Intradural microanatomy of the nerve roots S1–S5 at their origin from the conus medullaris

Laboratory investigation

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Object. The conus medullaris and the nerve roots from S-1 to S-5 regulate bladder function as well as movement and sensation of the lower extremities. This most caudal region of the spinal cord has not been studied in great detail anatomically despite its important regulatory role. The goal of this analysis is to characterize the normal intradural microanatomy of the sacral nerve roots at their origin from the conus medullaris.

Methods. The thecal sacs from 20 cadavers were fixated in formaldehyde and dissected under the operative microscope.

Results. More than 50 rootlets originated from the conus medullaris over a distance of < 3 cm. The rootlets were loosely organized into bundles by the arachnoid membrane with decreasing diameters. These diameters were 1.7 mm (ventral)/2.4 mm (dorsal) at S-1, and 0.17 mm (ventral)/0.4 mm (dorsal) at S-5. The roots were separated by neither the dentate ligament nor interradicular gaps. The number of rootlets decreased in the rostrocaudal direction with 2 ventral and 5 dorsal rootlets at S-1, but only 1 ventral (inconsistently found) and 2 dorsal rootlets at S-5. Typically, 1 nerve anastomosis was present between adjacent dorsal roots from S-1 to S-4. Nerve anastomoses between ventral roots or rootlets of the same root were less frequent. The dorsal segment of origin (linea radicularis) decreased in length from 7.2 mm at S-1 to 4.8 mm at S-5.

Conclusions. The current study provides anatomical details and specific morphometric data of the intradural contents at the level of the conus medullaris. This information is valuable for intraoperative orientation, endoscopic navigation, and possible intradural nerve stimulation. (DOI: 10.3171/SPIN/2008/9/8/207)

KEY WORDS • cauda equina • conus medullaris • microanatomy • sacral nerve root
Methods

Specimen Preparation

Twenty cadavers that were donated to the Institute of Anatomy in Münster were used for the current study. The bodies were prefixed in a solution of formaldehyde, methanol, and water. The mean age of the donors at the time of death was 76 years. Eight cadavers were female and 12 were male. Laminectomies were performed from T-7 to the sacrum. The spinal nerves were cut extradurally at the intervertebral foramina. The T-12 segment was marked on the right side. The entire thecal sac from T-7 to the sacrum was then harvested and fixated for 2 days in Karnowski solution (2% paraformaldehyde and 2.5% glutaraldehyde in 0.1 M sodium phosphate buffer). The microanatomical dissection was performed under the operative microscope (Type 614 100, Möller–Wedel). The cauda equina was submerged in isotonic saline solution to allow the nerve fibers to “float,” similar to the in vivo situation. Three specimens were excluded from the analysis because of poor quality and 1 specimen was excluded due to myeloschisis of the conus medullaris.

Orientation Points

We documented the location of anatomical landmarks such as the most caudal “tooth” (dural attachment) of the dentate ligament and large radicular veins. The arteries were not prominent. At the cervical, thoracic, and lumbar spinal cord, nerve roots of different segments are separated from each other by interradicular gaps. We documented the most caudal interradicular gap as an orientation point. Furthermore, the length of the “linea radicularis” for each sacral segment was measured. This line represents the origin of each nerve root in the dorsolateral sulcus of the conus medullaris.

Sacral Roots

The nerve roots were identified from distal (dural sleeve) to proximal (origin at the conus medullaris). Interestingly, nerve roots appeared to be loosely organized into bundles by the arachnoid membrane and could therefore be fairly reliably discerned even proximally (Fig. 1). We counted the number of rootlets per root. The number of anastomoses interconnecting adjacent ventral or dorsal roots was documented. Also, the number of anastomoses in between rootlets of the same root was analyzed (Fig. 2). To avoid double counting, each anastomosis was documented as part of the corresponding rostral nerve root. Finally, the nerve roots were cut proximally directly at the conus medullaris and 2 cm distally. The nerve root diameter was then measured under microscopic control with a micrometer screw at a 1-cm distance from the conus medullaris.

