of the spinal cord-feeding arteries, the I-pO₂ increased significantly from 13.9±7.8 to 30.5±6.6 mmHg (p<0.01), presenting little fluctuation through to the end of perfusion (Fig. 7, left square). The difference from the baseline control value prior to clamping disappeared after 20 min of perfusion of the feeding arteries. In contrast, the I-pO₂ did not show any significant change throughout perfusion of the non-feeding arteries: 16.5±7.6 to 18.8±6.4 mmHg (Fig. 7, right square). There remained
Fig. 7. Changes in I-pO₂, the proximal and distal aortic blood pressures in experiment 2. *: \( p < 0.01 \) as compared to the control value. **: \( p < 0.01 \) as compared to the I-pO₂ value not only before perfusion of the spinal cord-feeding arteries but also by perfusion of non-feeding arteries at each corresponding time point. #: \( p < 0.01 \) as compared to each control value and the corresponding PAP/DAP value. The abbreviations are the same as in Fig. 6.

Discussion

Postoperative paraplegia caused by spinal cord ischaemia remains a major problem of thoracic and/or thoracoabdominal aortic surgery. The spinal cord-feeding arteries are located at different sites in different individuals and are therefore difficult to identify during operation. We tried to use the I-pO₂ not only for monitoring of the spinal cord ischaemia, but also for identifying the spinal cord-feeding arteries. This is because we know that there is a good correlation between the epidural pO₂ and the spinal blood pressure and that I-pO₂ responds faster to and correlates better with changes in pO₂ of the spinal cord parenchyma than those in pO₂ of the epidural space. On the other hand, electrophysiological monitoring methods such as ESP, spinal motor evoked potential, and somatosensory evoked potential have been used for the monitoring of the spinal function. Therefore, in this study we used ESP as such an indicator in combination with the circulatory indicator of I-pO₂.

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The mechanism for the spike-like elevation of I-pO$_2$ observed after injection of saline into the spinal cord-feeding arteries is thought to be as follows. Injected oxygenated saline goes into the anterior spinal artery, reaching the pia mater and the spinal cord parenchyma. Oxygen then promptly diffuses into cerebrospinal fluid, reaching the pO$_2$ probe, which responds with a spike-like increase. This view was derived from our observation that the pia mater was stained more clearly than the spinal cord parenchyma when a dye was injected into the spinal cord-feeding arteries. It took 30 s before the initial upstroke of I-pO$_2$, even though it took only a few seconds for oxygenated saline to reach the pia mater and for oxygen to diffuse into the cerebrospinal fluid and reach the pO$_2$ probe. We think this is because the Medspect takes 20–30 s to respond to changes in tissue pO$_2$. A different baseline control I-pO$_2$ value was observed in individual dogs, although the blood pO$_2$ was approximately the same. This may have been dependent upon the location of the I-pO$_2$ probe. When the I-pO$_2$ probe was placed somewhat distant from the anterior spinal artery and/or the radicular artery from which oxygenated saline was delivered, the increase in the I-pO$_2$ was small and slow.

In experiment 1, 15.4% of the segmental arteries were erroneously identified, including false-positive and negative cases. One reason for the false-positive cases might be that the segmental artery tested had collateral circuits to the real feeding artery. Alternatively, when a posterior radicular artery was thick and therefore might supply the anterior part of the spinal cord, the I-pO$_2$ would elevate despite the artery not being a real feeder. A possible reason for false-negative cases might be that, when the pO$_2$ probe was placed too far from the anterior spinal artery, it would be difficult to measure the I-pO$_2$ increase. In fact, nine (28.1%) of 32 segmental arteries, which were misjudged, were observed in dogs 1 and 8 and the accuracy in these dogs was far below the overall average of 84.6%. The pO$_2$ probe may thus have been placed improperly in these two animals. Another possible reason for false-negatives is the problem with injection of oxygenated saline into several segmental arteries in the limited time. The oxygenated saline may have leaked from the ostia of segmental arteries,
the amount of saline may have been insufficient, or it may not have been injected at sufficient pressure. In support of this, for experiment 2, in which the evaluation was limited to a small number of segmental arteries, namely those of L4 and L5, an excellent accuracy rate of 97.5% (39/40) was obtained.

The selective perfusion of the feeding arteries to the spinal cord not only improved spinal cord ischaemia indicated by the I-pO$_2$ but also spinal cord function indicated by ESP. It would be desirable to know the lowest safe limit of I-pO$_2$, i.e. the I-pO$_2$ value at which the operation could be continued safely without perfusing the feeding arteries. It was observed in experiment 2 that the decreases in amplitude of ESP were most significant when I-pO$_2$ was lower than 25 mmHg and were most pronounced when below 20 mmHg. However, the critical level is not yet clear. It will be important to further study the lowest I-pO$_2$ in relation to the duration of ischaemia within which one can operate safely.

The major concern with the present method is how to place the I-pO$_2$ probe safely and conveniently at the most suitable site. With human beings, it may be possible to insert the I-pO$_2$ probe from below cauda equina and to place it almost anterior to the spinal artery without laminectomy, as did Svensson et al.

However, the pO$_2$ probe used here was relatively rigid and likely to damage the spinal cord during insertion. It would therefore be necessary to develop a softer and more flexible one for clinical use.

In conclusion, we have successfully developed a new monitoring method for spinal cord ischaemia, by continuously measuring the I-pO$_2$ using a medical mass spectrometer. With this method, we can identify segmental arteries as being spinal cord-feeding arteries. Selective perfusion of spinal cord-feeding arteries protected the spinal cord from ischaemia.

References


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