

Echo-guided Identification of Key Lumbar Arteries Supplying the Spinal Cord in a Canine Model

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ABSTRACT

The aim of this study was to anatomically verify echo-guided identification of key lumbar arteries supplying blood to the spinal cord and to examine whether changes in nerve root motion could be used for detecting malperfusion following aortic cross-clamping. In two beagle dogs, nerve root motion was monitored through the intervertebral disc using transesophageal echocardiography. Communications between each lumbar artery and the spinal vasculature were assessed by echogenic signals in the spinal cord following saline injection into each lumbar artery. Nerve root motion immediately disappeared after clamping the aorta and recovered as soon as it was declamped. These changes were induced specifically by clamping the aorta at the first lumbar level. The changes were instantaneous and may be beneficial because of minimal ischemic insult of the spinal cord. In dog #1, the result of the saline injection test was anatomically verified with the presence of a spinal branch. However, in dog #2 echogenic signals appeared in the muscles as well as in the spinal artery. A morphological study showed no spinal branch of the lumbar artery but only an indistinct artery in the intervertebral foramen. These findings probably account for those cases in humans where there is unsuccessful visualization of the Adamkiewicz artery by angiography. Consequently, the above two assessments identified the key artery. Cessation of nerve root motion following segmental clamping of the aorta and echogenic signals in the spinal cord following saline injection into a lumbar artery may represent the key artery with respect to hemodynamics and perfusion, respectively.

Key words: *Spinal artery, Echocardiography, Spinal cord ischemia, Adamkiewicz artery*

Preservation of the key intercostal artery and/or lumbar artery (LA) that gives off a spinal branch predominantly perfusing the spinal cord, the Adamkiewicz artery, is a prerequisite for avoiding paraplegia following surgery on the thoracoabdominal or descending thoracic aorta. A number of modalities have been introduced for identifying this artery including computed tomography (CT) and magnetic resonance imaging (MRI) as a preoperative morphological assessment^{4,8)} and motor evoked potentials (MEPs) as an intraoperative, real-time electrophysiological monitor. However, the Adamkiewicz artery cannot be visualized in 30% of patients with the former modalities. Although the latter are helpful for determining whether the segmentally-clamped aorta contains the Adamkiewicz artery, ischemic insults of the spinal cord are inevitable as part of the diagnostic process. When the clamped segment contains several arteries, MEP monitoring cannot specify the single artery to be preserved.

Recently, we developed a novel method of identifying the key LAs by means of ultrasonography⁷⁾. This preliminary study using a canine model

showed that: 1) the spinal cord could be visualized through the intervertebral disc by a direct scan; 2) echogenic signals were detected in the spinal cord following saline injection into some LAs (positive LAs) but not when injected into other LAs (negative LAs); 3) resin injected into the positive LA entered the spinal artery; and 4) there was a rich collateral circulation among positive LAs or among negative LAs, respectively, but there were few collaterals connecting these two groups of LAs. However, evidence of communication between positive LAs and the spinal artery was not anatomically verified in that study.

In 1994, Godet et al. reported that the spinal cord and its oscillating motion could be visualized with intraoperative transesophageal echocardiography (TEE) and referred to the potential use of monitoring this motion for detecting malperfusion of the spinal cord during cross-clamping of the aorta²⁾. However, the spinal cord motion transmits longitudinally^{3,5,6)} and oscillating motion may remain in the spinal cord during ischemia. In clinical cases, we have found that nerve roots as well as the spinal cord can be visualized with TEE in

nearly all patients. The nerve roots show a pulsating motion which is more distinct than the spinal cord motion. Since this motion is generated by arterial pulsation in the nerve root, malperfusion in the spinal cord may be detected by monitoring nerve root motion. However, the accuracy of this method cannot be evaluated clinically for ethical reasons.

