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Size of Human Lower Thoracic and Lumbosacral Nerve Roots

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Background: **Nerve root size may determine degree of blockade after epidural or spinal anesthesia, but good measures of this fundamental anatomic parameter have not been published. Models of subarachnoid anesthetic distribution have lacked valid cauda equina dimensions. In this study, the author sought to measure cross-section areas of anterior and posterior roots at different levels for basic anthropomorphic analysis.**

Methods: **Samples from 12 adult autopsy subjects were obtained from roots at levels T6 through S5. Cross-section area was determined by dividing the root sample weight by length and correcting for tissue density.**

Results: **Roots were variably composed of as many as five easily separable independent strands. Areas of anterior roots are approximately half the area of posterior roots. On average, the largest anterior and posterior root is at S1, but this may occur at L3 through S2. There is a large degree of interindividual variability (*e.g.*, range of posterior L5 root is 2.33–7.71 mm^2).**

Conclusions: **The large size of low lumbar and high sacral roots may cause resistance to anesthetic effects, whereas the smaller dimensions of the thoracic roots may facilitate neural blockade. The small size of the low sacral roots may, in part, explain selective neurotoxic damage of these fibers after subarachnoid injections. Interindividual variability in root sizes may contribute to lack of predictability in anesthetic response. (Key words: Anatomy: vertebral column. Anesthetic techniques: epidural; spinal.)**

SPINAL nerve roots, the most proximal component of the peripheral nervous system, convey efferent and afferent neural traffic between the spinal cord and the spinal nerve and rami communicantes at each segmental level. Local anesthetic action on the nerve roots within the subarachnoid space produces the major portion of anesthetic effect after spinal[1] and epidural[2] anesthesia, although other sites contribute.[3] Despite this central role, nerve root anatomy has not been examined adequately. Typical accounts[4,5] depict the posterior root as a singular cylindric structure or as composed of two bundles that exit the dura separate from the solitary anterior root bundle, but no details or documentation are provided. Laterally, the posterior root merges into the distal pole of the posterior root ganglion. Multiple fascicles then emerge distal from the ganglion, which join components of the anterior root to form the anterior and posterior primary rami of the spinal nerve.*

It is well documented that epidurally administered local anesthetic does not produce anesthetic effects uniformly at various segments. Specifically, thoracic nerve roots are blocked by smaller doses and concentrations than those at lumbosacral levels,[6] and a delay in onset or failure of blockade may cause an anesthetic gap at L5 and S1 neural segments.[7,8] This was attributed by Galindo *et al.*[8] to the particularly large size of nerve roots at those levels. However, in their study, they do not distinguish between anterior and posterior roots, they examined only seven levels, and they made no attempt to correlate findings to body size. Most importantly, measurements in that study were made not of the roots but of the spinal nerve enclosed in the epineurial sheath, which is, at most, a secondary site of neural blockade during epidural and spinal anesthesia. Therefore, data in regard to size of the roots is needed to provide an accurate anatomic image of this important site of anesthetic action.

Models have been prepared to examine distribution of subarachnoid anesthetic solutions. However, either roots are not included in the model[9] or they are of uniform and arbitrary dimensions.[10,11] The cauda equina displaces cerebrospinal fluid (CSF), which causes less dilution of anesthetic and possibly limits distribution of injected solution, but the volume of CSF at various levels and in individuals of different size has not been determined. Therefore, a further incentive

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* Kostelic JK, Haughton VM, Sether LA: Anatomy of the lumbar spinal nerves in the intervertebral foramen. Clinical Anatomy 1991;4:366–72.

for anthropometric data on spinal nerve roots is the need for a subarachnoid space model based on valid dimensions. Volumetric analysis of nerve roots by currently available *in vivo* imaging techniques such as computed tomography and magnetic resonance imaging is not feasible because the size of the roots is at the limit of resolution of the methods.

To generate accurate data on nerve roots size, I measured fresh autopsy material from lower thoracic, lumbar, and sacral nerve roots and spinal nerves. The total root cross-sectional area at different vertebral levels and in subjects of different size was determined.

