Local blood flow, oxygen tension, and oxygen consumption in the rat spinal cord

Part 2: Relation to segmental level

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Using a reliable and reproducible microelectrode technique, consistent simultaneous measurements of local spinal cord blood flow (SCBF), tissue oxygen tension, and tissue oxygen consumption were made at cervical, thoracic, and lumbar levels in the rat spinal cord. These observations showed that the metabolic state is maintained constant along the cord, despite significant variations in vasculature. The physiological and anatomical aspects of these findings are discussed.

KEY WORDS: local spinal cord blood flow • spinal cord metabolism • spinal cord vasculature • segmental level • spinal cord oxygen consumption

One of the major functions of the spinal cord is neuronal conduction. Nerve fiber tracts project in both directions between central and peripheral nervous system elements. Nerve tract components including sensory and motor neurons and their processes are present and functional at all spinal cord levels. In contrast to the relatively consistent neuroanatomical architecture of the spinal cord, its vascular supply varies significantly throughout its length.7,10,17-19

Bingham, et al.,1 reported local spinal cord blood flow (SCBF) values as lower in the thoracic cord than at cervical and lumbar levels. These values corresponded to the relatively scant thoracic vascular supply. Cerebral circulation studies have shown that local cerebral blood flow varies proportionally with the density of the vasculature3 and/or the local tissue metabolic activity.16 A similar relationship is presumed to exist in the spinal cord. Therefore, differences in local SCBF between spinal cord levels are related to differences in local spinal cord metabolism. One must, therefore, wonder how the functional neuronal integrity of sensory and motor tracts is maintained in spite of the significant variation between levels in blood flow and metabolism.

Local SCBF and local tissue oxygen metabolism were measured simultaneously in the cervical, thoracic, and lumbar spinal cord. The anatomicophysiological mechanisms responsible for maintenance of neuronal function at various spinal cord levels were studied using blood flow and tissue metabolism as parameters related to specific spinal cord structures.

Materials and Methods

Seventy-eight male Sprague Dawley rats, each weighing 300 to 350 gm, were prepared as described previously.9 Laminctomies were performed exposing the spinal cord at C-5, T-3, and L-2 levels. Mean total SCBF values at the cervical, thoracic, and lumbar levels are dependent upon differences in spinal cord dimensions, ratios of gray to white matter, and local SCBF. These values were assessed using the mean total SCBF demand index (MTSCBFDI), which was calculated by Equation 1 as follows:

$$
(A1 \times F1) + (A2 \times F2) + (A3 \times F3) + \\
(A4 \times F4) + (A5 \times F5) + (A6 \times F6) 
$$

where $A1 = $ dorsal funiculus area; $A2 = $ lateral funiculus area; $A3 = $ ventral funiculus area; $A4 = $ dorsal horn area; $A5 = $ intermediate gray area; $A6 = $ ventral horn area; $F1 = $ dorsal funiculus mean local SCBF; $F2 = $ lateral funiculus mean local SCBF; $F3 = $ ventral funiculus mean local SCBF; $F4 = $ dorsal horn mean...
Rat spinal cord metabolism at different segmental levels

local SCBF; F5 = intermediate gray local SCBF; and F6 = ventral horn mean local SCBF.

Local SCBF was measured in the ventral horn, dorsal horn, and intermediate gray matter, and in the ventral, dorsal, and lateral funiculi of the white matter at each level studied. Spinal cord gray and white matter areas were planimetrically measured using a standardized slide magnification technique. Local tissue oxygen tension (TO2) and local tissue oxygen consumption (TO2C) were measured as described previously.9

Results

Values for local SCBF, TO2C, and TO2C within cervical, thoracic, and lumbar spinal cord levels are summarized in Table 1. These data were obtained using systemic parameters as previously described.9

