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Anatomical study of lumbar spine innervation

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To precisely evaluate low back pain, identification of the detailed innervation of the lumbar spine is necessary. On twenty-five sides of adult cadavers we investigated various patterns of rami communicantes (RC) and their relationship to the psoas major muscle (PM). In ten sides, we focused our dissection on the minute nerve supply of the anterior (ALL) and posterior longitudinal ligaments (PLL), vertebral bodies and the intervertebral discs (IVD).

According to the mode of piercing PM, two types of RC were observed: superficial oblique rami (SOR) and deep transverse rami (DTR). SOR ran obliquely between superficial heads of PM, connecting sympathetic trunk (ST) and T12-L2 (3) spinal nerves non-segmentally. DTR ran segmentally close to the vertebral bodies and were situated deep to the PM slips.

On the lateral side of the lumbar spine, the vertebral bodies and IVD received branches from DTR and ventral rami segmentally, as well as branches from the sympathetic trunk (ST) and, in the upper lumbar region, SOR non-segmentally. On the anterior aspect of the lumbar spine, ALL received branches from ST and splanchnic nerves non-segmentally. Within the vertebral canal, the posterior aspect of IVD and PLL received the sinu-vertebral nerves originating from DTR.

These findings suggest the coexistence of two different types of innervation: one originating directly from the spinal nerve segmentally, and one reaching vertebral structures via the sympathetic nerves non-segmentally. Therefore, sympathetic nerves are likely involved in the proprioception of the spinal column.

key words: rami communicantes, sympathetic trunk, sinu-vertebral nerve, clinical anatomy

INTRODUCTION

A comprehensive understanding of the lumbar spine innervation is necessary for the clinical evaluation of low back pain. Thus, it is critical to investigate minutely the origins and courses of the nerves of the spinal column.

Many histological studies on spinal innervation described the existence of nervous elements or endings in the spinal column [4–6, 9, 12, 15, 30]. The branches that innervate the spinal column are the spinal nerve, sympathetic trunk (ST) and rami communicantes (RC); these have been shown to form plexuses on the surface of the spine [11]. Interestingly, however, within the spinal canal, the sinu-vertebral nerve (SVN) (ramus meningeus; Nomina Anatomica 1989) is reported to be responsible for lumbar spine innervation [1, 11, 13, 14, 17–20, 22, 24]. More recent studies have suggested that the pain sensation from the lumbar spinal column is transmitted via the sympathetic nervous system [21,

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23, 32]. However, to date, few data are available to support these microscopic anatomy findings from the viewpoint of macroscopic anatomy [1, 31]. Few studies have been carried out from the viewpoint of clinical and macroscopic anatomy to clarify the typical pattern of origin, branching and course of the nerves innervating the lumbar spine. This is due to the large variation of ST and RC, and also the presence of the psoas major (PM), which impedes observation of the nerves in the lateral lumbar region.

The aim of the present study was to identify a typical pattern and location of RC based on the positional relationship to PM, and also to investigate the origin, course, and innervation patterns of the nerves supplying the lumbar spinal column as well as their minute distribution.

MATERIAL AND METHODS

In order to analyse different patterns of relationship of PM to the sympathetic trunk and their rami communicantes, twenty-five sides of adult Japanese cadavers (2 males, 11 females, 68–97 years old) were examined. Each specimen was fixed in a solution containing 10% formalin and 80% ethanol; the thoraco-lumbar spine, together with the abdominal aorta, the inferior vena cava and the psoas muscle, was extracted and dissected in detail under a stereomicroscope. By carefully separating the slips from each origin of PM, the positional relationship of this muscle's bundles to the sympathetic trunk and their rami communicantes was examined.

To investigate the innervation pattern of the structures of the spinal column (the anterior and posterior longitudinal ligaments (ALL, PLL), the vertebral body, the outer surface of the intervertebral discs (IVD) and the ligamentum flavum), ten sides of adult Japanese cadavers (1 male and 4 females, 65–91 years old) were further dissected. From each cadaver the thoraco-lumbo-sacral vertebral column was removed, together with the abdominal viscera and vessels, the diaphragm and the psoas. After removal of the psoas, special attention was paid to the nerves which pierce this muscle: we specifically examined the origin, course and supplying pattern of these nerves to reach constituent elements of the spinal column, as well as their minute distribution. For closer observation, each specimen was dissected with the aid of a dissecting stereomicroscope. Then, in order to facilitate observation of the nervous elements in the proximity of the intervertebral foramina and those innervating PLL, the specimens were immersed in a 37%HCl — formic acid — $AlCl_3$ solution for decalcification for one week, and then in 5% sodium sulphate for neutralisation for one week. After this treatment, the specimens were washed in flowing water for three days. After removal of each vertebral arch from the lumbar spine, the nerve supply of PLL, the dorsal surface of IVD, and the ligamentum flavum were investigated in detail under a stereomicroscope.

