EXPERIMENTAL RESEARCH - NEUROSURGICAL ANATOMY

Anatomy of the spinal dorsal root entry zone: its clinical significance

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Abstract

Background The posterolateral sulcus (PLS) is an important surgical landmark, especially for DREZ (dorsal root entry zone) operations.
Methods The present study aimed to show the variations of the PLS using human spinal cord histological sections and report the variability in the number of dorsal rootlets of the spinal nerves in each the spinal cord segment. Further, measure the height and width of the dorsal horn on histological sections for cervical, thoracic, and lumbar levels.
Results The results of the present study showed various patterns of PLS 1.clearly present PLS, 2. short PLS, 3. absent PLS or 4. irregular PLS. Height and width measurements of the dorsal horn showed that the average width was greatest at lower cervical (0.48±0.04 mm) and least at lower thoracic levels (0.41±0.04 mm), whereas the average height was greatest at upper cervical (3.0±0.06 mm) and smallest at lower lumbar levels (1.8±0.08 mm). The average number of rootlets varied considerably, at cervical level it was 7.6±1.4 mm, at thoracic 6.6±0.8 mm and at lumbar 6.1±0.4 mm.
Conclusions The detailed anatomy of the variations of the PLS and the average number of rootlets at each spinal level can increase the success of regional surgery. Further, fine measurements on histological sections can give detailed knowledge on the size necessary for lesioning in DREZ operations.

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Introduction

Anatomical structures are used as a guide during surgery. The posterolateral sulcus (PLS) of the spinal cord is an important landmark for the dorsal root entry zone (DREZ) operation and for the removal of laterally located spinal intramedullary tumors.

Afferent information is conveyed to the central nervous system via the dorsal roots. The nociceptive impulses are mainly carried in the lateral division of the dorsal root. In the spinal cord, these nociceptive fibers do not synapse immediately with the second-order neurons of the gray mater. Instead, they ascend 1–2 segments in Lissauer's tract (dorsolateral tract) located proximal to the dorsal horn [3, 5, 19]. Lissauer's tract has a function of increasing or inhibiting the pain signals before they reach the Rexed laminae I–V [3, 19]. These axons synapse with cells in

the sensory laminae I–V whose axons then ascend within the lateral spinothalamic tract.

DREZ operations are performed for the purpose of lesioning patients with advanced cancer, brachial plexus avulsion, postherpetic neuralgia, spinal cord injury, or hyperspasticity that is unresponsive to medical or neuromodulatory treatment or to implantation of a medical device. The PLS is the major guide for DREZ operations, which include the lesioning of the proximal portion of the dorsal nerve rootlets, Lissauer tract, and laminae I–V of the dorsal gray column of the spinal cord. The major complication of DREZ occurs if the region is not completely ablated, when the intended outcome of pain relief may not be achieved. If the lesion is too large, the adjacent funiculi are destroyed and cause motor and sensory disabilities.

In order to achieve a successful surgical outcome, detailed knowledge of the anatomy and of the variations of the region is necessary. During DREZ, the dorsal rootlets must be carefully elevated, the PLS should be defined, and the lesion should be made in the appropriate direction. There have been numerous surgical and gross anatomical studies of the DREZ, however, there are no studies on the anatomy of the PLS itself [1, 5, 10, 16, 21, 27]. The aim of the present study is to provide insight on three topics: (1) to describe the PLS and its variations using histological sections, (2) to report the variability in the number of dorsal rootlets of the spinal nerves, (3) to measure the height and width of the dorsal horn on histological sections for cervical, thoracic, and lumbar levels.

The detailed anatomy of the region and the fine measurements of histological sections can give precise knowledge about the size of lesions necessary and can increase the success of DREZ operations. Further, it provides additional anatomical knowledge on the variations of the PLS.

Materials and methods

Anatomical dissection

Five formalin-embalmed adult human cadavers (one female and four males) were used. All procedures were approved by the ethics committee of Koc University. The age range of the cadavers was 59 to 75 years (mean, 67 years). None had grossly visible deformities of the vertebral column, spinal cord, or spinal canal. Each cadaver was placed in prone position, and the skin, subcutaneous tissue, and superficial and deep musculature were removed along the height of the spine. The spinous processes and laminae of all vertebrae were removed using a high-speed drill and rongeurs. The dura mater was exposed, incised, and retracted laterally, and the arachnoid membrane was dissected. The dorsal roots of the spinal nerves were exposed. The segmental level of each dorsal root was defined and confirmed according to the corresponding intervertebral foramen. The number of posterior

rootlets at each spinal level was identified and documented. The dorsal rootlets were incised and the spinal cord specimens were excised. The spinal cords were further divided into right and left halves for histological evaluations. The dorsal roots were examined at 40× magnification under a microscope.