Mean local SCBF values in the cervical, thoracic, and lumbar gray matter were 63, 62, and 64 ml/100 gm/min, respectively, and the corresponding white matter values were 20, 19, and 20 ml/100 gm/min, respectively. In the gray matter of the cervical cord, local SCBF in the intermediate zone (78 ml/100 gm/min) was higher than in the ventral horn (60 ml/100 gm/min) and dorsal horn (51 ml/100 gm/min). Similar blood flow distribution patterns were observed in the cervical, thoracic, and lumbar spinal cords (Table 1 and Fig. 1). Local white matter SCBF for the ventral, lateral, and dorsal funiculi was relatively homogeneous when compared to gray matter values. Local SCBF within these three funiculi in the cervical, thoracic, and lumbar spinal cord were 21, 20, and 20 ml/100 gm/min; 19, 19, and 19 ml/100 gm/min; and 23, 19, and 21 ml/100 gm/min, respectively. Local SCBF distribution for the three funiculi varied most within the lumbar cord, with a range of 18 to 23 ml/100 gm/min. Similar differences in local white matter SCBF distribution between the cervical and thoracic spinal cord were not noted. These data illustrate that mean local SCBF is uniformly maintained at various spinal cord levels.

Local TO2 values for gray and white matter at the cervical, thoracic, and lumbar levels were 17 and 15 torr, 19 and 16 torr, and 17 and 15 torr, respectively. At the same levels, local TO2C values of gray and white matter were 3.5 and 3.4 ml/100 gm/min, 1.1 and 1.0 ml/100 gm/min, and 3.6 and 3.4 ml/100 gm/min, respectively. There were no significant differences in local TO2 and local TO2C (tissue oxygen metabolism) between various spinal cord levels.

Variations in spinal cord cross-sectional areas and gray to white matter distribution ratios at the three spinal cord levels are shown in Fig. 2. The spinal cord cross-sectional area in the cervical cord (74 - 99 x 10^-3 sq cm) was greater than in the thoracic (46 - 68 x 10^-3 sq cm) or lumbar (83 - 91 x 10^-3 sq cm), as illustrated. The largest areas were found at C-1 to C-4 (99 x 10^-3 sq cm) and the smallest areas at T-7 to T-9 (46 x 10^-3 sq cm). The thoracic level

### TABLE 1

<table>
<thead>
<tr>
<th>Source of Tissue</th>
<th>Local SCBF (ml/100 gm/min)</th>
<th>Local TO2C (ml/100 gm/min)</th>
<th>Local TO2 (torr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cervical spinal cord</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gray matter</td>
<td>63 ± 5.7</td>
<td>3.5 ± 0.34</td>
<td>17 ± 4.3</td>
</tr>
<tr>
<td>white matter</td>
<td>20 ± 3.5</td>
<td>1.1 ± 0.37</td>
<td>15 ± 5.4</td>
</tr>
<tr>
<td>thoracic spinal cord</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gray matter</td>
<td>62 ± 4.8</td>
<td>3.4 ± 0.59</td>
<td>19 ± 3.9</td>
</tr>
<tr>
<td>white matter</td>
<td>19 ± 2.8</td>
<td>1.0 ± 0.01</td>
<td>16 ± 4.6</td>
</tr>
<tr>
<td>lumbar spinal cord</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>gray matter</td>
<td>64 ± 5.1</td>
<td>3.6 ± 0.09</td>
<td>16 ± 4.7</td>
</tr>
<tr>
<td>white matter</td>
<td>20 ± 3.3</td>
<td>1.1 ± 0.31</td>
<td>15 ± 5.2</td>
</tr>
<tr>
<td>mean gray matter values</td>
<td>63 ± 5.2</td>
<td>3.4 ± 0.34</td>
<td>17 ± 4.2</td>
</tr>
<tr>
<td>mean white matter values</td>
<td>20 ± 3.2</td>
<td>1.0 ± 0.23</td>
<td>15 ± 5.0</td>
</tr>
<tr>
<td>no. of animals</td>
<td>21</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

* SCBF = spinal cord blood flow; TO2C = tissue oxygen consumption; TO2 = tissue oxygen tension. Values are means ± standard deviations.