Results

Orientation Points

Microanatomical dissection revealed 13 large radicular veins on either side below T-9. Most commonly, the largest vein was located at L-1 (8 occurrences) or L-2 (5 occurrences). Following a sacral root, typically there was no large radicular vein. We only found a total of 3 veins asso-
associated with sacral roots, 2 at S-1 and 1 at S-3. Interradicular gaps in between sacral nerve roots were extremely uncommon (Fig. 3). On the right side, the lowest gap was between the roots of L-5 and S-1. On the left side, we found a small gap between S-1 and S-2 in 1 specimen. Most commonly (50%), we found the most caudal interradicular gap between L-1 and L-2. Dorsal and ventral sacral roots were not separated by the dentate ligament. The lowest dural attachment of the ligament (the tooth) was found between L-1 and L-2 on either side. Typically, the last attachment was between the T-12 and L-1 root (20 occurrences) on either side. The length of the lineae radiculares was decreasing in the craniocaudal direction from 7.2 ± 1.3 mm at S-1 to 4.8 ± 1.0 mm at S-5. The median length of the dorsolateral sulcus of the conus medullaris (sum of the lineae radiculares from S-1 to S-5) was 29.3 mm (Table 1).

Microanatomy of the Sacral Roots

A total of 150 ventral roots and 184 dorsal roots were found in 16 specimens including both sides. There was always a nerve root present at either side ventrally for the segments S1–S4 and dorsally for the segments S1–S5. The motor root for S-5 was inconsistently found, as was the coccygeal dorsal root. We never found a ventral coccygeal root. The ventral S-5 root was absent on 1 side in 25% and on both sides in 19% of specimens. The coccygeal root was absent on 1 side in 13% and on both sides in 19%. The number of rootlets per nerve root decreased in the rostrocaudal direction. There were typically 2 ventral and 5 dorsal rootlets for the S-1 nerve root, but only 1 inconsistently found ventral and 2 dorsal rootlets for S-5. Accordingly, the diameter of the sacral roots decreased in the rostrocaudal direction. The nerve root diameter was 1.70 ± 0.25 mm (ventral) and 2.39 ± 0.33 mm (dorsal) at S-1, and 0.17 ± 0.10 mm (ventral) and 0.40 ± 0.14 mm (dorsal) at S-5 (Table 1).

Several small nerve anastomoses were found to be interconnecting adjacent dorsal or ventral roots. The anastomoses were never located past the adjacent root. The ratio

Fig. 2. High power magnification views of anatomical details of the conus medullaris and adjacent nerve roots. A: The arrow points at a proximal nerve anastomosis between the dorsal S-3 and S-2 roots. B: The coccygeal nerve root attaches to the filum terminale before joining the cauda equina (arrows). C and D: The smallest caudal sensory root on the left (S-5, marked by an asterisk) is similar in size to the ventral root of S-4 (asterisk in panel D). The arrow in panel D points to the S-5 motor root. The dorsal roots are carefully retracted. Unlike in higher regions, there is no dentate ligament separating the dorsal and ventral roots.

Fig. 3. High power magnification views of anatomical details of the conus medullaris region. A: The left dorsal S-3 nerve root consists of 2 rootlets (asterisks). B: A very small interradicular gap (arrow) can be seen between the dorsal L-4 and L-5 nerve roots on the left. C: The lowest attachment (or “tooth”) of the dentate ligament is fairly solid on the left side between the T-12 and L-1 nerve root (asterisk). D: On the right side, the dentate ligament extends as a thin fibrous band to the dura below the L-1 nerve root (arrows).
of proximal anastomoses (within 2 cm of the conus medullaris) to distal anastomoses was 54/46 ventrally and 60/40 dorsally. We found 80 anastomoses between 150 ventral roots and 204 anastomoses between 184 dorsal roots (Table 1). In ventral roots, 64% had no anastomosis with an adjacent root, 27% had 1 anastomosis, and 9% had multiple anastomoses. In dorsal roots, 39% had no anastomosis with an adjacent root, 32% had 1 anastomosis, and 29% had multiple anastomoses. Anastomoses between rootlets of the same nerve root were less common. We found only 8 such intraradicular anastomoses ventrally and 52 dorsally. These anastomoses could be found typically close to the conus medullaris.