RESULTS

Classification of rami communicantes in the lumbar region (Fig. 1)

The RC were hidden by PM in the lateral lumbar region. The psoas covered the lateral surface of the lumbar spinal column and RC, making observation difficult. Minute dissection revealed that PM had two muscular origins: a deep head from the 12th rib and from the transverse process of each lumbar vertebra, and a superficial head from the bodies of the vertebrae and IVD.

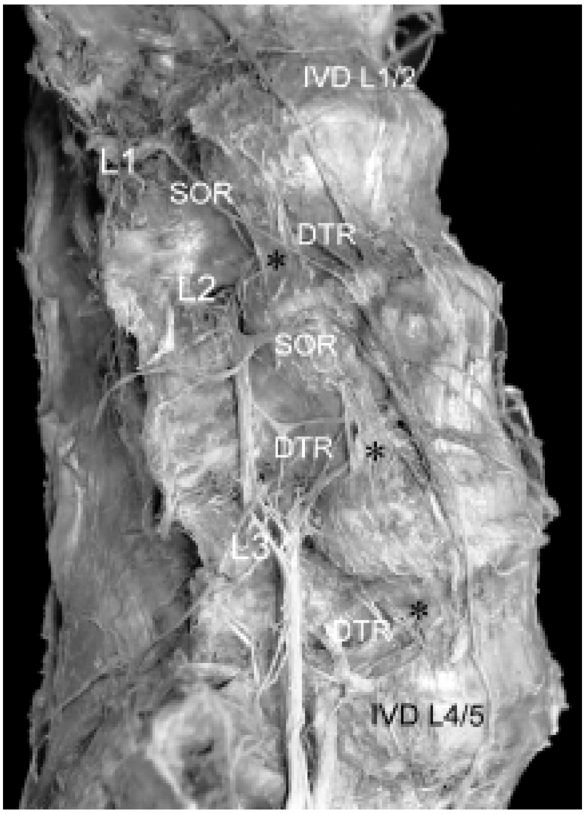

Figure 1. The lumbar spine after removal of the psoas major muscle (right side view). The superficial oblique rami (SOR) and the deep transverse rami (DTR) are separated by the fibrous bridge (*), from which the psoas originates; IVD — intervertebral disc, L1–L3 — lumbar spinal nerves.

According to the mode of piercing PM, two types of RC were observed (Fig. 1). The first type of rami, which we termed superficial oblique rami (SOR), ran obliquely between the psoas major and the lateral surface of the vertebral column, connecting ST and the spinal nerves in a non-segmental manner. In most specimens, these rami were observed at the level of the T12-L2 spinal nerves, and in only four cases a ramus which connected between the L3 spinal nerve and ST was noted. The T12 ramus ran on the anterior surface of PM, while the L1 to L2 (or 3) rami penetrated the slips of PM. The lowermost point where SOR connected with ST was located in the vicinity of the L3 vertebral body or IVD between L3 and L4 (Fig. 1).

We termed the second type of rami deep transverse rami (DTR). These rami were situated deep to each superficial head of PM, running close to the vertebral bodies and along the lumbar arteries and veins, but never piercing the slips of the psoas. DTR ran transversally along the lateral side of each lumbar vertebral body and connected to the corresponding lumbar spinal nerve and ST in a segmental manner.

It was consistently observed that, compared to SOR, DTR connected with the spinal nerve closer to the spinal nerve root. After removing all the superficial heads of PM, we observed the aponeurosis, which covered the lateral surface of each vertebral body like a ligament (Fig. 1). It was here, on the surface of the aponeurosis, that the superficial heads of the psoas originated. All SOR ran upon the surface of this aponeurosis, while DTR ran beneath the aponeurosis close to each vertebral body.