Histological analysis

Two spinal cord specimens from each segmental level of the spinal level were evaluated. The specimens were post-fixed in 10 % formalin for 48 h, dehydrated in an ascending ethanol series, and embedded in paraffin. Transverse sections (10 μm) were cut and mounted on slides. To visualize white and gray mater of the spinal cord, slides were stained with Luxol Fast Blue. The PLS and the dorsal horns were defined and measurements were made at ×40 magnification, and photographed using a Nikon Coolpix S2700 Digital camera.

Height measurements

Three measurements were made from the entrance of the dorsal root to the base of the dorsal horn (base of the dorsal horn corresponds to lamina V): (1) from the medial side of the dorsal horn, (2) the lateral side of the dorsal horn, and (3) the center of the dorsal horn, and the average of the three measurements was then calculated (Fig. 1). The measurements are expressed as mean±SD.

Width measurements

On the same section, three measurements were made from the medial border to the lateral border: (1) the proximal end of the dorsal horn (the straight line at the bottom follows the ventral border of lamina V, (2) distal end of the dorsal horn, and (3) the center of the dorsal horn). The average of the three measurement was then calculated (Fig. 1). The measurements are expressed as mean±SD.

Results

Gross anatomical evaluations

The spinal cord and the meninges within the vertebral canal were exposed (Fig. 2a). The dura and the arachnoid were excised (Fig. 2b). The level and the segmental number of each dorsal root was defined for each spinal level, for all the five cadavers and for both the left and the right side and the average number of rootlets was calculated (Fig. 2b) (Table 1) for each segmental level. The number of dorsal rootlets at cervical levels ranged between 2 and 10 and the mean number was 7.6±1.4. The number of rootlets was lowest at C2 and

Fig. 1 Schematic illustration of a transverse section of the spinal cord showing the localization of the three width and three height measurements from the dorsal horn of cervical, thoracic, and lumbar levels
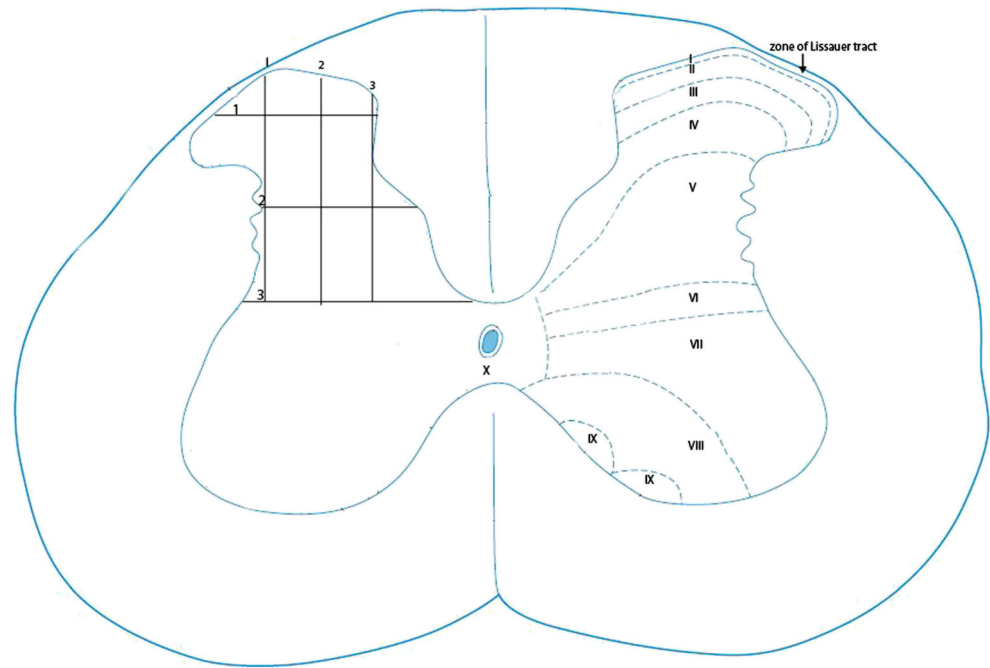