The aims of the current study were twofold: 1) to anatomically verify the results of echo-guided identification of key arteries by examining the presence of the spinal branch of the LA; and 2) to examine whether the nerve root motion is clearly altered by aortic cross-clamping. In addition, we discuss the feasibility of and problems with the clinical application of these two methods.

MATERIALS AND METHODS

Animals

Animals received humane care in compliance with the "Principles of Laboratory Animal Care" formulated by the Institute of Laboratory Animal Resources and the "Guide for the Care and Use of Laboratory Animals" prepared by the Institute of Laboratory Animal Resources and published by the National Institute of Health.

Two adult beagle dogs weighing 8.0 and 10.0 kg (#1 and #2) were used. After the dog was premedicated with intramuscular atropine sulfate (0.5 mg), anesthesia was induced with an intramuscular injection of ketamine hydrochloride (0.3 ml/kg). Endotracheal intubation was performed after intravenous administration of thiamylal sodium (15 mg/kg) and pancuronium bromide (0.05 mg/kg), and general anesthesia was maintained with isoflurane (1.5–2.0%) carried by oxygen (2 liters/min) under volume-controlled mechanical ventilation. With the dog in the right decubitus position, the abdomen was opened on the left side. The abdominal aorta was exposed from the level of the diaphragm to the bifurcation. Visceral branch arteries were isolated and snared.

Visualization of the spinal cord

The spinal cord was visualized as previously reported⁷. A 5MHz biplane TEE probe for pediatric use (SSD-870, UST-5246S-5, Aloka Co., Tokyo, Japan) was placed perpendicularly to the vertebral column and the spinal cord was scanned through the intervertebral disc with a transducer for longitudinal scanning. The spinal cord was examined at the intervertebral level where the best visualization was obtained. In the pulsed-wave Doppler mode, a sampling volume (3 mm in length) was placed on the anterior portion of the spinal cord.

Aortic cross-clamping and saline injection test

Before aortic clamping and saline injection, every visceral branch artery was clamped. In dog

#1, the nerve root motion was monitored at the time of clamping and declamping of the aorta below the diaphragm and proximal to the bifurcation. Under proximal and distal aortic clamping, the aortic wall was longitudinally opened anteriorly. The spinal cord was monitored for echogenic signals while 2 to 3 ml of saline was injected into each LA within a few seconds. In dog #2, the aorta was segmentally clamped above and below the right and left LAs at the same level, while the nerve root motion following clamping and declamping was recorded. After the aorta was opened anteriorly, 2 to 3 ml of saline was injected into each LA while monitoring for the appearance of echogenic signals.

Anatomical examination

Resin (MERCOCX, CL Series, Oken-Shoji, Tokyo, Japan) was prepared for injection by adding 0.1 g of catalyst to 5 g of acrylic casting material to start polymerization. After the dog was exsanguinated, resin was injected into each LA. The lumbar vertebrae and spinal cord were eviscerated en bloc. Each LA was carefully dissected distally. The small branches that apparently distributed to the muscles were transected and close attention was paid to preserving the arteries that entered the intervertebral foramina. The spinous processes and laminae were removed and the artery that entered the intervertebral foramen was examined. The spinal cord was isolated from the spinal column by cutting the nerve roots, and the anterior and posterior aspects of the spinal cord were morphologically examined.

Data storage and image processing

All echo data were recorded on S-VHS videotape for later analysis. Echo images were captured on a personal computer by using video-capture software (Ulead MediaStudio Pro 7.0, Ulead Systems Inc., Taipei, Taiwan). To create digital subtraction images for expressing movement in two-dimensional (2D) images, a pair of images at systole and diastole were captured frame by frame and were digitally subtracted using Photoshop version 6.0 (Adobe Systems Inc., San Jose, USA).

RESULTS

Changes in nerve root motion

The spinal cord was visualized with a TEE probe most clearly at the L2-3 intervertebral level in two dogs. The pulsating movement of the nerve roots was apparent at this level. They presented an expanding or twisting motion which was crisp and in phase with the cardiac cycle.

