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# Anatomy of soft tissue of the spinal canal

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## Headnote

**Background and Objectives.** Important issues regarding the spread of solutions in the epidural space and the anatomy of the site of action of spinal and epidural injections are unresolved. However, the detailed anatomy of the spinal canal has been incompletely determined. We therefore examined the microscopic anatomy of the spinal canal soft tissues, including relationships to the canal walls.

**Methods.** Whole mounts were prepared of decalcified vertebral columns with undisturbed contents from three adult humans. Similar material was prepared from a macaque and baboon immediately on death to control for artifact of tissue change after death. Other tissues examined included nerve root and proximal spinal nerve complex and dorsal epidural fat obtained during surgery. Slides were examined by light microscopy at magnifications of 10-40X. **Results.** There is no fibrous tissue in the epidural space. The epidural fat is composed of uniform cells enclosed in a fine membrane. The dorsal

fat is only attached to the canal wall in the dorsal midline and is often tenuously attached to the dura. The dura is joined to the canal wall only ventrally at the discs. Veins are evident predominantly in the ventral epidural space. Nerve roots are composed of multiple fascicles which disperse as they approach the dorsal root ganglion. An envelope of arachnoid encloses the roots near the site of exit from the dura. Conclusions. These features of the fat explain its semifluid consistency. Lack of substantial attachments to the dura facilitate movement of the dura relative to the canal wall and allow distribution of injected solution. Fibrous barriers are an unlikely explanation for asymmetric epidural anesthesia, but the midline fat could impede solution spread. Details of nerve-root structure and their envelope of pia-arachnoid membrane may be relevant to anesthetic action. *Reg Anesth Pain Med* 1999; 24: 303-310.

## Key words

epidural anesthesia, spinal anesthesia, vertebral column, nerve roots, epidural space.

The lumbar spinal canal is the site of numerous anesthetic interventions including injection of solution and the passage of catheters into the subarachnoid and epidural spaces. However, certain basic anatomic issues are unresolved. The distribution of blood vessels, particularly veins, is often portrayed as uniform throughout the epidural space, whereas examination by epidural venography (1,2) and cryomicrotome section (3) show them to be mainly confined to the ventral spinal canal. The presence of a fibrous septum in the dorsal epidural space has been invoked as a cause for asymmetric epidural anesthetic effect (4). Although no fibrous tissue is evident on histologic study of epidural fat in animals (5) or by cryomicrotome examination of humans (3), others have identified partitions in the epidural space by epidurography after contrast injection (6) and by epidural endoscopy (7).

The arrangement of the nerve roots in the subarachnoid space and their relationship to other tissues is a further area of anatomic uncertainty. Typical descriptions (8) portray a dorsal root made of two divisions and a singular ventral root exiting the dural sac at each level through separate dural perforations, acquiring dural sheaths that unite only at the proximal pole of the dorsal root ganglion. These features, however, have not been subjected to careful scrutiny. Because the spinal nerve roots and ganglia are an important site of anesthetic action after epidural and subarachnoid local anesthetic injection (9,10), further descriptive analysis is desirable.

The spinal canal is a particularly difficult region for anatomic study. Flexible and semifluid tissues are held in place by the balance of subtle forces [cerebrospinal fluid (CSF) pressure, subatmospheric epidural space pressure] which are disrupted on entering the spinal canal. Furthermore, these tissues are enclosed within a barrier of bone and ligament. Exposure by dissection inevitably destroys the natural relationships of the soft tissues. Various methods other than dissection have been used to discern tissue relationships in this region. Contrast injected for epidurography (6), and air (7) required for endoscopic examination all alter the native anatomy, and these methods of imaging cannot discern the types of tissue present. Cryomicrotome sectioning (3) avoids distortion but lacks resolution adequate to identify fine tissue layers and cannot differentiate between tissues that are attached to each other or merely adjacent and nonadherent.

Histologic study of the various epidural tissues is necessary to resolve these anatomic issues. Usual preparations which remove soft tissues from the surrounding bony and ligamentous structures will not

provide data regarding the relationship of spinal canal contents to the walls of the canal. We therefore examined whole mount sections of decalcified lumbar vertebral column which were prepared from nonhuman primate and human cadaver material using a method designed to minimally disrupt the relationships of soft tissues within the bony spinal canal. Additional specimens of epidural fat and nerve roots were examined for confirmation of findings in a larger number of individuals.