The nervous supply of the lateral aspect of the spinal column (Fig. 2)

After the removal of each head of PM, we observed first the postero-lateral part of the spinal column, namely the part of the lumbar spine near the intervertebral foramen. Here, in particular, branches arising from the lumbar ventral primary rami near the foramen innervated each IVD and vertebral body in a segmental manner (Fig. 2).

In the antero-lateral aspect of the spinal column, ST and RC lay in close proximity to IVD and the vertebral bodies. By separating and removing the superficial heads of the psoas one by one, we revealed that, in this muscle, SOR were running obliquely across IVD and the surface of the aponeurosis where the psoas originated. The upper lumbar spinal column received branches from SOR. SOR ran in close proximity to the lateral surface of IVD, being partially buried in the connective tissue of the surface of IVD, or distributed to this tissue. As each SOR was separated from the

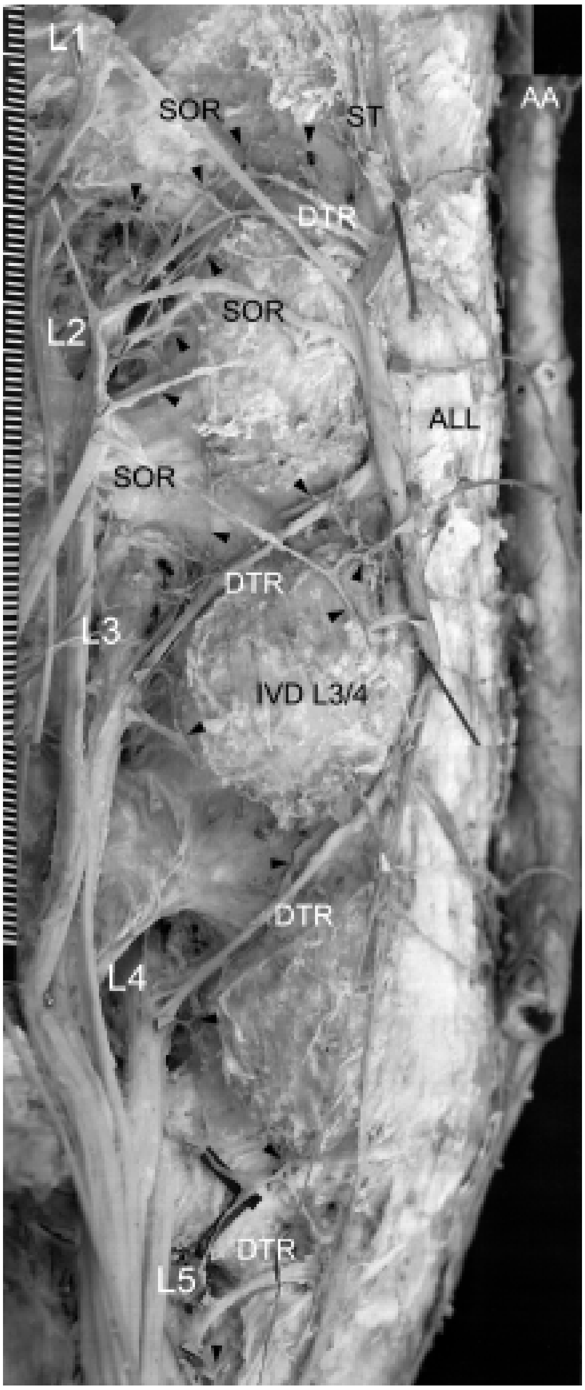

Figure 2. The innervation of the lateral aspect of the lumbar spinal column (right side view). Numerous branches (indicated by arrows) from the superficial oblique rami (SOR), the deep transverse rami (DTR), the sympathetic trunk (ST) and the lumbar ventral primal rami (L1–L5) are distributed into the lumbar spine; IVD — intervertebral disc, AA — the abdominal aorta, ALL — anterior longitudinal ligament.

vertebral body by the aponeurosis from which the psoas originated, it was not clear whether or not branches from SOR directly innervated the lateral surface of the vertebral body. SOR arose from L1 and L2 spinal nerves and reached the level of L3 or IVD between L3 and L4. These rami innervated the spinal column in a non-segmental manner from the viewpoint of connection with the spinal nerves (Fig. 3).