In dog #1, the pulsating movement of the nerve root was markedly reduced following proximal clamping of the aorta at the subdiaphragmatic level and completely disappeared following distal clamping of the aorta at the aortic bifurcation

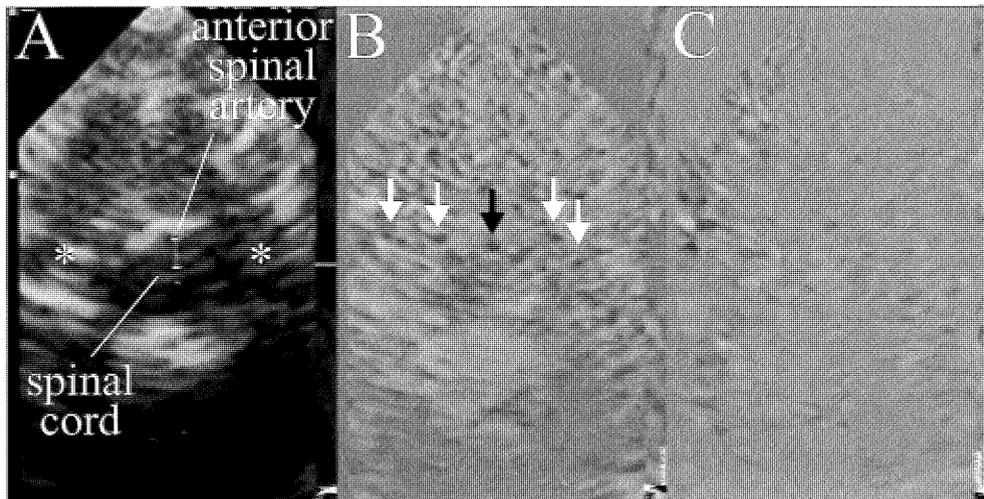


Fig. 1. Ultrasonogram showing motion of the nerve roots and pulsating movement of the anterior spinal artery. A: short-axis view of the spinal cord. B: digital subtraction echogram before aortic clamping. C: digital subtraction echogram after aortic clamping. The asterisks (A) indicate the right and left nerve root. Pulsating motion of the nerve root and the anterior spinal artery before aortic clamping is shown as black dots (white arrows and black arrow, respectively). It disappeared after clamping.

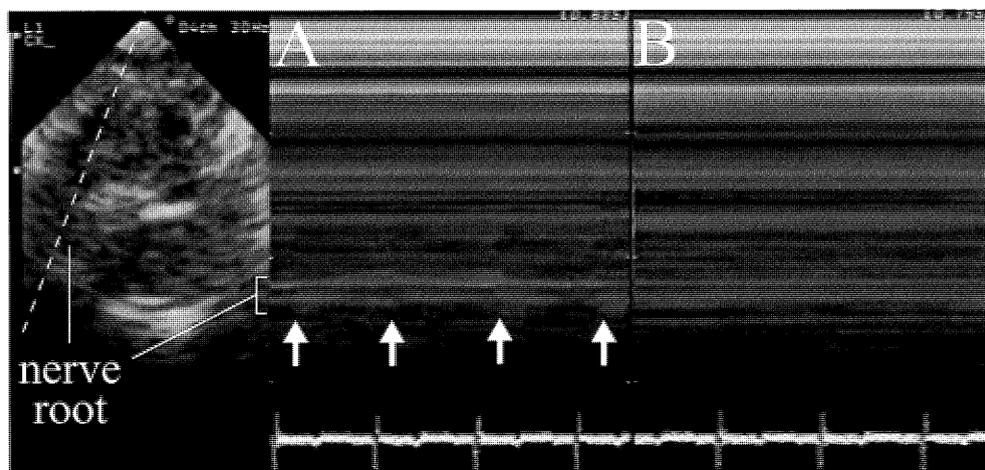


Fig. 2. Ultrasonogram showing changes in right nerve root motion following aortic clamping, demonstrated in M mode.