Discussion

The current study characterizes the microanatomy of the sacral and coccygeal nerve roots in detail (Fig. 1; Table 1). The sacral nerve roots form a dense neural network around the conus medullaris with multiple interconnections and without the segmental separation typically encountered in the lumbar, thoracic, and cervical spinal cord. However, the roots are loosely organized into bundles by arachnoid membranes. Each root has a typical number of rootlets, a certain length of the segment of origin from the conus medullaris (linea radicularis), and a certain size. Furthermore, orientation points such as the last dorsal attachment of the dentate ligament, larger radicular veins, and the most caudal interradicular gaps are described in this study. With this information, the study aims to improve the understanding of the microanatomy of the conus medullaris with its nerve roots. The measurements and the descriptions of microanatomical characteristics are valuable for intraoperative orientation for resection of intradural tumors or application of cuff electrodes for intradural nerve stimulation and electrophysiological monitoring.10

Lineae Radiculares

The length of the linea radicularis dorsalis has also been measured by Lang and Geisel.11 These investigators found a similar decrease in size of the spinal cord segments in the rostrocaudal direction. The S-4 segment was found to be 3.9 mm long, and L-5 was found to be 6.7 mm long. Overall, Lang and Geisel found a slightly shorter length of the lineae radiculares. These authors also measured within the dorsolateral sulcus and stated that the measurements were complicated by the frequent occurrence of interradicular anastomoses. D’Avella and Mingrino1 also measured the length of the segments L-1 to S-5 and found significant differences among their specimens. The mean length of the S-1 segment in their study was 8 mm, and 4 mm for S-4. The measurements of the linea radicularis in the current analysis are between those from the study by d’Avella and Mingrino and the study by Lang and Geisel. Thus, our data are supported by the literature and should be helpful for intradural orientation at the level of the conus medullaris.

Orientation Points

Elser was the first to describe the end point of the dentate ligament. He documented the final dorsal attachment at L-1. Carlsson and Sundin2 mentioned the last attachment of the dentate ligament to be a valuable orientation point. However, Schalow30 found significant variation of the last attachment between T-12 and S-1. Furthermore, MacDonald and McKenzie13 have systematically analyzed the position of the last attachment and again found large variation and asymmetry. Their findings are more consistent with our results, and therefore, we do not believe that the last attachment of the dentate ligament is helpful for intraoperative orientation because of its variations.

Typically, nerve roots of different spinal cord segments are separated by interradicular gaps. At the level of the conus medullaris, these gaps are no longer present and make orientation more difficult.20 The work of Pallie18 confirms our observation and showed that there were no gaps found at the level of the conus medullaris. Hoepfner6 measured the interradicular gaps down to the level of L1–2; at that level, she found a gap of 3 mm on average. The position of

<table>
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<tr>
<th>Segment</th>
<th>Location</th>
<th>No. of Nerve Roots Analyzed</th>
<th>Rootlets*</th>
<th>Anastomoses†</th>
<th>Diameter‡ (mm)</th>
<th>Linea Radicularis (mm)</th>
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<tr>
<td>S-1</td>
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<td>32</td>
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<td>S-3</td>
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<td>0 (0.6)</td>
<td>0.71 ± 0.19</td>
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<tr>
<td>S-4</td>
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<td>32</td>
<td>2 (1.4)</td>
<td>0 (0.3)</td>
<td>0.43 ± 0.18</td>
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<tr>
<td>S-5</td>
<td>ventral</td>
<td>22</td>
<td>1 (0.3)</td>
<td>0 (0.1)</td>
<td>0.17 ± 0.10</td>
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<tr>
<td>S-1</td>
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<td>32</td>
<td>5 (3.0)</td>
<td>1 (0.4)</td>
<td>2.39 ± 0.33</td>
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<td>coccygeal</td>
<td>dorsal</td>
<td>24</td>
<td>1 (0.3)</td>
<td>0 (0.1)</td>
<td>0.20 ± 0.07</td>
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</table>

* The number of rootlets is given as median (minimum, maximum) and decreases from the rostral to the caudal direction.
† Typically, 1 anastomosis is present for the dorsal roots at S1–4. Results are again displayed as median (minimum, maximum).
‡ The nerve root diameter also decreases from the rostral to the caudal direction. Dorsal roots are larger and have more rootlets. The corresponding segments of the conus medullaris (linea radicularis) are largest for S-1 and smallest for S-5.
the last interradicular gap has not been determined before; however, it appears to be variable, most commonly found at L1–2 and as low as S1–2.

To our knowledge, the position of enlarged veins following nerve roots has not been described in this anatomical region before. Based on our results, there is often an enlarged radicular vein at L-1 or L-2. If these veins can be identified on preoperative imaging, they could be valuable landmarks for intraoperative orientation.