After removal of the psoas' aponeurosis, which covered the lateral surface of each vertebral body, we observed DTR, which ran close to each vertebral body. On each lumbar vertebral segment, the branches from DTR were distributed to the lateral surface of the vertebral body, to the upper and lower margins of IVD and to the lumbar blood vessels. The innervation of the spinal column by DTR tended to preserve the segmental manner from the viewpoint of connection with the spinal nerves.

Furthermore, in this aspect, the IVD and the periosteum of the vertebral bodies received branches directly from ST non-segmentally.

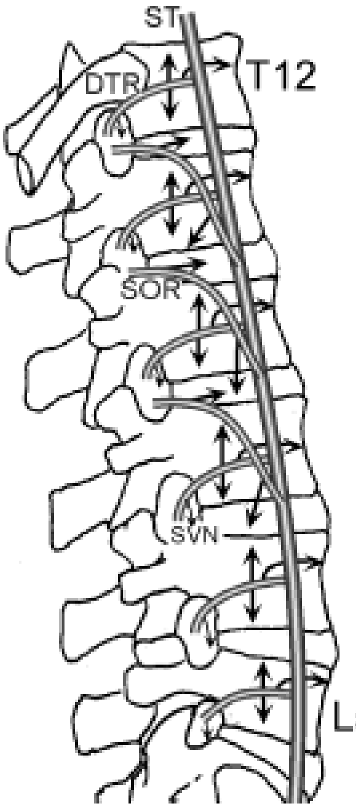

Figure 3. Drawing of the lumbar spine innervation, showing the branching patterns of the superficial oblique rami (SOR) and the deep transverse rami (DTR); SVN — sinu-vertebral nerve, ST — sympathetic trunk.

The nervous supply of the anterior aspect of the spinal column (Fig. 4, 5a, b)

Both the anterior and posterior surfaces of ALL received branches from ST, while DTR passed deep to ALL, between the vertebral body and this liga-

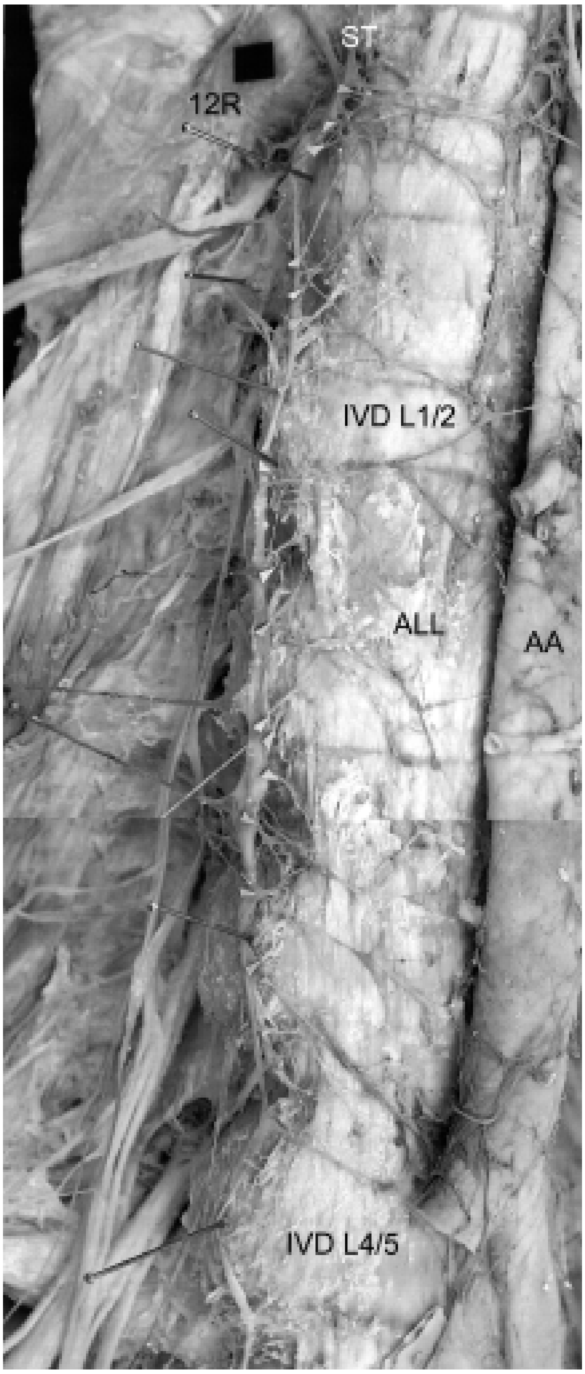

Figure 4. The innervation of the anterior aspect of the lumbar spinal column (anterior view). The sympathetic trunk (ST) sends many branches to the anterior longitudinal ligament (ALL). Some of these disappear behind ALL near its lateral edge; AA — the abdominal aorta, IVD — intervertebral disc, 12R — 12th rib.

