Directly measuring spinal cord blood flow and spinal cord perfusion pressure via the collateral network: Correlations with changes in systemic blood pressure

Yuya Kise, MD, Yukio Kuniyoshi, MD, PhD, Hitoshi Inafuku, MD, PhD, Takaaki Nagano, MD, Tsuneo Hirayasu, MD, PhD, and Satoshi Yamashiro, MD, PhD

Objective: During thoracoabdominal surgery in which segmental arteries are sacrificed over a large area, blood supply routes from collateral networks have received attention as a means of avoiding spinal cord injury. The aim of this study was to investigate spinal cord blood supply through a collateral network by directly measuring spinal cord blood flow and spinal cord perfusion pressure experimentally.

Methods: In beagle dogs (n = 8), the thoracoabdominal aorta and segmental arteries L1-L7 were exposed, and a temporary bypass was created for distal perfusion. Next, a laser blood flow meter was placed on the spinal dura mater in the L5 region to measure the spinal cord blood flow. The following were measured simultaneously when the direct blood supply from segmental arteries L2-L7 to the spinal cord was stopped: mean systemic blood pressure, spinal cord perfusion pressure (blood pressure within the aortic clamp site), and spinal cord blood flow supplied via the collateral network. These variables were then investigated for evidence of correlations.

Results: Positive correlations were observed between mean systemic blood pressure and spinal cord blood flow during interruption of segmental artery flow both with ($r = 0.844$, $P < .01$) and without ($r = 0.834$, $P < .01$) distal aortic perfusion. In addition, we observed significant correlations between spinal cord perfusion pressure and spinal cord blood flow with and without distal perfusion ($r = 0.803$, $P < .001$ and $r = 0.832$, $P < .01$, respectively), and between mean systemic blood pressure and spinal cord perfusion pressure with and without distal perfusion ($r = 0.898$, $P < .001$ and $r = 0.837$, $P < .001$, respectively). The spinal cord was perfused from the collateral network from outside the interrupted segmental arteries, and high systemic blood pressure (~1.33-fold higher) was needed to obtain the preclamping spinal cord blood flow, whereas 1.68-fold higher systemic blood pressure was needed when distal perfusion was halted.

Conclusions: Spinal cord blood flow is positively correlated with mean systemic blood pressure and spinal cord perfusion pressure under spinal cord ischemia caused by clamping a wide range of segmental arteries. In open and endovascular thoracic and thoracoabdominal surgery, elevating mean systemic blood pressure is a simple and effective means of increasing spinal cord blood flow, and measuring spinal cord perfusion pressure seems to be useful for monitoring perioperative spinal cord blood flow. (J Thorac Cardiovasc Surg 2015;149:360-6)

See related commentary on pages 366-8.

The complication of greatest concern in thoracoabdominal surgery is spinal cord injury (SCI) from sacrifice of the segmental arteries (SAs), which serve a crucial role in supplying blood flow to the spinal cord. Various methods are used to avoid this (monitoring motor evoked potential, determining the origin and revascularization of the Adamkiewicz artery [AKA], perfusing the distal aorta, draining cerebrospinal fluid, cooling the spinal cord, and administering certain drugs), but a definitive method has yet to be established.[1]

Recent research on the blood supply to the spinal cord has reported that there is a rich network of spinal cord blood vessels and tissue around the spinal cord that plays an important role in spinal cord circulation.[2] In actual clinical practice, increasing systemic blood pressure is useful as a means of increasing the blood supply from the collateral network. However, it is not possible to measure spinal cord blood flow (SCBF) in clinical settings, and there are few reports showing a correlation between systemic blood pressure and SCBF.

In this experiment, SCBF was measured directly via the collateral network while blood flow from several SAs,

From the Department of Thoracic and Cardiovascular Surgery, Graduate School of Medicine, University of the Ryukyus, Okinawa, Japan.

Disclosures: Authors have nothing to disclose with regard to commercial support.
Received for publication May 25, 2014; revisions received Sept 11, 2014; accepted for publication Sept 14, 2014

Address for reprints: Yuya Kise, MD, Department of Thoracic and Cardiovascular Surgery, Graduate School of Medicine, University of the Ryukyus, 207 Uehara, Nakagamigun, Nishihara, Okinawa 903-0215, Japan (E-mail: yuya1022@med.u-ryukyu.ac.jp).

0022-5223/$36.00

http://dx.doi.org/10.1016/j.jtcvs.2014.09.121

Abbreviations and Acronyms

AKA = Adamkiewicz artery
ASA = anterior spinal artery
CSFP = cerebrospinal fluid pressure
mDAP = mean distal arterial pressure
mPAP = mean proximal arterial pressure
mSBP = mean systemic blood pressure
SA = segmental artery
SAP = segmental arterial pressure
SCBF = spinal cord blood flow
SCI = spinal cord injury
SCPP = spinal cord perfusion pressure

including the AKA, was interrupted, and the correlation between SCBF and mean systemic blood pressure (mSBP) was clarified. Spinal cord perfusion pressure (SCPP), which is sometimes used to monitor SCBF perioperatively, was also measured, and its correlations with SCBF and mSBP were examined.

In addition, changes in SCBF with and without distal perfusion were measured, and the degree to which distal perfusion affects SCBF via the collateral network was investigated. Finally, the mSBP conditions to maintain SCBF before interruption of the SAs were investigated. The aim of this study was to investigate spinal cord blood supply through a collateral network by directly measuring SCBF and SCPP experimentally.