Fila Radicularia

The ventral roots of S1–S5 consisted of only 1–2 rootlets. In contrast, the dorsal roots typically had more rootlets with an overall decreasing number of rootlets from the rostral to caudal direction, an observation consistent with data from the literature. Hogan also found only 1 or 2 rootlets for ventral roots and typically several more for dorsal roots. The work of Schalow supports this observation as well. D’Avella and Mingrino found more rootlets for ventral roots with as many as 11 rootlets from L-4 to S-3 (2–6 rootlets on average). Dorsally, these investigators typically found 2–6 fila in the sacral segments, and 2–4 fila ventrally at S-4 and S-5. These results considerably deviate from our results and others. Mersdorf and colleagues also investigated the same intradural anatomy in 9 anatomical specimens and also found the ventral S-5 root to be inconsistently present. They did not identify coccygeal roots in their specimens; perhaps fixation or age of the specimen could account for these differences. We believe that the sacral nerve roots can be identified by their rootlets, by knowing the number of the rootlets (Table 1), and by appreciating the fact that rootlets of the same root are loosely organized to units (nerve root bundles) by the arachnoid membrane.

Anastomoses

Lugaro was the first to report nerve anastomoses in the lumbosacral region. Mersdorf and colleagues also found an abundance of both ventral and dorsal nerve anastomoses in the sacral roots in 9 anatomical specimens. Because of the unexpected high frequency of anastomoses, they called the neural network around the conus medullaris the “perispinal plexus” with loss of symmetry and metameric organization. In accordance with our results, they found anastomoses frequently between dorsal roots and less frequently between ventral roots, but never found a bridge between the dorsal and ventral roots. Kikuchi and associates found an even higher incidence of anastomoses within sacral nerve roots. These investigators found interradicular anastomoses in 80% of sacral nerve roots dorsally and in 20% ventrally. D’Avella and Mingrino documented almost 3 times more anastomoses dorsally than ventrally.

The results from these studies support our observations. Clinically, the high frequency of anastomoses in this anatomical region may translate into the loss of dermatomal organization with subsequent misleading findings or symptoms. In surgery, the presence of frequent anastomoses increases the density of the neural network around the conus medullaris and thus makes orientation as well as dissection more difficult. Intradural nerve stimulation might be less successful, considering the loss of strict segmental organization due to the numerous interconnections.

Root Diameter

Schalow systematically measured the root sizes of sacral roots and found the dorsal roots to be larger than their corresponding ventral partners. The diameter of S-1 was found to be 2.0 mm ventrally and 2.7 mm dorsally on average. At S-4, the ventral diameter was 0.4 mm and was 0.8 mm dorsally. These data from Schalow are very consistent with our observations. Hogan analyzed the root cross-sectional area. For dorsal roots, Hogan found the cross-sectional area to be about twice the size of ventral roots, and the size was increasing from the caudal to rostral direction. At S-1 ventrally, Hogan calculated a cross-sectional area of 2.62 mm²; based on our data, we calculated a median area of 2.27 mm². For S-5, Hogan calculated a cross-sectional area of 0.07 mm²; based on our data, we calculated a median area of 0.02 mm² for S-5. Dorsally, Hogan found a cross-sectional area of 4.99 mm² for S-1 and 0.16 mm² for S-5, whereas we calculated a median area of 4.48 mm² for S-1 and 0.13 mm² for S-5 dorsally. Sunderland and Bradley measured the cross-sectional area for the S-3 roots and documented a measurement of 0.88 mm² ventrally and 1.00 mm² dorsally.

These data from the literature support our measurements and may help intraoperative orientation. Furthermore, differences in root size may account for various effects of anesthetics during epidural or spinal anesthesia. The measurements can also be used to select appropriate electrodes for intradural nerve stimulation.

Conclusions

The current study provides an anatomical foundation for the understanding, research, and medical and surgical therapy of disease affecting the conus medullaris and the sacral nerve roots. The sacral nerve roots form a dense neural network with > 50 rootlets originating from the conus medullaris over a distance of < 3 cm. The roots of different segments are separated by neither the dentate ligament nor interradicular gaps. Numerous nerve anastomoses between both dorsal and ventral roots increase the complexity of this neural network. The identified orientation points and the measurements documented in this study are valuable for intraoperative navigation and create a basis for nerve stimulation and a deeper understanding of this anatomical region.

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