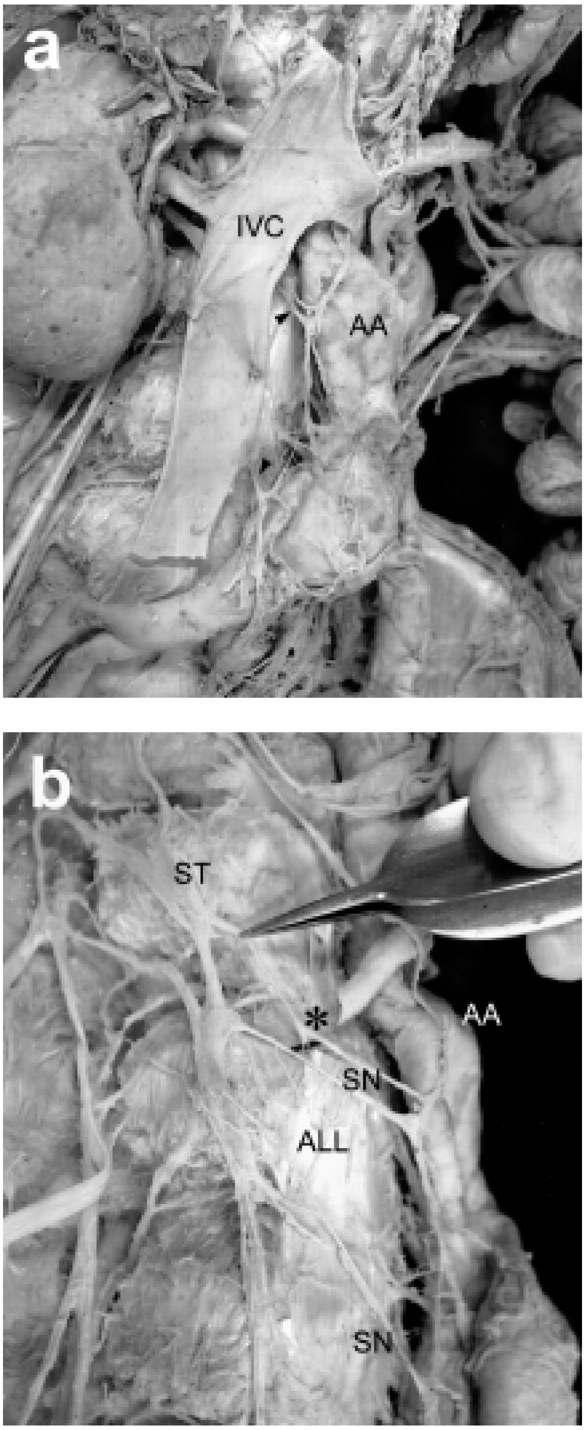

Figure 5. The splanchnic nerve and its branches to the anterior longitudinal ligament (ALL) in the abdominal region (anterior view); **a**) The right splanchnic nerves (indicated by arrows) pass underneath the inferior vena cava (IVC) and between IVC and the abdominal aorta (AA) to reach the anterior side of AA; **b**) Branches from the splanchnic nerves (SN) to ALL (*).

ment (Fig. 4). In addition, the anterior surface was supplied by twigs from the splanchnic nerves, which originated from ST. The right lumbar splanchnic nerves, arising from lumbar ST, ran underneath the inferior vena cava. These nerves passed between the inferior vena cava and the abdominal aorta to exit on the anterior side of the latter, where they formed a nervous plexus (Fig. 5a). In passing beneath the vena cava, some branches from the lumbar splanchnic nerves ran particularly close to the connective tissue of the anterior surface of ALL. Upon close examination of the lumbar splanchnic nerves deep to the inferior vena cava, by reflecting this vein to the left, a direct branch of the splanchnic nerve to the anterior aspect of ALL was also observed (Fig. 5b). On the left side, the splanchnic nerves, after originating from ST, passed along the aorta and its main branches, supplied the organs of the abdominal cavity and, like the right splanchnic nerves, sent branches to ALL.