Left: short-axis view of the spinal cord showing position of the M cursor. A: nerve root motion before aortic clamping. B: nerve root motion after aortic clamping. Nerve root motion was present before clamping, shown as a stripe pattern in phase with the cardiac cycle (white arrows). After clamping, this stripe pattern disappeared.

level (Fig. 1). In the digital subtraction echograms, the black dots indicate the portion that moved between systole and diastole. The dots at the anterior spinal artery (black arrow) and at the nerve roots (white arrows), recognized before clamping (Fig. 1B), disappeared following proximal and distal aortic clamping (Fig. 1C). After the aorta was declamped, the pulsating motion recovered within a few seconds.

In dog #2, the nerve root motion was recorded in M mode as well. The cursor was positioned on the right nerve root (Fig. 2, dotted line). The nerve root motion was visualized as a striped pattern during systole at the depth corresponding to the nerve root (Fig. 2A, arrows). When the aorta was

segmentally clamped above and below the first LA, the motion immediately disappeared (Fig. 2B), but recovered within a few seconds after declamping. However, these changes were specific to the first LA level and nerve root motion was not reduced following clamping of the aorta at any other level (above and below each LA from the second to fourth segment).

Saline injection test and anatomical examination in dog #1

The aorta was clamped below the diaphragm and above the bifurcation and incised anteriorly. There were four pairs of LAs (first to fourth) and a fifth LA on the right. Two to 3 ml of saline was

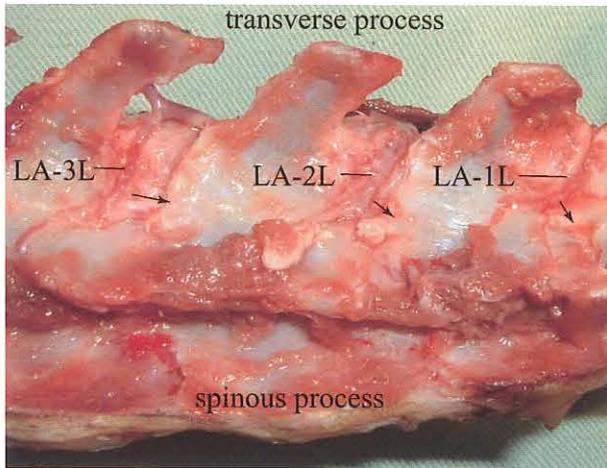


Fig. 3. Photograph showing spinal branches in dog #1. The first, second, and third left lumbar arteries (LA-1L, LA-2L, and LA-3L) gave off spinal branches (arrows) that entered intervertebral foramina.

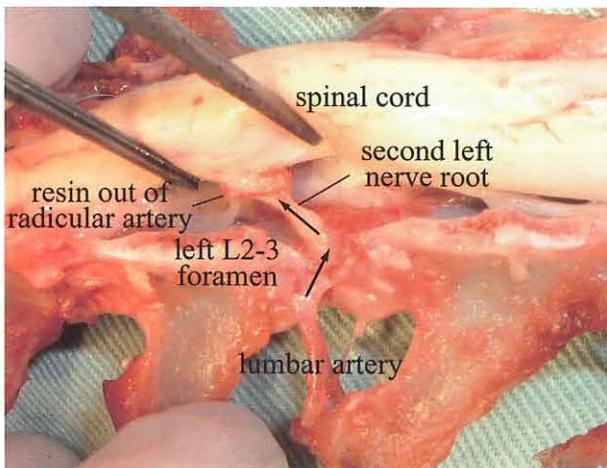


Fig. 4. Photograph showing the spinal branch that entered the L2-3 intervertebral foramen in dog #1. At this level, the spinal branch connects to the radicular artery and both of them filled with red resin.

injected into each LA within a few seconds while the spinal cord was being monitored by ultrasonography. Because the orifices of right and left LA at the same level were very close to each other, saline was injected into both LAs at the same time through a short silicon cannula (5 mm in diameter) with its end folded outside to smooth and round the tip of the cannula. Echogenic signals were detected in the spinal cord when saline was injected into the first to third LAs as reported before⁷⁾, but were not detected when injected into the fourth and fifth LAs.