highest at C5 and C6 spinal levels (Table 1). The number of dorsal rootlets at thoracic levels ranged between 3 and 9 and the mean number was 6.6±0.8. The number of rootlets was lowest at T7 and highest at T3 and T4 and T12 spinal levels (Table 1). The number of dorsal rootlets at lumbar levels ranged between 4 and 8 and the mean number was 6.1±0.4. The number of rootlet was lowest at L5 and the rest of the lumbar

levels were rather constant (Table 1). There were no significant differences between left and right at any of the spinal levels.

Table 1 The number of dorsal rootlets of cervical, thoracic, and lumbar spinal nerves (mean±SD)

	Right	Left
C1	–	–
C2	7.0±2.8	6.0±1.0
C3	7.5±2.1	6.7±1.0
C4	7.3±1.5	8.0±0.0
C5	10.3±0.6	9.0±2.6
C6	8.6±1.5	8.3±2.0
C7	7.0±0.5	8.3±2.0
C8	7.5±0.7	6.5±3.5
T1	6.5±0.7	6.5±2.1
T2	6.0±1.7	6.0±1.4
T3	7.6±1.5	6.5±2.1
T4	7.6±1.5	6.6±0.6
T5	6.0±1.0	6.0±1.0
T6	5.3±1.2	5.0±0.0
T7	4.3±0.6	6.3±1.2
T8	5.3±2.3	7.0±0.0
T9	5.7±1.2	6.7±1.2
T10	5.0±0.0	5.0±0.0
T11	7.0±0.6	5.3±1.2
T12	7.6±1.2	7.0±1.7
L1	6.3±0.6	5.7±0.6
L2	6.0±1.0	6.7±0.6
L3	6.7±1.2	6.0±2.0
L4	6.7±1.5	5.7±1.5
L5	4.7±0.6	6.0±1.7
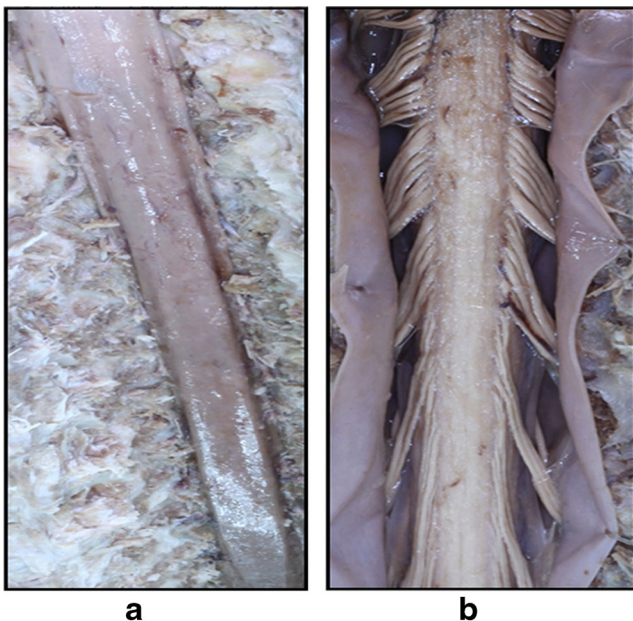
Fig. 2 The spinal cord of each cadaver was exposed by dissecting the skin, subcutaneous tissue, and superficial and deep musculature of the back and the bony components of the vertebral column. a The dura mater was exposed. b The dura and the arachnoid mater was incised and retracted laterally to expose the spinal cord and the dorsal rootlets

Histological evaluations

The anatomy of the PLS

Histological examinations of the PLS showed a single layer of pia that extended between the dorsal and the lateral columns. Any separations between the dorsal and the lateral columns that did not contain pia were not evaluated as the sulcus. There was no arachnoid tissue within the sulcus. The location and the extension of the pia into the PLS showed variations. Five different patterns of the PLS were found on histological sections of the cervical, thoracic, and lumbar segments of the spinal cord: (1) a complete PLS that extends to the base of the dorsal horn (Fig. 3a); (2) a short PLS that extends for a short distance, (Fig. 3b); (3) an irregular PLS that penetrates the white mater of the spinal cord (Fig. 3c) some distance from the

entering rootlets, (4) no apparent PLS (Fig. 3d), and (5) several separate sulci. PLS (Fig. 3e).

