Relation Between Spinal Cord and Epidural Blood Flow

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To test applicability of monitoring regional spinal cord blood flow by measuring regional epidural blood flow, both were simultaneously measured by the hydrogen clearance method in response to changes in Paco2 and mean arterial blood pressure in rats anesthetized with pentobarbital. An excellent correlation was found between regional spinal and epidural blood flow over a physiological range of Paco2 (27.8–66.7 torr) and blood pressure (30–130 torr), while a poor correlation was demonstrated between regional spinal or epidural blood flow and regional muscle blood flow in response to these same physiological parameters. Moreover, the rates of change in regional spinal and epidural blood flows were almost the same in response to both Paco2 and blood pressure. These results suggest that both regional spinal and epidural blood flow are regulated by a similar mechanism and suggest that regional spinal cord blood flow can be monitored by regional epidural blood flow. (Stroke 1987;18:1128–1132)

A catheter is frequently placed into the epidural space in the operating room or pain clinic for injection of local anesthetics or analgesics and for epidural stimulation of the spinal cord. Further, epidural recording of the spinal cord potential has made the technique applicable for monitoring spinal cord function during spine or spinal cord surgery.

Nevertheless, physiologic characteristics of epidural blood flow (EBF) have been little understood, though the anatomic characteristics of the epidural venous plexus have been substantially studied. From these anatomic studies of the epidural venous plexus it is assumed that tissue blood flow in the spinal epidural space is closely correlated with that in the spinal cord. If there is a linear relation between spinal cord blood flow (SBF) and EBF, measurement of EBF may be warranted as a technique for monitoring SBF in clinical practice. Although several methods are adopted for measuring cerebral blood flow, there have been no clinically available methods of monitoring SBF during anesthesia and surgery.

Prior to a clinical study, we simultaneously and sequentially measured regional SBF (rSBF) and regional EBF (rEBF) by the hydrogen clearance method in response to changes in Paco2 and mean arterial blood pressure (MAP) in rats.

Materials and Methods

Adult male Wistar rats weighing 350–400 g were anesthetized with 60 mg sodium pentobarbital/kg i.p. The right femoral artery and vein were cannulated for monitoring MAP and administering drugs intravenously. Ringer’s lactate solution was infused continuously at a rate of 2–3 ml/kg/hr via the venous cannula. The rats were tracheotomized, immobilized with 0.5 mg pancuronium bromide/kg i.v., and mechanically ventilated with a mixture of air and 35% oxygen by means of a Harvard respirator (South Natick, Mass.). The ventilation volume was changed in a stepwise fashion by checking Paco2 to determine the relation between Paco2 and rSBF, rEBF, or regional muscle blood flow (rMBF). For imposing hypercapnia, the rats inhaled 5% CO2 mixed with air and oxygen through the respirator. The relation between MAP and rSBF, rEBF, or rMBF was determined by means of stepwise exsanguination of arterial blood. Each step lasted at least 10 minutes before measurement to obtain a steady state of circulation, which was indicated by no change in MAP. These procedures were repeated until MAP reached approximately 30 torr. At termination of exsanguination and estimation, shed blood was reinfused, and regional blood flow–MAP relations were determined again at recovery. A small amount of arterial blood (0.2 ml) was sampled anaerobically for measurement of Paco2, pH, and Po2. Rectal temperature was monitored and maintained at 37°C by a water-circulating heating mat.

With the rat in the prone position, the skin over the lumbar region was infiltrated with 1% lidocaine, and laminectomy at L-5 was performed to open the small space (about 5 mm in diameter) over the spinal cord covered with dura. Three platinum (70%)-iridium (30%) electrodes 0.075 mm in diameter with a 0.08-mm bare tip were placed to a depth of 1 mm in the dorsal root entry zone of the spinal cord through a small hole in the dura, in the postero-lateral epidural space surrounding the cord (Figure 1) and in the sacrospinalis muscle of the same segment. The spinal and epidural electrodes were placed in their appropriate sites with the aid of a microscope to avoid interference...
FIGURE 1. Left: Schematic presentation of sites of spinal and epidural electrodes. After insertion of electrodes, the cord surface was gently covered with muscles and skin, which fixed electrodes in place. SBF, spinal cord blood flow; EBF, epidural blood flow; ES, epidural space; SC, spinal cord. Right: Camera lucida drawings showing tips of electrodes in spinal cord reconstructed from the Klüver-Barrera stained sections. Electrode tips were located in Llexed's laminas V and VI. CC, central canal.