Dissection was facilitated by the solid resin that filled the vasculature. As the LAs were dissected, five LAs on the right side and the fourth left LA were seen to distribute to the muscles along the transverse and spinous process (transversospinous

muscles). In contrast, the first, second, and third left LA gave off a spinal branch to the L1-2, L2-3, and L3-4 intervertebral foramina, respectively (Fig. 3), leaving a smaller artery towards the muscles. After laminectomy, spinal branch arteries filled with resin were found in the L1-2, L2-3, and L3-4 intervertebral foramina (Fig. 4). However, there was no artery found in the left L4-5 foramen or in any of the right intervertebral foramina. The anterior and posterior spinal arteries were filled with resin.

Saline injection test and anatomical examination in dog #2

After aortotomy, four pairs of LAs were found (first to fourth LA). Because the right and left LA were not close to each other in dog #2, 2 to 3 ml of saline was injected into each artery by using a 22G elastic needle. Echogenic signals in 2D images (Fig. 5 Bottom) and Doppler signals were detected in the spinal cord (Fig. 5 Above) when saline was injected from the first right, first left, second left, and fourth right LAs. Unlike dog #1, significant echogenic signals appeared in the muscles following saline injection (Fig. 5 Bottom, dotted circle). They appeared in the ipsilateral muscles, then in the anterior spinal artery when saline was injected into the first right and first left LAs. When saline was injected from the second left LA, echogenic signals appeared in the right (contralateral) muscles first, in the left nerve root second, and then finally in the anterior spinal artery. When saline was injected in the fourth right LA, signals appeared only in the anterior spinal artery.

Anatomical examination showed that every LA distributed to the transversospinous muscles and there was no significant spinal branch. Although spinal branch arteries filled with resin were found in the left L1-2 and L2-3 intervertebral foramina and were likely to extend toward the lumbar artery, fine branch artery was interrupted after dissection and no apparent communication could be shown. The anterior spinal artery and every radicular branch artery were filled with resin.

DISCUSSION

Nerve root motion following aortic cross-clamping

Nerve root motion was apparently reduced immediately following clamping of the aorta at the diaphragm level despite the maintenance of perfusion in the cerebral and intercostal arteries. This result indicates that nerve root motion reflects pulsatile blood flow in the nerve root but is not affected by spinal cord motion that can be transmitted longitudinally from the thoracic level. A similar finding was obtained by segmental clamping at the level of first LA in dog #2 but not by clamping at any lower level. The lumbar spinal