MATERIALS AND METHODS

Animals

Animal care and all procedures were performed in compliance with the Guide for Care of Laboratory Animals. This study was approved by the Research Committee for Laboratory Animal Science at the University of the Ryukyus. Experiments were performed on 8 female beagle dogs weighing 7.5 to 10.0 kg.

Anesthesia

The dogs were sedated by intramuscular injection of 3 mg/kg ketamine hydrochloride and 0.2 mg atropine sulfate. They were then intubated endotracheally and ventilated mechanically. One intravenous line was inserted into an anterior limb vein. They were placed in the prone position on an operating table under intravenous anesthesia with propofol (0.3 mg/kg/min) and ketamine hydrochloride (0.05 mg/kg/min).

During the surgical procedure, the mean arterial blood pressure was maintained between 70 and 100 mm Hg by controlling the propofol concentration and fluid infusion. Body temperature was monitored with a rectal temperature probe and maintained between 36°C and 37°C using a heating pad and blanket. Arterial blood gases were measured (i-STAT1; FUSO Pharmaceutical, Ltd, Osaka, Japan) at 60-minute intervals. Metabolic and respiratory acid-base balance was confirmed to maintain pH between 7.35 and 7.45, arterial oxygen tension was maintained at greater than 100 mm Hg, and arterial carbon dioxide tension was maintained between 35 and 45 mm Hg by adjusting respiratory volume and rate.

Surgical Procedure

Surgery was performed by a single cardiovascular surgeon to exclude effects on measurements related to surgeon expertise.

First, an L4 laminectomy was performed, and the dorsal aspect of the dura mater, measuring 1.5 × 1.5 cm, over the spinal cord was exposed. Second, the animals were placed in the right decubitus position. The chest was opened through a thoracotomy in the ninth left intercostal space. The abdominal aorta was exposed through a left flank incision and exfoliated from the descending aorta (Th11) to the trifurcation, with careful exposure of the L2-L7 SAs. After heparin was administered intravenously at 200 IU/kg, a temporary descending aorta to left external iliac artery bypass was created. At proximal sites, a 10F aortic cannula (Duraflo II; Edwards Lifesciences, Irvine, Calif) was inserted, and at distal sites, an 8-mm woven graft was anastomosed, and these devices were connected.

Then, 22-G cannulae were placed at the left common carotid artery, right femoral artery, and L5 level abdominal aorta to monitor the mean proximal arterial pressure (mPAP), mean distal arterial pressure (mDAP), and segmental arterial pressure (SAP), respectively. The SAP substituted for SCPP while the abdominal aorta was clamped (between L3 to L4 and L6 to L7) (Figure 1). Because the AKA branches from the L4 or L5 SA in dogs, this range of interruption included the AKA.[3-5]

Measurement of Spinal Cord Blood Flow

By referring to Fujimaki and colleagues' procedure,[6] SCBF was measured using laser Doppler flowmetry (Omegaflow FLO-N1; Neuroscience, Tokyo, Japan) to assess real-time microcirculatory changes in the spinal cord. The laser probe was placed in contact with the intact dorsal dura mater at the L5 segmental level of the spinal cord, which was at the upper L4 vertebral level and connected to the laser Doppler flow meter. The probe was affixed in a riding position over the spinal cord. Output signals were collected continuously throughout the experiment and averaged every 3 seconds.

Experimental Protocol

Mean blood pressures (mPAP, mDAP, SAP [SCPP]) and SCBF were measured at the same time under the following 3 conditions (Figure 2): condition 1, no aortic clamp and no SA clamp (control group); condition 2, aortic clamp (between L3 to L4 and L6 to L7), and L2, L3, and L7 SA clamps (L2-L7 SA flow halted) with distal perfusion; and condition 3, aortic clamp (between L3 to L4 and L6 to L7) and L2, L3, and L7 SA clamps (L2-L7 SA flow halted) with no distal perfusion.

The mean values of each measurement over 3 minutes from the start of measurements were taken as the baseline values. After completing the baseline measurements, condition 1 was created, and continuous administration of 0.5 μg/kg/min norepinephrine was started. Measurement data for each site were sampled every 15 seconds from the start of the increase in mSBP (the mPAP measurement value was taken to be mSBP). The continuous administration of norepinephrine was stopped after 5 minutes, and data sampling was performed for approximately 10 minutes as blood pressure naturally decreased and stabilized. The same procedure was continued for conditions 2 and 3. A difference of less than 10 mm Hg between mPAP and mDAP was taken to indicate that the distal bypass during the experiment was functioning effectively.

Data Analysis

All data were recorded by the monitor (PowerLab, ADInstruments, ADInstruments Pty Ltd, Castle Hill, Australia), which allowed constant real-time recording of the arterial blood pressure (mPAP, mDAP, SAP [SCPP]) and SCBF. Data were entered into a database and analyzed using SPSS statistical software (version 21.0J; IBM Corp, Armonk, NY).

Scatter plots of mSBP and SCBF, SAP (SCPP) and SCBF, and mSBP and SAP (SCPP) were created, and levels of correlation were analyzed with Spearman's rank correlation coefficient and regression analysis. A probability of 5% was considered significant.