from the nerve roots or large vessels. After insertion of the spinal and epidural electrodes, the dural hole was sutured and the exposed portion of the dura was gently covered with the surrounding muscle tissue to fill the epidural space and to fix the electrodes in place (Figure 1, left). A subcutaneous Ag/AgCl electrode was used as a reference electrode. Each electrode was connected to a flexible 0.015-mm-diameter wire to prevent movement of the electrode tip. Electrodes were polarized at 0.65 volts according to a modified method of Auckland et al. and Kobrine et al. The rats inhaled about 6% hydrogen gas via an endotracheal tube. Hydrogen saturation was attained without change in MAP or blood gases. The first 40 seconds of the desaturation curve was disregarded to avoid problems of recirculation.3 The signal was fed into a Biomedical Science Ltd. RBF-1 amplifier (Tokyo, Japan) and plotted by an X-Y recorder. Flows were calculated by a monoequimental least-squares program, and the function was plotted to check the fit of the curve to the data. After each experiment, the electrode tips were identified by fixing the whole body with formalin and cutting the cord, epidural tissue, or muscle with the electrodes in place. Electrodes in the spinal cord were located in Llexed’s laminas V and VI (Figure 1, right). No macroscopic bleeding was observed around the tips of electrodes in the cord, epidural space, or muscle.

Standard statistical methods, including paired t tests and the \( \chi^2 \) test for paired observations and a Bonferroni correction were used. Significance was defined as \( p \leq 0.05 \). Linear regression analysis was also performed, and the correlation coefficient was evaluated.

Results

\( r_{SBF} \), \( r_{EBF} \), and \( r_{MBF} \) in rats anesthetized with pentobarbital at Paco2 35–42 torr were (mean ± SD) 39.6 ± 7.3, 34.3 ± 9.0, and 35.2 ± 11.3 ml/100 g/min, respectively.

Figure 2 shows an example of changes in \( r_{SBF} \), \( r_{EBF} \), and \( r_{MBF} \) in response to hyperventilation, CO2 inhalation, and exsanguination in a rat during pentobarbital anesthesia. \( r_{SBF} \) and \( r_{EBF} \) demonstrated parallel changes in response to changes in Paco2, as well as MAP, while \( r_{MBF} \) did not always do so, particularly in response to MAP changes produced by exsanguination and reinfusion.

There were positive correlations between Paco2 and \( r_{SBF} \) or \( r_{EBF} \), but no significant relation between Paco2 and \( r_{MBF} \) (Figure 3, A, B, and C). Excellent correlation was obtained between \( r_{SBF} \) and \( r_{EBF} \) over a Paco2 range of 27.8–66.7 torr with minimum changes in MAP. Correlation coefficients between \( r_{SBF} \) and \( r_{EBF} \), between \( r_{SBF} \) and \( r_{MBF} \), and between \( r_{EBF} \) and \( r_{MBF} \) in response to changes in Paco2 were 0.946 (\( p < 0.001 \)), 0.520 (\( p < 0.01 \)), and 0.454 (\( p < 0.05 \)), respectively (Figure 3, D, E, and F). Moreover, the rate of change in both \( r_{SBF} \) and \( r_{EBF} \) was the same in response to Paco2 changes: \( r_{SBF} = 7.0 + 1.0 \times r_{EBF} \) (Figure 3, D).
FIGURE 2. Sequential and simultaneous measurements of regional spinal cord blood flow (rSBF), regional epidural blood flow (rEBF), and regional muscle blood flow (rMBF) affected by changes in arterial carbon dioxide tension (Paco2) and mean arterial blood pressure (MAP) in a rat anesthetized with pentobarbital. Paco2 modulated by hyperventilation or CO2 inhalation; MAP manipulated by exsanguination and reinfusion of blood. Note that both rSBF and rEBF change linearly in response to changes in Paco2 as well as MAP, while rMBF does not always do so.