The nervous supply of the spinal column in the vertebral canal (Fig. 6a–c).

In the vertebral canal, the posterior aspect of IVD and the posterior longitudinal ligament (PLL) received branches from SVN which arose from DTR near its origin (Fig. 3, 6). SVN never arose from SOR. On the ventral side of the spinal nerve root, SVN entered the vertebral canal through the intervertebral foramen along the ventral root, and gave off several branches. The main branch ascended along the lateral margin of PLL and supplied twigs to this ligament and to the vertebral body. Smaller branches arose close to the origin of SVN and innervated PLL and IVD near the intervertebral foramen (Fig. 6a). Among the SVN branches, rami connecting with SVN in the adjacent segments were not clear upon macroscopic observation. The ligamentum flavum received a branch directly from the dorsal root ganglion.

On the basis of these innervation findings, Figure 3 and Table 1 show that each component of the spinal column received branches from nerves in the vicinity.

DISCUSSION

Classification of rami communicantes

In this study, according to the course of RC in the lumbar region, two types of RC were distinguished: SOR and DTR. These two types of RC are clearly separated by the aponeurosis, from which the superficial heads of the psoas originate. The lumbar spine is surrounded by these two types of RC on the lateral sides of the vertebral bodies and IVD.

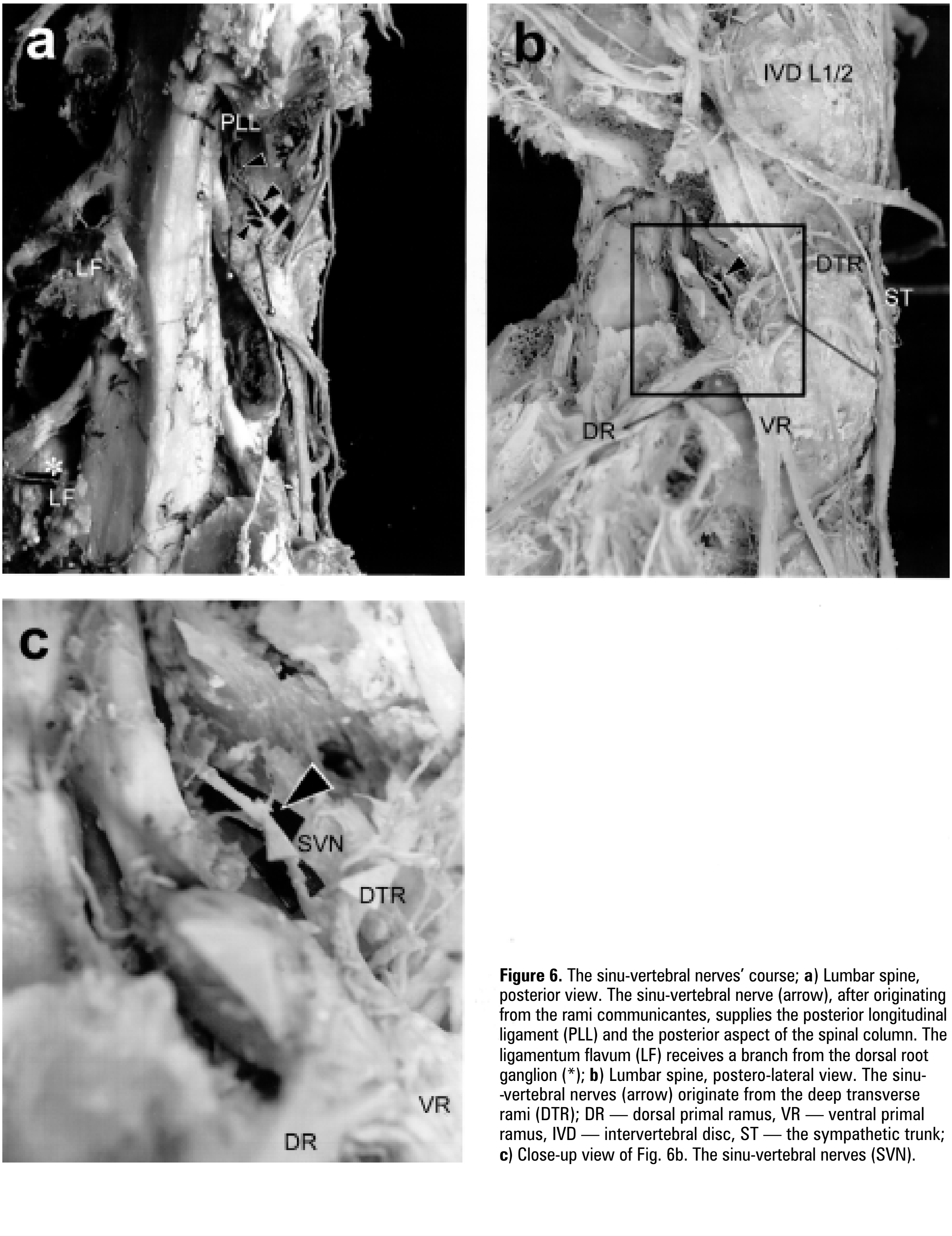

Figure 6. The sinu-vertebral nerves' course; **a**) Lumbar spine, posterior view. The sinu-vertebral nerve (arrow), after originating from the rami communicantes, supplies the posterior longitudinal ligament (PLL) and the posterior aspect of the spinal column. The ligamentum flavum (LF) receives a branch from the dorsal root ganglion (*); **b**) Lumbar spine, postero-lateral view. The sinu--vertebral nerves (arrow) originate from the deep transverse rami (DTR); DR — dorsal primal ramus, VR — ventral primal ramus, IVD — intervertebral disc, ST — the sympathetic trunk; **c**) Close-up view of Fig. 6b. The sinu-vertebral nerves (SVN).