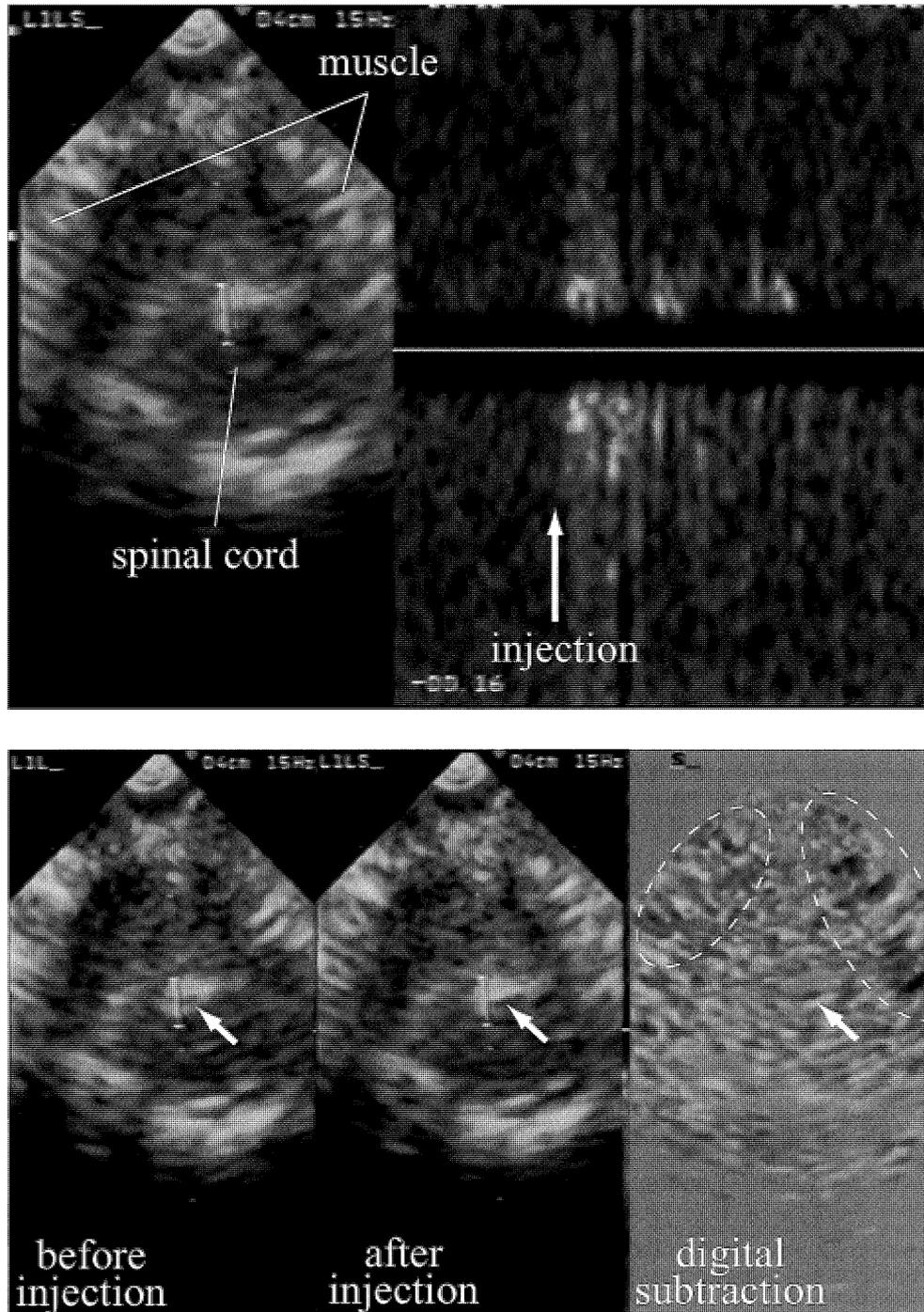


Fig. 5. Ultrasonogram showing echogenic signals in dog #2.

Above left: short-axis view of spinal cord with sampling volume placed on the anterior spinal artery. Above right: Doppler signal detected following saline injection in the anterior spinal artery. Bottom: short-axis view of spinal cord before (left) and after saline injection (center), with digital subtraction echogram (right). An echogenic signal appeared in the anterior spinal artery following saline injection, shown as a black dot in the digital subtraction echogram (arrow). An echogenic signal appeared in the muscle (circle with interrupted line) before it appeared in the anterior spinal artery.

cord was likely to be perfused mainly by either the right or left first LA in this dog. The changes in nerve root motion were instantaneous and reversible and appeared useful for monitoring spinal cord perfusion. Intraoperative monitoring of nerve root motion in clinical practice is probably feasible using TEE because the nerve roots at the

lower thoracic level can be visualized in nearly all patients undergoing repair of the thoracoabdominal aorta. Since the changes appear immediately, ischemic insult of the spinal cord during the diagnostic process would be minimal.