Methods

After institutional review board approval, nerve root measurements were obtained from subjects within 8 h of death. No subjects had obvious disease that involved the vertebral column. After laparotomy and evisceration, pedicles were sectioned in a coronal plane and the vertebral bodies removed from S2 to T6 levels. This exposed the anterior dural sac, which then was sectioned in the midline to reveal the spinal nerve roots and cord. Roots were enumerated by identifying the T12 vertebra by the lowest rib and the S1 vertebra by the sacral alae. A silk ligature was looped around the roots, which exited at a given level, and delicately lifted without stretching to identify the proximal origin of the roots at the cord. Anterior components were separated from posterior components of the root group by the position of their insertion into the cord either anterior or posterior to the dentate ligaments. Segments of anterior and posterior root were excised without deformation. Except at thoracic levels, where the root length diminished to approximately 1 cm, 2- to 3-cm sections were removed for analysis. Where branching or joining of roots occurred, the chosen sample was excised distal to connections, so that the portion exiting the foramen was consistently studied. Either the right or left was selected randomly for evaluation. No attempt was made to strip vessels or connective tissue from the roots.

Samples were kept wet in normal saline until analysis less than 30 min later. The number of easily separable components (referred to below as strands) in each root was defined as the number of free longitudinal elements into which the nerve root readily separated as the root sample twice was placed gently on an absorbent paper towel.

Average cross-sectional area of the roots was calculated by determining the volume of the root sample and dividing that by its length, as follows: The non-stretched length of each sample was measured by caliper, and each section was weighed by an analytic balance (Model AC210S, Sartorious, Goettingen, Germany) with a reproducibility of $< \pm 0.0001$ g. Nerve root density was determined in randomly selected samples by identification of the density of glucose solution that produced neutral buoyancy of the root sample. Average cross-section area was calculated by wt/(density × length). Duplicate determinations of samples obtained from different portions of root were analyzed to test reliability of measurements.

Differences were determined by two-way analysis of variance for repeated measures. Simple regression was used to examine dependency of root areas on height and body mass index (weight divided by height squared in kg/m^2). Measures are reported as mean ± SE. Significance was confirmed if P value was less than 0.05.

Results

Samples were studied from 12 subjects (4 women, 8 men): mean age 58 yr (range 21–80 yr), weight 79 ± 1 kg, height 1.72 ± 0.01 m. A typical set of specimens from a single individual is shown in fig. 1. The anterior root could not be identified at S4 in 5 subjects and at S5 in 9; the posterior root was not evident at S4 in 3 subjects and at S5 in 9. At only three segments, two in

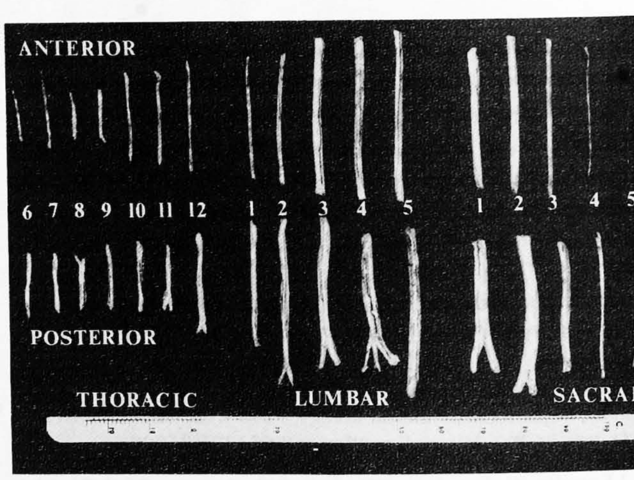

Fig. 1. A typical specimen set that demonstrates the range of root size, and the easily dissociated strands that compose the larger roots.

a single subject, were the posterior and anterior roots seen to exit the dural sac through separate dural perforations. Two cases of root branching were identified in different subjects.

Average root density was 1.0447 ± 0.0056 g/ml (n = 10). Repeat determinations of root area had a concordance of r = 0.95. Average root cross-sectional areas at each level are presented in table 1. In figure 2, the anterior and posterior root dimensions for all subjects are graphed. Anterior roots are significantly smaller than posterior roots at each level examined, generally by a ratio of approximately 2 to 1. The S1 and L5 posterior roots are the largest overall, whereas among the anterior roots, the S1, L3, and L5 are the largest, in that order. There is, however, a high degree of interindividual variability (*e.g.*, the areas for posterior L5, the most variable root, range from 2.23 mm^2 to 7.38 mm^2). In certain subjects, the posterior L4 or S2 was the largest root. The anterior root of L4 is significantly smaller, on average, than anterior roots at L3 and L5.