There were no significant changes in rSBF, rEBF, or rMBF within the MAP range of 70–130 mm Hg (Figure 4, A, B, and C). Both rSBF and rEBF showed a significant relation with MAP in the range of 30–90 mm Hg, while rMBF showed no significant relation to MAP even below 90 mm Hg (Figure 4, A, B, and C).

There was a close correlation between rSBF and rEBF in response to changes in MAP from 30 to 130 mm Hg, and the rate of change in both parameters was also almost the same: rSBF = 6.8 + 0.9 x rEBF (Figure 4, D). Although a significant relation (p<0.01) was also noted between rSBF and rMBF responding to changes in MAP, the value of the correlation was not so high (Figure 4, E). There was no correlation between rEBF and rMBF in response to changes in MAP (Figure 4, F).

Discussion
The present results demonstrate that rEBF has a strikingly linear relation with rSBF in response to changes in Paco2 and MAP, while rMBF does not show a close correlation with either rSBF or rEBF. Moreover, although the value of rEBF was slightly lower (approximately 7 ml/100 g/min) than that of rSBF, its rate of change was very similar to that of rSBF in response to variation in both Paco2 and MAP. This suggests that both rSBF and rEBF are regulated by a similar mechanism.

There are three possible interpretations for the measured values of rEBF in the present study. First, the epidural electrode may detect purely regional blood flow in the epidural tissue distinct from that in the cord. Second, the epidural electrode may measure the rate of clearance from the underlying spinal cord of hydrogen that diffuses through the dura to the electrode. Third, the epidural electrode may also measure the clearance rate of hydrogen from both the cord and epidural tissues. Nevertheless, the close relation between rSBF and rEBF demonstrated in the present study suggests that monitoring rSBF by the epidural catheter electrode is feasible without damaging the dura or spinal cord.

The epidural venous plexus drains both the cord and vertebral canal, as well as cerebrospinal fluid from the...
subarachnoid space. Cranially it communicates with the occipital, sigmoid, and basilar sinuses of the brain, while caudally anastomotic channels via the sacral canal form a connecting system between the vertebral plexus and inferior vena cava. Thus, the epidural plexus forms a venous network between the pelvis and brain, and works as an alternate pathway to the caval system. In view of these characteristic functions and behavior of the epidural venous plexus, there may be a close relation between SBF and EBF.

The values of SBF in lumbar gray matter reported so far vary from 10.8 to 67 ml/100 g/min, probably due to differences in measurement techniques, species, and the anesthesia employed. The hydrogen clearance technique to measure SBF was used in rhesus monkeys and dogs. The advantage of this technique is that measurements may be repeated over time to investigate the effect of various agents on SBF as in the present study. The disadvantages of the hydrogen clearance technique are the size of the electrode, which may damage the cord, and the difficulty in achieving resolution of very small areas. To minimize these disadvantages, we used small electrodes with fine, flexible leads.

The present study has further demonstrated that an autoregulatory mechanism also exists in rEBF of pentobarbital-anesthetized rats. There has been no report of the EBF, though anatomically close relations of the epidural venous plexus to blood flow through the cord have been noted in animals and humans. Further, spinal arteries reach the spinal cord via the intervertebral foramina and enter the epidural space to reach spinal nerve roots in the region of the dural cuffs. As expected by its intimate relation with SBF, EBF has demonstrated behavior similar to SBF in terms of response to changes in Paco2 and MAP in the present study in rats.

A similar close relation between rSBF and rEBF is assumed to also exist in humans, suggesting the applicability of monitoring rSBF by measuring rEBF. If measurement of human SBF becomes possible by simply placing an epidural electrode in the epidural space, it would provide a new technique for monitoring rSBF during major surgeries that might affect SBF.

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References


**KEY WORDS** • spinal cord blood flow • epidural blood flow • arterial carbon dioxide tension • mean arterial pressure
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