The PLS could pass through the white mater of the spinal cord either within the dorsal (Fig. 4a and b), or the lateral column (Fig. 4c).

Dorsal horn measurements

The average height (including Lissauer's tract and the laminae between laminae I and V) and the width of the dorsal horn were measured on the transverse sections for each of the cervical, thoracic, and lumbar spinal segments. The width of the dorsal horn of the spinal cord ranged between 0.28 and 0.78 mm among the spinal levels studied. The highest average width was measured at cervical levels (0.48±0.04 mm) and the lowest was at thoracic levels (0.41±0.04 mm) (Table 2).
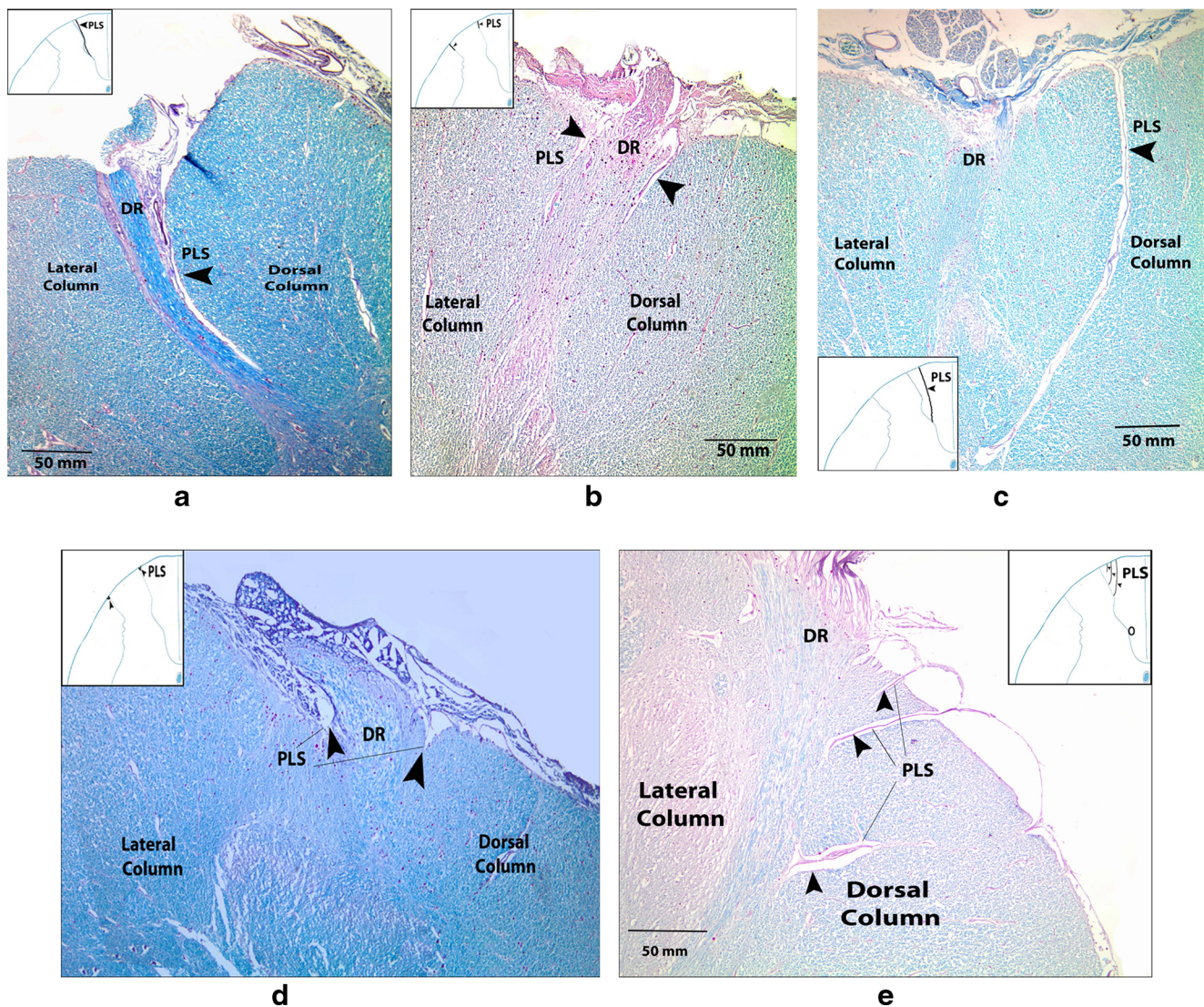
Fig. 3 Five different patterns of the PLS were described on histological sections of the spinal cord. **a** Complete PLS from C3 spinal level. **b** Short PLS from L1 spinal level. **c** Irregular PLS from T10 spinal level. **d** No apparent PLS from C7 spinal level. **e** Triple PLS from C1 spinal level (*DR* dorsal root, *PLS* posterior lateral sulcus)