The sum of areas for all roots inferior to and including T11 (chosen to represent the cauda equina) averaged 43.09 ± 1.91 mm^2 (range 35.03–58.02 mm^2). Regression analysis shows a dependence of root area on body mass index (fig. 3; r = 0.61; $P < 0.05$) but not against height (r = 0.05). The average total cross-section area for all the roots present at each level is

Table 1. Average Root Cross-sectional Area

	Anterior			Posterior	
Level	Area (mm^2)	SE (mm^2)	Level	Area (mm^2)	SE (mm^2)
T6	0.56	0.03	T6	0.89	0.05
T7	0.55	0.01	T7	1.00	0.02
T8	0.67	0.03	T8	1.16	0.03
T9	0.67	0.02	T9	1.32	0.03
T10	0.67	0.02	T10	1.43	0.02
T11	0.80	0.02	T11	1.33	0.03
T12	0.70	0.02	T12	1.56	0.04
L1	0.73	0.02	L1	1.60	0.03
L2	1.30	0.03	L2	2.56	0.06
L3	2.40	0.04	L3	3.60	0.05
L4	1.87*	0.02	L4	3.82	0.05
L5	2.31	0.10	L5	4.45	0.10
S1	2.62	0.04	S1	4.99	0.08
S2	1.18	0.04	S2	3.08	0.15
S3	0.43	0.01	S3	1.12	0.03
S4	0.17	0.01	S4	0.64	0.03
S5	0.07	0.01	S5	0.16	0.02

* Significant difference *versus* adjacent anterior roots.

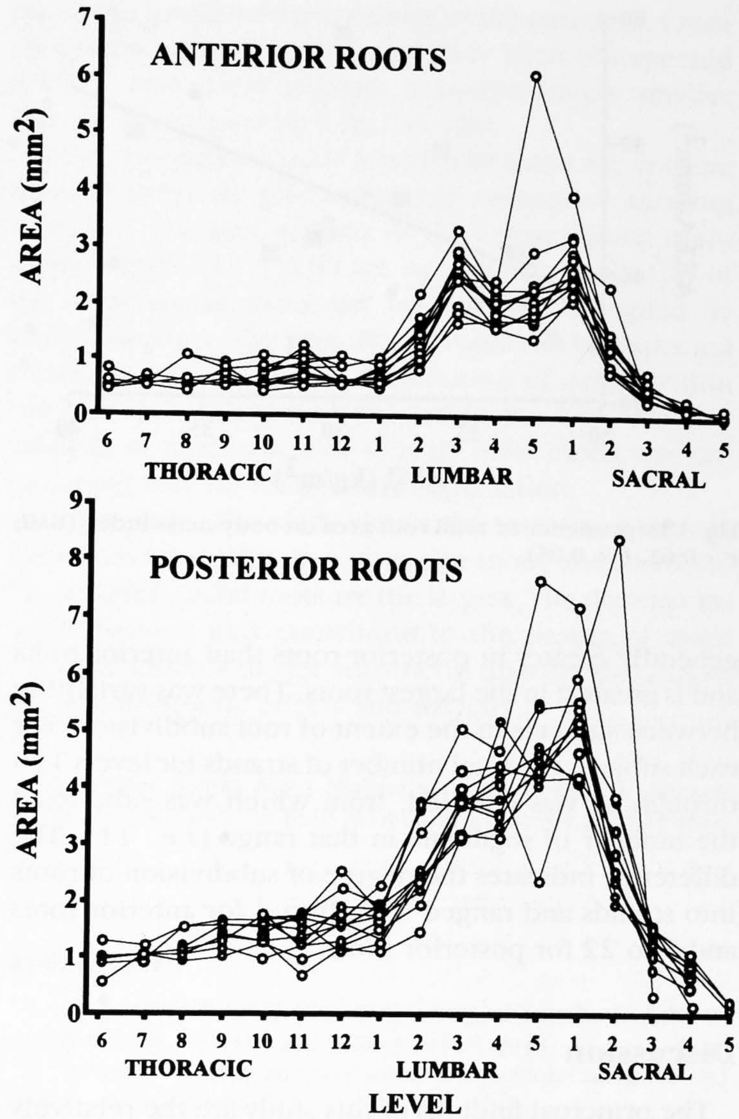

Fig. 2. Cross-section area for anterior and posterior roots of all subjects. Moderate interindividual variability is evident, especially for the larger roots.

graphed in figure 4. The roots can be seen to occupy the greatest total area at the level of L1 and L2.