According to many textbooks, RC are generally classified into white and grey [7, 25, 29, 34, 35]. Based on fibre composition from the viewpoints of histology and physiology, both white and grey rami can be identified through microscopic observation; however, these are extremely difficult to distinguish by macroscopic observation [36] due to 1) the great variation of ST and RC in the lumbar region [8, 10, 26–28], and 2) the presence of the psoas, which conceals RC lateral to the spine. Due to such difficulty in observation, few reports include macroscopic identification of RC branching patterns, course and man-

Table 1. The nervous elements surrounding the vertebral column and their segmentation

Location	Vertebral canal	Lateral side of the column		Anterior side of the column		
Components of the column	VB (posterior) IVD (posterior) PLL	VB IVD		VB IVD ALL (deep)		ALL (superficial)
Innervation	**Segmental**	**Segmental**	**Non-segmental**	**Segmental**	**Non-segmental**	**Non-segmental**
	SVN	DTR VR (postero-lateral aspect)	SOR (upper lumbar region) ST	DTR	ST	ST SN

VB — vertebral body, IVD — intervertebral disc, ALL — anterior longitudinal ligament, PLL — posterior longitudinal ligament, SVN — sinu-vertebral nerve, DTR — deep transverse ramus, SOR — superficial oblique ramus, ST — sympathetic trunk, SN — splanchnic nerve, VR — ventral ramus

ner of innervation of the spine. Bogduk [1–3] described various RC: RC which cross the vertebral bodies deep to the psoas ("typical RC"), RC which pierce the psoas and pass between the second lumbar sympathetic ganglion and the L1 ventral primary ramus, and RC which are embedded in the connective tissue of IVD ("paradiscal RC"). We believe that, despite their great variation, RC can be classified into SOR and DTR, according to their positional relationship to the fibrous bridge from which the psoas originates. We can argue that the "typical RC" described by Bogduk correspond to DTR, while the remaining RC variations correspond to SOR. Bogduk observed a ramus equivalent to SOR at the level of L1 only, while we found SOR in the thoracolumbar transitional region, generally to L2 or L3. We also found that some lower SOR adhered to the connective tissue on the surface of IVD, like Bogduk's "paradiscal RC". Our classification of RC may facilitate a clear understanding of lumbar spine innervation for spinal surgery.