The height of the dorsal horn ranged between 1.3 and 2.5 mm among spinal levels. The average longest height was observed at upper cervical (3.0±0.06 mm) and shortest at lower lumbar levels (1.8±0.08 mm) Table 2.

Discussion

Major findings

The results of the present study showed that the PLS does not have a constant anatomical structure, and can form various patterns (clearly present, short, absent, or irregular). Height and width measurements of the dorsal horn showed that the average width was greatest at lower cervical and least at lower thoracic levels, whereas the average height was greatest at upper thoracic and smallest at lower lumbar levels. The average number of rootlets at each spinal level varied considerably (see Table 1). Knowledge of the variations of the PLS and the average number of rootlets at each spinal level can increase the success of regional surgery. Further, fine measurements on histological sections can give detailed knowledge of the size of lesion necessary for lesioning in DREZ operations.

Anatomy of PLS

Ablation techniques are being used for intractable pain that is refractory to medical therapy (opioid and nonopioid analgesics) or for implantations of a medical device (neurostimulation). Numerous studies have been conducted on the cause of these neuropathic pains [6, 7, 9]. Intraoperative recordings from dorsal horn neurons of the human spinal cord have shown hyperactivity [6, 7, 9]. The DREZ operations are based on destroying the hyperactive dorsal horn neurons; particularly the lateral portion of the dorsal rootlets along which the nociceptive impulses enter, providing the excitatory inputs to Lissauer's tract.

The PLS defines the plane between the dorsal and lateral columns of the spinal cord. This partition is made of pia. This plane leads to Lissauer's tract and the Rexed laminae I–V of the dorsal horn of gray matter. DREZ can either be accessed laterally or medially, and the PLS provides a necessary surgical guide for both approaches. The major considerations when performing DREZ is inadvertent lesioning of adjacent structures. Therefore, the anatomy of the PLS is surgically important. The PLS is an important landmark not only for DREZ surgery but also for the exposure of intramedullary tumors situated laterally in the spinal cord [25]. Identification of the PLS can be difficult in traumatic root avulsions and in lateral medullary tumors and there may also be atrophic and gliotic changes that can distort the anatomy of the region and cause difficulties in identifying the structures accurately. A knowledge of the anatomy and of the variations of the PLS can be of value in understanding distorted anatomy.

The extension and the variation of the PLS has not been studied previously. This study has shown an irregular penetration of the PLS into the white mater of the spinal cord either in the dorsal or lateral column of the spinal cord as illustrated in Fig. 4a, b and c. In these cases, if the PLS is used as a guide, this can cause damage to the fiber of either the dorsal or lateral columns and may result in loss of either sensory or motor functions.

Histological studies of the structure of the posterior median sulcus (PMS) have shown that the PMS is not a sulcus but a septum or a raphe, which consists of thin blade of capillary-carrying collagen that extends from the pia [8]. However, the PLS consists of a layer of pia.