## Methods

### Whole Vertebral Column

Human lumbar vertebral columns were prepared from three subjects obtained through an approved anatomic donor program and included a 58-year-old male, a 64-year-old female, and an 80-year-old female. None died from disease that involved the vertebral column. Bodies were refrigerated for between 1 and 4 days following death before tissues were fixed in situ by arterial administration of an aqueous solution of 9% glycerine, 30% isopropanol, 5% formaldehyde, and 6% phenol. After excising the lumbar spine with care so as not to distort spinal canal contents, samples were further fixed by storage in neutral buffered 10% formalin. A 10% solution of disodium EDTA was used to decalcify the specimens for 1 month to 1 year. Calcium content was monitored weekly by radiograph to confirm decalcification. EDTA was rinsed out in running tap water for 1 day. Following dehydration in progressively concentrated solutions of ethanol, the blocks of tissue were cleared in xylene, and infiltrated and embedded in paraffin. Sections 10  $\mu$ m thick were made through the entire spine in axial and sagittal planes by rotary microtome. Stains included hematoxylin and eosin (H and E), vanGieson's (to highlight collagen in connective tissue), and VerHoeff's iron hematoxylin (to highlight elastin). Examination was by light microscope at magnifications of 10-40x.

To control for effects of delay in tissue preservation, material was examined from nonhuman primates in which fixation occurred immediately after death. After receiving approval from the animal care committee, lumbar vertebrae were examined from an adult male macaque (7 kg) and an adult female baboon (14 kg) after completion of other research on the animals which did not involve the vertebral column. Immediately following death by anesthetic overdose, tissues were fixed in situ by intra-arterial 3% glutaraldehyde. The animal material was otherwise processed in the same manner as the human material.

### Excised Specimens

Portions of relevant tissues were obtained from several sources. After laparotomy and exposure of the spinal canal by vertebral body removal, 10 blocks of distal nerve root, dorsal root ganglion, and proximal spinal nerve were excised from 7 unembalmed autopsy subjects (ages 45-87). A surrounding margin of dura and connective tissue up to the periosteum in the intervertebral foramen was included. These were fixed with 10% formalin and embedded in paraffin. Sections 10  $\mu$ m thick transverse to the axis of the nerve and roots were obtained at 250  $\mu$ m intervals and stained with H and E. Additionally, axial sections were obtained from each root from the tenth thoracic to the fifth sacral from two autopsy subjects. These were subsequently fixed and embedded in the same fashion, and stained with H and E. Finally, dorsal epidural fat was obtained from 17 surgical subjects during laminectomy after receiving institutional review board approval. Fat was removed only as clinically indicated, so no

attempt was made for a complete specimen in each case. This material was similarly fixed, embedded, and stained with H and E.

## Results

The decalcification and large block sectioning of vertebral bone and canal contents produced slides with minimal to moderate artifact including shrinkage of adipose tissue and fracturing and wrinkling of bone and ligament during microtome processing. These characteristic features were readily identified. Soft tissue deformation had taken place to the extent that CSF drainage during harvesting had allowed canal contents to fall away from the canal wall. This highlighted sites of connection soft tissues to the canal walls.

Fat in the epidural space is generally sparse and does not form an encircling layer around the dura. The triangular space bounded ventrally by the dorsal dura and dorsally by the ligamentum flavum and lamina of the vertebra is occupied by fat enclosed in a single cell epithelium (Fig. 1). This fat is attached to the canal wall in the dorsal midline to the point at which the ligamenta flava meet in the midline, and a small vein and artery are often seen to enter the fat at this site. Often, the fat has tenuous attachment to the dorsal dura (Fig. 1). These points of adherence are present only for a few millimeters longitudinally.

Laterally, the fat tapers to a termination or continues as intermittent wisps of attenuated membrane. There are no fibrous elements in the fat, which is composed of cells of uniform size and lacks septation. These findings were confirmed in the larger set of excised operative specimens. In most specimens, no vessels were evident in the dorsal space except at the base of the mesentery-like attachment of the fat to the ligamenta flava. In one specimen at one level, large vessels were present in the dorsal epidural space.