An approximation of total cauda equina volume was made by assuming an average vertebral segment length of 3.46 cm[12] and that roots T12 through L5 are present at bony midvertebral level T12; L1 through S3 are present at L1; and at each lower level, the roots of that level and all lower roots are present. This results in a cauda equina volume of 7.08 ± 0.33 cm^3 (range 5.74–8.31 cm^3).

For many roots, the slightest handling resulted in dissociation into several strands. The multiplicity of root strands was consistent in duplicate determinations and is tabulated for anterior and posterior roots at each level in table 2. The number of easily separable strands is

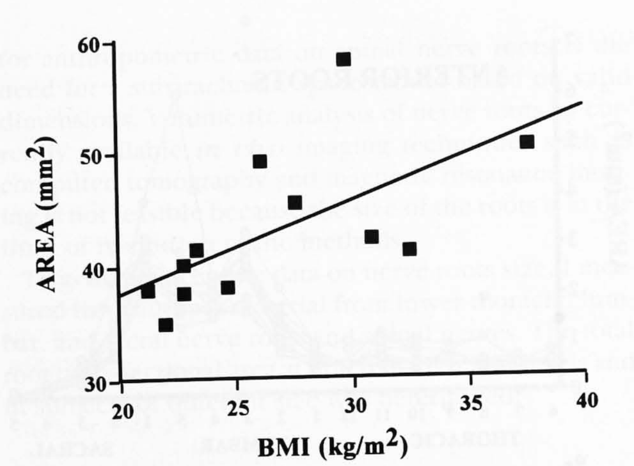

Fig. 3. Dependence of total root area on body mass index (BMI; r = 0.61, $P < 0.05$).

generally greater in posterior roots than anterior roots and is greatest in the largest roots. There was variability between subjects in the extent of root subdivision. For each subject, the total number of strands for levels T10 through S3 was counted, from which was subtracted the number of segments in that range (*i.e.*, 11). The difference indicates the degree of subdivision of roots into strands and ranged from 0 to 4 for anterior roots and 5 to 22 for posterior roots.

Discussion

The principal findings of this study are the relatively larger size of posterior roots compared with anterior roots, the increase in root size at the segments of L3 through S2, the great interindividual variability in root sizes, and the multiplicity of easily separable components that make up the roots, especially posterior roots.

There have been several previous efforts to determine root size. The only one to appear in the anesthesia literature has flaws, as noted above. Sunderland and Bradley[13] determined the area of only the S3 anterior and posterior roots from 27 autopsy subjects by a method that was not described. There was a great deal of interindividual variability in sizes, and the anterior root was larger than the posterior root in 10 subjects. There was good agreement between right and left in six individuals, and sizes were in the approximate range found in this investigation. Both observations support the methods used here. In an early report, Ingbert[14] collected numbers from his work and two predecessors. The limitations of these studies are the use of fixed

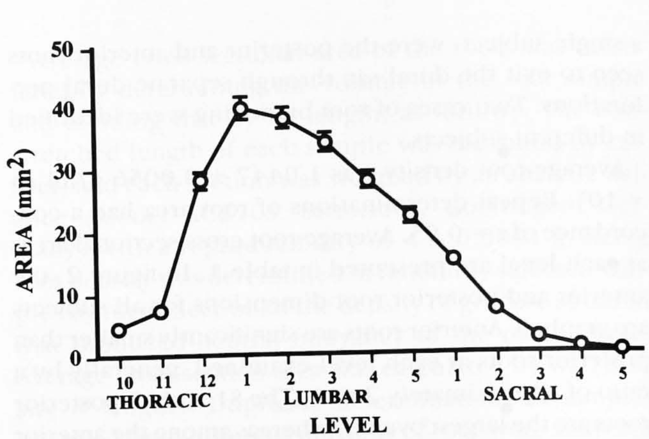

Fig. 4. Average total area occupied by roots at the level of the pedicle at each vertebral level. The cauda equina occupies the greatest area at L1 and L2.

material, examination of only one or two subjects and of only posterior roots, and size determination by weighing paper cut to the size of a projected image. The methods of the current study are validated by high reproducibility of the measurement of duplicate samples, which indicates a reliable method of determination and a root cross-sectional area consistent along its length.