The present study has been done on formalin fixed and embedded in paraffin sections; the major question is how comparable are the height and width measurement to the living subject. Quester and Schröder compared the amount of shrinkage of human brain stem during fixation and embedding in paraffin with human fresh brain stem and showed that the transverse values were unchanged and that the shrinkage led to decrease in longitudinal distances of 1–8 % [18]. Choi et al. [2] assessed the degree of shrinkage or expansion of the spinal cord that occurs during the embalming process by comparing the diameters of cadaveric spinal cord to that of sagittal magnetic resonance scans of living subjects [2]. They showed that spinal cord dimensions increase after embalming. They did not embed the spinal cords in paraffin. They used a Vernier gauge for the spinal cord measurements. In the present study, the spinal cord specimens from embalmed cadavers were further processed using routine histological paraffin fixation (see Materials and methods section) and the measurements were achieved under 40× magnification. Therefore, the increased dimensions of the spinal cord obtained in Choi et al.'s [2] study may not be the case for the present study because in the present study we further processed the spinal cord specimens with routine paraffin procedures. The shrinkage or expansion behavior of individual tissue can vary, therefore, the shrinkage should be taken into consideration in DREZ operations.

Height and width of dorsal horn of the spinal cord

Different techniques have been used to produce lesions such as microsurgical, radiofrequency, ultrasonic, and laser ablations [4, 13–17, 21–24, 28]. Whatever instrument is used to make a lesion, the major important point is the size of the lesion in the appropriate area. An inappropriate lesion may result in unsatisfactory pain relief or too large a lesion may destroy adjacent structures and cause motor and sensory disabilities. There are studies that have tried to optimize the amount of radiofrequency appropriate to avoid the complications [16]. The present study

Fig. 4 The PLS penetrated in the white mater of the spinal cord. **a**, **b** A PLS penetrating into the dorsal column, **a** from C2 and **b** from C8 spinal level. **c** A PLS penetrating into the lateral column from L5 spinal level (*DR* dorsal root, *PLS* posterior lateral sulcus, *PIS* posterior intermediate sulcus, *PMS* posterior median sulcus)
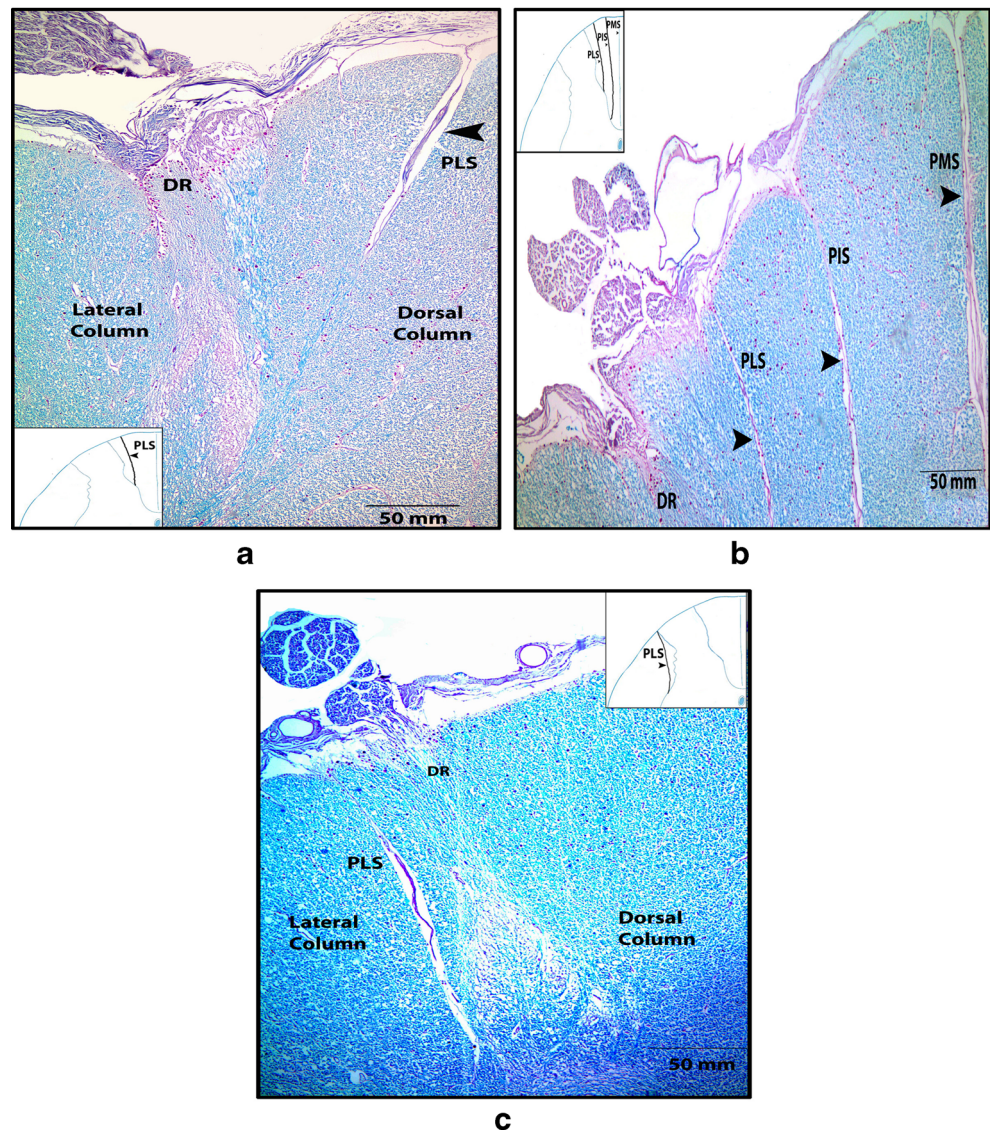
introduces data on the height and the width of the dorsal horn of spinal levels. These measurements can be helpful in deciding on the precise size of lesion necessary for the DREZ operations for different segments of the spinal cord.