The dura is thicker dorsally than elsewhere. Attachment of the dura to the spinal canal wall is noted only ventrally at the level of the disc, where elements of the dorsal longitudinal ligament merged with the lamellae of the dura. These attachments were inconsistent between levels and specimens. The intervertebral foramen (Fig. 2) is occupied by fat, veins, and segmental nerves (dorsal root ganglion and ventral nerve root, or spinal nerve after they join). The fat is distributed in irregular lamellae that are bound by a thin membrane nonadherent to each other or the foraminal wall. Veins in the foramen are found only ventral to the coronal plane of the posterior longitudinal ligament, and irregularly fuse and divide. In the midline of the spinal canal ventral to the dura, epidural veins are continuous with the basivertebral vein of the vertebral body.

Within the subarachnoid space, the nerve roots of the cauda equina are composed of minor elements (fascicles) which are grouped into gross structures (bundles). From 1 to 10 fascicles are joined together into a bundle by an encircling piaarachnoid that appears as a fine membrane. Between 1 and 5 principal bundles constitute the dorsal root that exits at each level (Fig. 3); the most common format is 2 or 3 bundles. In most cases, the ventral root is formed as a single bundle. At a given level, ventral roots are smaller than the corresponding dorsal roots.

As the exiting root bundles diverge laterally, the limiting pia-arachnoid membranes of all the exiting bundles fuse and distend to loosely surround the fascicles of the exiting roots (Fig. 4A,B). A single, deep

sulcus of dura forms around the roots as they leave the sac (Fig. 4C). At only one level of a single specimen did the ventral and dorsal roots exit the subarachnoid space by separate dural fenestrations.

As the roots travel more inferiorly and laterally, the dural sleeve closes around the root bundles, comprising the nerve root sheath. Once leaving the dural sac, the dorsal root fascicles diverge from each other into separate components. At this point, each fascicle is surrounded by a slender extension of the subarachnoid space, separated from each other by connective tissue (Fig. 4D). Further laterally, the subarachnoid space extensions terminate, and the individual fascicles expand and fuse as the dorsal root ganglion (Fig. 4D). The extent of the divergence of fascicles medial to the dorsal root ganglion varies between specimens. The ganglia are almost always bilobed, even when more than two bundles lead into them, and laterally are continuous with multiple peripheral fascicles which fuse with components of the ventral root.



Fig. 1. Photomicrograph of human dorsal lumbar spinal sac. The sac is closed in a thin epithelial rind around and is not adherent to the ligamenta flava (LF) except in the dorsal wall. The sac fills away from the ligamenta flava during tissue harvest, and a space is not naturally present. The sac attaches to the dura inward across by a slender filament (long straight arrow). Anomalous roots (yellow arrow) to exit inside the dura (H and V stain, scale bar = 1 mm).

Fig. 1

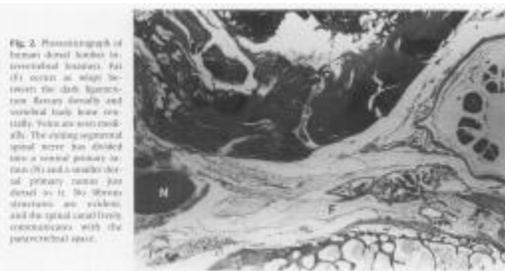


Fig. 2. Photomicrograph of human dorsal lumbar invertebral foramen. Fat (F) occurs at stage between the dura. Spine-root fibers densely and somewhat freely have scattered. The exiting segmental spinal nerve has divided into a neural plexus or root (N) and a smaller dorsal primary rami just distal to it. No obvious sheath is present, and the spinal cord freely communicates with the perineural space.

Fig. 2.

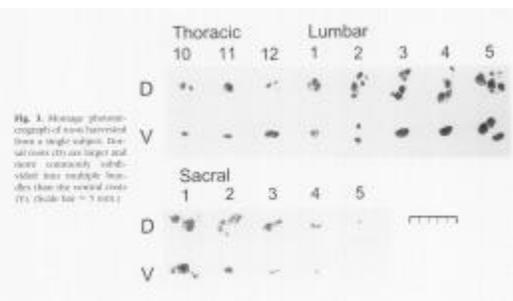


Fig. 3. Average photomicrograph of nerve fibers from a single subject. Dorsal roots (D) are larger and more consistently subdivided into multiple fascicles than the ventral roots (V) (scale bar = 1 mm).