In a clinical setting, it is not practical to scan the spinal cord at multiple levels associated with

repeated aortic cross-clamping. This method is clinically useful if nerve root motion at a single level reflects perfusion in the anterior spinal artery. The current study revealed that: 1) a pulsating motion was apparently detected in the second right nerve root where no direct communication was present between the radicular artery and the LA; 2) the nerve root motion became undetectable immediately following aortic cross-clamping; and 3) the anterior spinal artery in the lumbar spinal cord was uninterrupted in two dogs as well as in another two dogs in a previous study⁷⁾. Based on these findings, pulsating blood pressure is likely to be propagated from the anterior spinal artery to a nerve root that has no direct blood supply from the spinal branch of LA (such as the second right nerve root in this dog). If the nerve root has direct blood supply from the spinal branch, nerve root motion would be markedly reduced by aortic cross-clamping. Thus, monitoring of nerve root motion at a single lumbar level appears to reflect perfusion of the anterior spinal artery of the lumbar spinal cord in dogs.

In this report, we demonstrated changes in nerve root motion using a digital subtraction method to facilitate objective validation in still images. Typically, this type of image processing is used in angiography but not in ultrasonography. However, in the operating theater, such image processing takes time and is not practical. Image processing of "color kinesis," which is available in several echo systems, demonstrates the segment in motion and may be useful for this purpose. M mode recording, as shown in Fig. 2, would also be convenient for clinical use because it takes little time and is available in every echo system.

Detection of echogenic signals following saline injection

Anatomical examination verified the accuracy of echo-guided identification of key LAs that perfused the spinal cord in dog #1, although the right and left LAs could not be individually assessed. Based on the results of the morphological study, the first, second, and third left LAs were positive and the incidence of positive LAs was 33% (3/9), similar to the results of our previous study. However, the findings in dog #2 were different from those in dog #1. Echogenic signals appeared in the muscles as well as in the anterior spinal artery, which was not found in dog #1 not in the two dogs in our previous study⁷⁾. The reason for these unusual echo findings was revealed by anatomical examination. There was no significant spinal branch that entered the intervertebral foramen. There were arteries in the left L1–2 and L2–3 intervertebral foramina but they were indistinct. The spinal cord appeared to have been perfused through multiple muscle branches. When saline was injected into the second left LA,

echogenic signals appeared in the contralateral muscles first, indicating dominant communications across the spinous process. These findings remind us of the 30% of patients in whom an apparent Adamkiewicz artery cannot be visualized with CT or MRI.

In dog #2, the fourth right LA was diagnosed as positive. Although the echogenic signal appeared exclusively in the anterior spinal artery following saline injection, anatomical examination showed no spinal branch in the right L4–5 foramen. Saline might have entered the anterior spinal artery through the muscles at the L4 level, which was out of the scanning level, and echo signals were detected only in the anterior spinal artery at the scanning level. Thus, it was not clear which LA should be preserved in dog #2 in order to avoid spinal cord ischemia.

Integrated assessment by two methods

In dog #2, changes of nerve root motion under segmental aortic clamping suggest that the first LA is most likely to be the key artery with respect to hemodynamics. However, from the results of the saline injection test, the first LA or the fourth right was probably the key artery with respect to perfusion. The result of anatomical examination (morphologic aspect) was consistent with these two ways of assessment (spinal branch found at the L1–2 intervertebral foramen). Nerve root motion was not altered by segmental clamping at the fourth LA level despite the fact that the fourth right LA communicated with the anterior spinal artery. The spinal cord was probably perfused from the first LA during segmental clamping at the fourth LA level. Thus, monitoring of nerve root motion is specific to the key artery at the uppermost level. Clinically, distal perfusion during aortic clamping is maintained by means of artificial circulation and the spinal cord is perfused through a key artery at a lower level (as the fourth right LA in this dog). Because the artificial perfusion is non-pulsatile, the nerve root motion would be altered to non-pulsating by segmental clamping at the level of the first LA.