Although absent from many current descriptions,[15] the subdivision of spinal nerve root into independent strands was noted before in passing.[14,16] Unlike pe-

Table 2. Number of Strands per Root

Anterior			Posterior		
Level	Mean	Range	Level	Mean	Range
T6	1.5	1–2	T6	1.2	1–2
T7	1	1	T7	1	1
T8	1	1	T8	1.43	1–2
T9	1	1	T9	1.14	1–2
T10	1	1	T10	1.33	1–2
T11	1	1	T11	1.22	1–2
T12	1	1	T12	1.33	1–2
L1	1.1	1–2	L1	1.44	1–2
L2	1.44	1–3	L2	2.11	1–3
L3	1.33	1–3	L3	2.22	1–3
L4	1.11	1–2	L4	3.11	1–5
L5	1.22	1–2	L5	3.22	2–5
S1	1.11	1–2	S1	2.89	1–5
S2	1.22	1–2	S2	2.67	1–4
S3	1.11	1–2	S3	2	1–5
S4	1	1	S4	2.14	1–5
S5	1	1	S5	1	1

ripheral nerves, which possess substantial connective tissue elements, nerve roots contain minimal collagen.[17,18] In previous studies, it was demonstrated that roots may be made up of as many as 40 fascicles,[14] each enclosed by a modest fascicular pia and held to one another by an encircling lace-like radicular pia.[19] The ease with which roots dissociate into a few components indicates that fascicles are bundled into strands that are in turn only loosely bound to each other by the insubstantial radicular pia. In studies in rats, it was shown that the outer cellular layers of root sheath lack basement membranes and possess minimal collagen,[20] which may account for the mechanical frailty evident in this study.

The importance of root size has its basis in the ratio of surface area to tissue volume, as was demonstrated in peripheral nerves.[21] Small roots have a high ratio of surface to volume, and thereby allow exposure of tissue more readily to substances that penetrate from the CSF, whereas the opposite is true for large roots, in which superficial layers of tissue insulate deeper layers from agents in the CSF. The resistance to anesthesia of low lumbar and high sacral segments may be due to this effect, because roots at these levels have the greatest cross-sectional area and would thereby offer the greatest impediment to local anesthetic penetration. The separation of roots into smaller component strands may mitigate this effect, because it exposes a greater surface to anesthetic in the CSF than a solitary structure, and the largest roots have the highest degree of division into root bundles. The degree to which this dispersion into bundles might aid anesthetic penetration would depend on how tightly packed the elements are. Variability between individuals in the extent of subdivision of roots into strands may contribute to variability in anesthetic effect.

The wide variation in root size among individuals also may contribute to the variability in response to epidural and subarachnoid local anesthetics,[22] because individuals with generally smaller root areas will have facilitated anesthetic penetration into the roots. Diminished dose requirements for thoracic epidural blockade[6] may be due, in part, to the much smaller size of thoracic roots. The very small dimensions of the S3 through S5 roots may predispose these roots particularly to neurotoxic effects, such as occasionally follow subarachnoid hyperbaric lidocaine administration,[23] by allowing critical tissue concentrations of anesthetic to be achieved throughout the root rather than within a small superficial portion, as would occur with large roots. The predictably small size of the anterior L4 root compared with its larger neighbors is an unexpected finding, and could indicate a comparatively smaller muscle mass innervated by this root.

Using estimates of root length and dural sac volume derived from *in vivo* magnetic resonance imaging analysis,[12] the total volume of the cauda equina is approximately 7.31 ± 0.34 ml, or approximately 15% of the lumbosacral dural sac volume not occupied by cord. Therefore, the presence of roots can be expected to be a partial barrier to distribution of drugs within the CSF and should be included in models. The correlation of total root area to body mass index was unexpected and has no obvious explanation.

In summary, this study shows that anterior roots are consistently smaller than posterior roots, and low lumbar and high sacral roots are the largest. The dimensions reported here may contribute to the design of more accurate models to test anesthetic distribution and to predict anesthetic effects and toxicity.

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