Innervation of the lumbar spine

We have shown that the components of the spinal column are supplied by many branches from the neural elements surrounding them. These branches can be classified as branches which arise from: 1) ST directly; 2) SOR, DTR, SVN and the splanchnic nerves; and 3) directly from each lumbar ventral primary ramus.

Macroscopic anatomical studies of spinal column innervation in monkeys [31] and humans [1] demonstrated that the lumbar spine receives branches arising from ST, RC and the spinal nerves. Further, numerous histological studies have demonstrated the existence of nervous endings in the vertebral bone, IVD, ALL and PLL [4–6, 9, 12, 15, 30]. The present results concur with these reports and indicate that the sympathetic branches (including splanchnic nerves) and the spinal nerves both participate in the innervation of the lumbar spine.

It is generally accepted that the sympathetic nervous system contains efferent and afferent fibres which innervate the viscera and blood vessels [7, 29, 34, 35]. It can be conjectured that the rami which run along blood vessels, like DTR, might influence lumbar spine vascular changes and thus may be related to IVD degeneration. Recently, both clinical [16, 23] and basic [21, 32] research have demonstrated that the sympathetic nervous system is involved in non-segmental pain transmission from the spinal column. From the viewpoint of macroscopic anatomy, our results confirm these clinical and experimental studies. The sympathetic branches we observed are likely to participate in pain transmission from the spinal column.

Our results show that, with regard to innervation patterns, the lumbar spine can be divided into three regions: anterior, lateral, and posterior (within the vertebral canal) (Table 1).

In the anterior part, we noted that ALL receives branches directly from the lumbar splanchnic nerves. Considering that the splanchnic nerves originate from the thoracic and upper lumbar nerve segments (L1, L2), it can be inferred that ALL branches from the lumbar splanchnic nerves originate from the upper lumbar nerve segments as well (non-segmental innervation). These findings clearly indicate that pain from ALL can be transmitted to the upper lumbar nerve segments, causing referred pain in the L1, L2 segments. This might explain why some patients with lesions of the lower lumbar spine complain of inguinal pain. Webber [33] observed branches that arise from the connecting rami between the right and left ST to reach ALL, while, more recently, using the immunohistochemical whole mount method on the foetus, Groen et al. [11] reported that many branches from ST form plexuses in ALL. The present study also confirmed that numerous fine branches arising from ST innervate ALL.

In the lateral part of the lumbar spine, Bogduk [1–3] described that IVD received branches from the grey rami and ventral primary rami segmentally. Our study revealed that the upper lumbar nervous segments participate, via SOR, in the innervation of a more extensive area, which spreads over the lower lumbar region. On the other hand, DTR innervate only the corresponding lumbar segment, and each ventral primary ramus is segmentally distributed to the posterolateral aspect of the spinal column (Fig. 3).

Finally, within the vertebral canal, each SVN is distributed to PLL, to the posterior aspect of IVD and to the vertebral body segmentally. Moreover, we noted that SVN originates from DTR and not from SOR. Since Luschka's reports in 1850 and 1863 [19, 20], the innervation of the vertebral canal has been the subject of many studies. Some of these reported that SVN originates from RC or the spinal nerve [1, 20, 24]. Our findings show that the only RC giving off SVN is DTR. This is an important point for the clinical understanding of SVN. Furthermore, some reports state that each SVN sends branches to two or three segments [17]. More recently, minute investigations using an immunohistochemical method on the human foetus [11] and rat [14, 18, 22] revealed that SVN spread over several segments to finally form nervous plexuses within the vertebral canal. However, in the present study SVN did not appear to be connected between segments. Our result is congruent with Bogduk's report [1] on SVN.

In conclusion, the present study provides important information for the classification of lumbar spine innervation patterns, based on the differences in the course of nerves from the viewpoint of macroscopic anatomy. We have shown the coexistence of two different types of innervation: a segmental type directly from the spinal nerve and a non-segmental type reaching vertebral structures via the sympathetic nervous system. Considering that the lumbar splanchnic nerves and SOR originate from the upper lumbar nerve segments, we propose L1–L2 as the centre for non-segmental lumbar spine innervation. To evaluate low back pain and various types of referred pain from the viewpoint of clinical anatomy, a comprehensive understanding of lumbar spine innervation is necessary. We hope that our dissection findings may enhance the understanding of the intricate nerve supply to these structures, and may aid in the development of future surgical techniques for the spine.

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