Fig. 3.

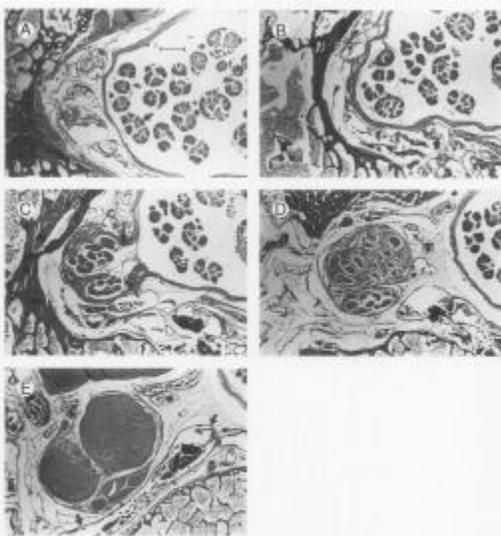


Fig. 4. Photomicrograph of dura and nerve roots of the lumbar canal region, showing a sequence ventral to caudal to the spinal nerve roots near the dorsal sac (D) and (E) status. (A) The existing membrane of the three exiting dorsal root fascicles have been covered (arrow). The membrane of the single dorsal root fascicle is clearly evident (large arrow). (Large vein) (B) The spinal nerve root outside the dura. (Scale bar = 1 mm) (C) Shows directly the dorsal and ventral root membranes (arrow) have been found and attached to the dura. (D) The roots have the dorsal sac through a single fenestration, slipping along a subarachnoid pocket (arrow). The nerve fascicles are showing into their component fascicles. (E) The nerve roots are fully separated from the dorsal sac and entered in a dorsal root ganglion. The individual fascicles are no longer grouped as bundles and are each surrounded by a tubular extension of the subarachnoid space. (G) The dorsal root ganglion forms a two masses, with the ventral one adjacent and ventral to it. A large vein (artery) passes through the transverse fissures related to the neural foramina.

Fig. 4.

Other than size, the baboon and macaque appeared similar. The histologic features are the same as human specimens, although the topographic design is different. Specifically, dorsal root ganglia are found within the spinal canal at the mid and lower lumbar levels, and the basivertebral veins are large. As in humans, the epidural fat is free of any fibrous tissue, and the dura is minimally attached to the spinal canal wall. Unlike humans, the fascicles of the nerve roots are consistently organized into single bundles.

## Discussion

This study reveals several findings that have not previously been observed or have not been emphasized in prior studies. There is no fibrous tissue in the dorsal epidural space. The dorsal epidural fat is securely attached to the canal wall only at its dorsal midline pedicle and is often focally tethered to the dura in the midline. The fat in the dorsal epidural space and elsewhere is otherwise not adherent to the spinal canal. Spinal nerve roots are multifascicular and bundled into several separate strands at each level. Prior to exit of the roots through a single dural fenestration at each level, the pia-arachnoid covering of the roots merges and forms a loose sac-like enclosure. Roots branch into their component fascicles surrounded by CSF prior to expanding into the dorsal root ganglion.

There are several possible sources of artifact in the preparations used here. The absence of evidence of autolysis and the similar histologic appearance of the immediately preserved nonhuman primate material ensures that postmortem changes in the human autopsy and cadaver material are a minimal source of error. Movement of tissues during harvest and sectioning produced characteristic fracturing that could be distinguished from natural anatomy. The adipose tissue is inevitably cleared of fat by xylene, and other tissues are dehydrated by alcohols. However, cellular structure remains, and shrinkage will not alter points of attachment or general spatial relationships. Because only lumbar levels were examined, the findings do not necessarily reflect anatomy at other vertebral levels (11).

Fat is the principal occupant of the epidural space (3). Our findings of uniform cellularity, lack of fibrous tissue, and a thin enclosing membrane mostly unattached to the canal wall are in agreement with the work by Ramsey (5). These features explain the semifluid nature of epidural fat, as has been noted in dissection and during epiduroscopy. This may be important for allowing relative movement of the dura and canal wall as has been documented with flexion and extension of the vertebral column (12) and changing dural dimensions (13-15). The general lack of attachment of the dura to the epidural fat and canal wall allows passage of solution and catheters introduced into this plane. The few sites of attachment of the dura to the dorsal epidural fat in the midline are limited longitudinally and not likely to impede the distribution of catheters or solution introduced into the epidural space. However, these points of adherence may account for the tenting of the dura in the midline, known as a plica dorsalis medianalis (16), which occurs when air or solution injected into the epidural space displaces the dura inward except where it is tethered.