![Fig. 1](Fig. 1.png)

**Fig. 1.** Variations of local spinal cord blood flow (lSCBF) at the cervical (C-5), thoracic (T-3), and lumbar (L-2) spinal cord levels in 21 rats. **Upper:** Mean lSCBF for gray and white matter at each vertebral level. **Lower:** Mean lSCBF at different sites in the gray and white matter at each vertebral level. 1: ventral horn; 2: intermediate gray; 3: dorsal horn; 4: ventral funiculus; 5: lateral funiculus; 6: dorsal funiculus.
had less gray matter area (25% to 35%) than either the cervical (35% to 45%) or lumbar (40% to 60%) spinal cord levels. The MTSCBFDI values at various spinal cord levels were calculated from the local SCBF, spinal cord cross-sectional areas, and gray to white matter distribution ratios using Equation 1 (Fig. 3). Thoracic MTSCBFDI (ranging from 13 to 32.5) was lower than cervical (27 to 38) and lumbar (28 to 38.5) values.

Discussion

Most of the spinal cord extrinsic blood supply is provided by the radicular arteries,14,17,19 which arise from extraspinal arteries (C1-6), the ascending cervical branch of the subclavian (C7-8), the superior intercostal branch of the subclavian (T1-2), the intercostal vessels (T3-12), the lumbar vessels (L1-4), the lower lumbar vessels (L-5), and the medial and lateral sacral arteries (S1-3).18

Our previous findings that the distribution of the radicular arteries is variable (unpublished data) agrees with other studies.1~ At the cervical level there are usually two or three vessels of equal size, and this is found most consistently at the C-6 level.18 In the upper thoracic levels, only one or two small vessels are present. The lower thoracic and lumbar spinal cord levels are supplied by one to three vessels. The most prominent usually lies on the left, between L-1 and L-3 (the artery of Adamkiewicz).18 The most significant vessels for distal supply accompany the L3-5 roots.

Transverse blood flow is in continuity with the bidirectional flow between two adjacent radicular arteries via the longitudinally directed blood flow on the spinal cord surface. The region demarcated by this junction of the transversely directed and longitudinally directed blood supply creates an intrinsic watershed zone at certain spinal cord levels.18 These watershed zones are susceptible to microcirculatory
Rat spinal cord metabolism at different segmental levels

insufficiency with potential damage to the spinal cord parenchyma. The exact location of these zones has been described as being between ascending cervical or superior intercostal branches of the subclavian and the thoracic intercostal vessels. It has been suggested that intrinsic capillary anastomoses provide a protective mechanism for maintenance of local SCBF in the face of ischemia caused by obstruction of a single radicular artery.18

Sapirstein's indicator fractionation technique13 was first adapted for measurement of SCBF by Flohr, et al.,4,27 in 1969. Flohr used noninvasive iodine-131-labeled macroaggregated albumin particles as the tracer. Whole-segment blood flow values (white and gray matter flow) at the cervical, thoracic, and lumbar levels were found to be 20, 16, and 23 ml/100 gm/min, respectively. Bingham, et al.,1 further modified the technique, using carbon-14-antipyrine as a tracer to overcome methodological limitations within nonhomogeneous spinal cord tissue. This technique seems to be more suitable to the measurement of local SCBF. However, as we shall discuss, limitations still exist for studying differences in local SCBF at various spinal cord levels.

Local SCBF values reported for gray and white matter at the cervical, thoracic, and lumbar levels were 48 and 19 ml/100 gm/min, 40 and 18 ml/100 gm/min, and 43 and 21 ml/100 gm/min, respectively. Local SCBF’s at the thoracic level were lower than flows measured at the cervical and lumbar levels. In the thoracic white matter, which contains both sensory and motor fiber tracts, local SCBF was 6% lower than that found at cervical levels, and 16% lower than at lumbar levels. Local SCBF in thoracic gray matter was 20% lower than found at cervical levels, and 7% lower than at lumbar levels. These data suggested the possibility of diminished metabolism at thoracic spinal cord levels.

On the other hand, mean local SCBF and TO2C values for cervical, thoracic, and lumbar spinal cord levels, obtained using our microelectrode technique, were not significantly different (Fig. 1 and Table 1). Similar values were also obtained within white and gray matter areas at each level. These data are obviously in conflict with previously reported studies.