Table 2 The average height and the width of the dorsal horn of the cervical, thoracic, and lumbar spinal segments (mean±SD)

	Dorsal horn Width (mm)±SD	Dorsal horn Height (mm)±SD
Upper cervical (C1–C4)	0.46±0.03	3.0±0.06
Lower cervical (C5–C8)	0.48±0.04	2.4±0.02
Upper thoracic (T1–T6)	0.46±0.05	2.3±0.05
Lower thoracic (T7–T12)	0.41±0.04	2.3±0.02
Upper lumbar (L1–L3)	0.43±0.01	2.1±0.06
Lower lumbar (L4–L5)	0.45±0.02	1.8±0.08

Number of rootlets

The number of rootlets varies at each spinal cord segment, which may be related to the sensation coming from body regions. The more sensitive regions of the body may have an increased numbers of rootlets. However, the thickness of each rootlet is equally important. Sindou and Goutelle reported the average number of rootlets to be four at C2–C4 and six at the C5–C8 dorsal roots [20]. Tanaka et al. [26] counted 8–12 rootlets between C5 and C8. Karatas et al. [11] reported that cervical dorsal rootlets ranged from 2 to 13, and the minimum number was found at C2 and maximum at C6, C7, and C8 spinal segments. In accordance with former studies, in the present study the number of dorsal rootlets at the cervical level ranged between 2 and 10 and the number of rootlets was lowest at C2 and highest at C5 and C6 spinal levels.

A recent study relating to the number of thoracic dorsal rootlets was by Boskurt et al. [1]. They counted the largest (6.7±0.6) number of dorsal rootlets at T1 and fewest at T6 (4.4±1.1), T7 (4.2±0.6), and T8 (4.6±1.7). Kubo et al. [12] and Xiang et al. [27] studied only the rootlets of the T1 segment and reported 6.8 and 7.7, respectively. Our results at T1 were 6.5±0.7 for right and 6.5±2.1 for left, which corresponded with the numbers reported by Boskurt et al. [1] and Kubo et al. [12]. Sindou and Goutelle [20] counted 4–5 dorsal thoracic rootlets. In the present study we have found the average number of thoracic rootlets as 6.6±0.8, which was higher than the results of Sindou and Goutelle. The high number of dorsal rootlets at T1 can be explained by its contributions to the brachial plexus and the high number of rootlets at T11 and T12 segment of the spinal cord is consistent with its contribution to the lumbar plexus. However, the high number of rootlets observed at T3 and T4 segments cannot be explained.

In the present study, the number of dorsal rootlets at lumbar levels ranged between 4 and 8, the number of rootlets was lowest at L5, and the rest of the lumbar levels were rather constant. We could not find any study to compare our results at lumbar levels.

Conclusions

The anatomy of the PLS can be useful in the surgical approach for DREZ and lateral intramedullary tumors. Detailed anatomical knowledge of the region will help in the success of the surgery of the region. Further, the morphometric measurements of the dorsal horn of the spinal cord can provide potentially useful information to avoid post-operative neurological deficits.

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria, educational grants, participation in speakers' bureaus, membership, employment, consultancies, stock ownership, or other equity interest, and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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