No fibrous tissue was identified in the epidural space. Therefore, the presence of a fibrous septum is an unlikely cause of aberrant spread of solution and asymmetric epidural anesthesia. It is improbable that a larger sample would identify cases of a substantial midline fibrous septum, because such a structure has never been identified in magnetic resonance images (17,18). The midline material observed by computed tomography after contrast injection into the epidural space (6) or by epiduroscopy after air injection (7) is identified in the present study as epidural fat. It is possible that compression of the dorsal fat against the dura by fluid injected between the fat and canal wall could prevent passage of solution across the midline. This barrier would fail once the volume of injectate was adequate to compress the dura as well, unless longitudinal distribution prevented dural compression. The variability in such subtle pressure relationships may partly account for the unpredictability of epidural anesthetic distribution.

The nerve roots are not only the putative site of local anesthetic action during spinal and epidural anesthesia, but also the site of injury from disc disease and other inflammatory or compressive etiologies. The large number of fascicles and bundles composing the roots is not reported in typical descriptions (8). We have previously observed that there are from one to five easily separable strands making up the roots on gross inspection (19), and others have noted multiple elements held together only by a mesh-like membrane of arachnoid (2023). The multiplicity of elements within a porous membrane may aid local anesthetic action by increasing the surface area for penetration. The formation of the ventral root into a single substantial bundle may preferentially impede entry of anesthetic and onset of motor block, compared to the typically multistranded dorsal root, and thus lead to diminished motor block compared to sensory block.

The far lateral subarachnoid space and nerve root sheath may be the dominant site of action for neuraxially applied local anesthetics, accounting for the segmental effects of spinal and epidural block (10). This complex junction at which roots leave the subarachnoid space and enter the nerve root sheath and dorsal root ganglion is particularly relevant to epidural anesthesia, but the anatomic details of this region remain incompletely described. Several anatomic factors favor this site for anesthetic penetration and action. Fixed proximity of the roots to the meninges brings the neural target close to the anesthetic source. As it branches from the dural sac, the nerve root sheath has a large ratio of surface to contained volume of CSF surrounding the roots, which optimizes uptake and minimal

dilution of the anesthetic at this site. An additional factor noted in our study is a membranous partition of the subarachnoid space enclosing the exiting roots, which may constrain local anesthetic in this region and limit dilution with the larger pool of CSF, thereby further amplifying anesthetic action. The particular frailty and loose structure of the nerve root membranes (21,24) makes it possible that the enclosing layers we observed are artifactual. However, adjacent nonexiting roots did not show this, and scanning electron microscopy in dogs has revealed a membrane surrounding the root components as they exit (25), similar to our observations.

We also observed the dispersion of fascicles as the dorsal roots approach the ganglion, which may make neurons at this site especially available to subarachnoid anesthetic, and possibly favor action on the more divided dorsal (sensory) roots compared with the ventral (motor) components. The extension of the subarachnoid space as fine tubular channels surrounding the fascicles may be an important route for local anesthetic delivery to possible sites of action at the fascicles as they disperse and enter the dorsal root ganglion. Anesthetic penetration into the ganglion may be particularly relevant, because impulse conduction through the ganglion is naturally prone to failure (26), and this structure is particularly sensitive to local anesthetics (27).

In conclusion, using a method of tissue examination with minimal and readily distinguishable artifact, we have identified various clinically relevant anatomic features of soft tissues of the spinal canal. Lack of adherence of fat and dura to the spinal canal provides a plane for distribution of solution and catheters in the epidural space. Points of attachment of dorsal fat and dura produce the plica dorsalis medianalis observed during dural compression. Enclosure of the root components by a loculating membrane, division of the roots into multiple strands prior to entering the dorsal root ganglion, and CSF passages into the ganglion may facilitate epidural anesthesia. No fibrous tissue is noted in the epidural space, making fibrous barriers an unlikely contributing factor in asymmetric anesthetic effect.

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