There are, however, several disadvantages of radioisotope indicator fractionation methods for measurement of local SCBF: 1) there is radioisotope contamination of white matter by diffusion from the adjacent gray matter areas;12 2) a false autoradiographic interpretation can result from imaging of intravascular isotope,13,16 which varies with vessel caliber at different spinal cord levels; 3) changes in spinal cord perfusion pressure during the measurement of local SCBF can affect the resultant data, especially within the watershed zones, and may lead to inaccurate values;16 and 4) local SCBF values vary depending upon whether invasive or noninvasive tracers are used.12

With previous studies using hydrogen clearance techniques, there have been difficulties with the measurement of local SCBF within white and gray matter areas.16,11,16 We have discussed these methodological pitfalls previously.8,9 Using our floating microelectrode apparatus, it has been possible to take simultaneous measurements in gray and white matter areas, including measurements of the different laminae of Rexed within the gray matter and major fiber tracts of the white matter. Our data have revealed that local SCBF and local tissue oxygen metabolism are maintained at constant values within the various spinal cord levels, in spite of variations in blood supply and parenchymal architecture. A special mechanism appears to compensate for these variations, and results in the maintenance of consistent mean intrinsic local SCBF and metabolism at various spinal cord levels.

It has been reported that central nervous system local blood flow values are dependent on local blood supply at the capillary level and on local tissue metabolic activity.8,16 Therefore, to maintain consistency of mean intrinsic local SCBF and metabolism between various cord levels, blood supply must be maintained at the capillary level. The spinal cord can maintain its intrinsic blood supply in spite of decreased extrinsic vascular supply, as best illustrated at thoracic levels. The decreased size of the thoracic spinal cord allows the maintenance of mean local SCBF values similar to those at cervical and lumbar levels, in spite of its decreased total SCBF. A decrease in gray to white matter area ratio and the smaller area of the thoracic cord produces a decreased total SCBF demand. In addition, the thoracic spinal cord has a unique hemodynamic blood flow pattern different from that observed at cervical and lumbar levels. Variations in spinal cord parenchymal architecture at various levels are shown in Fig. 2 upper. The ratio of gray to white matter area within each spinal cord level is shown in Fig. 2 lower.

The white matter area in the thoracic spinal cord was three times greater than gray matter. In the cervical spinal cord, it was 1.8 times greater, but in the lumbar spinal cord, white and gray matter areas were almost equal in size. From these data, we can see that demands upon total SCBF at the thoracic level have been maintained at lower values than at the cervical or lumbar levels because of its specific anatomical architecture.

Variations in intrinsic vasculature supply between the various human spinal cord levels have been described by Crock and Yoshizawa.5 In the cervical and lumbar regions of the spinal cord, dorsal and ventral penetrating arteries lie in a straight line along the horizontal plane. At thoracic levels, the central arteries are more widely spaced at the origins along the anterior spinal arteries. They course backward obliquely and branch out. On sagittal section, the main stems of the central thoracic arteries form wedge-like patterns with arteries penetrating the posterior surface of the
cords. This specific configuration of intrinsic thoracic vessels seems hydrodynamically to be very effective in perfusing a large area with a decreased number of small-caliber vessels.

The MTSCBF DI was used as an indicator of mean total SCBF values at the various spinal cord levels. Variations of MTSCBF DI correlated well with intrinsic vascular density distributions reported by Jellinger. The thoracic spinal cord intrinsic hemodynamic blood flow pattern was not considered in the calculation of these indices. Therefore, quantitative mean total SCBF at the thoracic levels may be higher than represented by the MTSCBF DI.

Our data and those of other investigators suggest the existence of specific anatomicophysiological mechanisms responsible for the maintenance of consistent values for blood flow and oxygen metabolism at all spinal cord levels. There are no differences in mean local SCBF and oxygen metabolism values between white and gray matter areas within the cervical, thoracic, and lumbar spinal cord.

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References


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