Nerve root motion and saline injection provide assessment in different aspects. The former identifies the level of key LA that is situated at the most proximal side, while the latter reveals every LA that communicates with the spinal artery. In clinical cases, segmental clamping of the diseased aorta at each LA level is not feasible and the clamped segment usually contains several intercostal or lumbar arteries. Loss of nerve root motion would indicate whether the key artery arises from the clamped segment. Following aortotomy, selective injection of saline would clarify the communication of each artery to the spinal artery. If saline injection accurately identifies the "positive" and "negative" arteries, unnecessary anasto-

moses may be avoided and the operation time can be minimized.

It is clinically difficult to visualize the spinal cord at multiple intervertebral levels in the lower thoracic to lumbar level, and the spinal cord may be monitored at a selected level that provides the best imaging, as we did in the current study. This may potentially lead to underestimation of malperfusion. However, there is clinical evidence that spinal cord damage caused by malperfusion usually extends longitudinally by several vertebral levels between T5 to T11 because the watershed area is situated at T6 to T8¹⁾. In this sense, malperfusion may be detected by monitoring at a single level within this range.

Further investigations are necessary before clinical application of echo-guided identification of the key lumbar artery for the spinal cord. First, confirmation is needed that nerve root motion is immediately reduced after aortic cross-clamping in humans. Second, the dose of saline and speed of injection to detect echogenic signals in the spinal cord needs to be determined. Third, the safety of saline injection should be confirmed. Fourth, a cannula needs to be devised for safe and secure injection of saline.

In conclusion, cessation of nerve root motion detected by ultrasonography promptly indicates malperfusion in the spinal cord following aortic cross-clamping and the level of the key LA can be located by segmental aortic clamping. The accuracy of assessment by monitoring nerve root motion and by saline injection was verified by anatomic examination. Based on these results, these assessments may accurately identify the key LA, although further investigations are necessary before these methods are used clinically.

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REFERENCES

1. **Cheshire, W.P., Santos, C.C., Massey, W. and Howard, J.F.** 1996. Spinal cord infarction: Etiology and outcome. *Neurology* **47**: 321–330.
2. **Godet, G., Couture, P., Ionanidis, G., Gosgnach, M., Kieffer, E. and Viars, P.** 1994. Another application of two-dimensional transesophageal echocardiography: spinal cord imaging. A preliminary report. *J. Cardiothorac. Vasc. Anesth.* **8**: 14–18.
3. **Jokich, P.M., Rubin, J.M. and Dohrmann, G.J.** 1984. Intraoperative ultrasonic evaluation of spinal cord motion. *J. Neurosurg.* **60**: 707–711.
4. **Kudo, K., Terae, S., Asano, T., Oka, M., Kaneko, K., Ushikoshi, S. and Miyasaka, K.** 2003. Anterior spinal artery and artery of Adamkiewicz detected by using multi-detector row CT. *Am. J. Neuroradiol.* **24**: 13–17.
5. **Levy, L.M.** 1999. MR imaging of cerebrospinal fluid flow and spinal cord motion in neurologic disorders of the spine. *Magn. Reson. Imaging. Clin. N. Am.* **7**: 573–587.
6. **Mikulis, D.J., Wood, M.L., Zerdoner, O.A. and Poncellet, B.P.** 1994. Oscillatory motion of the normal cervical spinal cord. *Radiology* **192**: 117–121.
7. **Orihashi, K., Kumagai, H., Isaka, M., Arihiro, K. and Sueda, T.** 2005. Echo-guided identification of key lumbar arteries for the spinal cord: preliminary study in the canine model. *Hiroshima J. Med. Sci.* **54**: 29–34.
8. **Yamada, N., Okita, Y., Minatoya, K., Tagusari, O., Ando, M., Takamiya, M. and Kitamura, S.** 2000. Preoperative demonstration of the Adamkiewicz artery by magnetic resonance angiography in patients with descending or thoracoabdominal aortic aneurysms. *Eur. J. Cardiothorac. Surg.* **18**: 104–111.