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Anatomical Review

# Anatomy of the Intervertebral Foramen

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The intervertebral foramen serves as the doorway between the spinal canal and periphery. It lies between the pedicles of neighboring vertebrae at all levels in the spine. A number of categorization schemes have been attempted to describe the boundaries of the intervertebral foramen. No uniform agreement has been made on which classification best describes this area.

Studies of the nerve root canals have clearly noted variations in the angle of take-off from the thecal sac, length of the nerve root, and placement of the dorsal root ganglion from different lumbar levels. The nerve root canal receives a dual blood supply from central and peripheral sources. The dorsal root ganglion also has a dual vascular supply that aids in preventing damage to this vital foraminal structure. The presence of ligamentous structures within the foramen has been demonstrated by a number of recent studies. These ligaments serve a protective and organizational role for the neurovascular structures of the foramen.

A thorough knowledge of the intervertebral foramen will allow the understanding of the pathological and degenerative changes that cause compression or injury to these foraminal structures.

**Keywords:** Intervertebral foramen, nerve root, canal, ligaments

The intervertebral foramen transmits the spinal nerves, spinal arteries and veins, the recurrent meningeal nerves and lymphatics (1). This foramen is unique in comparison to other foramens of the body due to its boundaries consisting of two movable joints; the ventral intervertebral joint and the dorsal zygapophysial joint (2). The proximity of these joints increased susceptibility of narrowing from arthritic structural alterations. The foramen is essentially a large osseous hole through which neurovascular structures pass. Within its boundaries is an intricate network of ligaments that divide the intervertebral foramen into multiple sub-compartments containing specific anatomic structures. It is conceivable these ligaments may serve a protective role in preventing injury to the vasculature that pass through them.

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## LIGAMENTS OF THE FORAMEN

Bourgery in 1832 was the first to report upon the presence of ligaments passing across lumbar foramen (3). In the 1940's Larmon (4) and Magnuson (5) also noted foraminal bands crossing the intervertebral foramen of the L5 segment. Golub and Silverman (6) in 1969 were amongst the first to report on the presence of ligamentous bands running across foramina of the lumbar spine at all lumbar levels. They examined 10 cadaveric lumbar spines and noted the inconsistent presence of band-like structures in the foramen, most commonly occurring at the L1-2 foramen. They identified five major types of transforaminal ligaments: superior corporotransverse, inferior corporotransverse, superior transforaminal, mid-transforaminal, and inferior transforaminal. The superior corporotransverse ligament was the most frequently observed ligament. They postulated these bands were anomalous in origin and are a potential source of nerve root entrapment (6). Subsequent anatomic studies similarly documented the presence of foraminal ligaments (7-10). These studies indicated an increased presence of ligaments in the fifth lumbar foramen. The results of these studies created many discrepancies in the identification of these band-like structures as ligaments or fascial condensations of overlying muscles.

Golub and Silverman (6) hypothesized that the ligaments were condensations in the fascia of overlying muscles adjacent to the lumbar foramen. They described the obliquely running bands as superior and inferior corporotransverse ligaments and transversely directed bands as transforaminal ligaments. Macnab (7) in 1977 categorized the bands as corporotransverse ligaments. Bachop and others (8-10) identified the ligaments in a directional capacity only, primarily consisting of superopostero-laterally running bands.

A more recent anatomic study of twelve lumbar spines investigated the presence of ligamentous structures in the foraminal canals of the first four lumbar levels (1). In contrast to earlier works, this study documented ligaments at all foraminal levels. No muscular attachments to the ligaments were noted. The ligaments were much better defined in the upper lumbar levels than lower levels. In fact, the upper lumbar foraminal ligaments had a more thick, rounded appearance in comparison to the lower lumbar ligaments.

The ligaments were also found to exist in three different zones of the lumbar foramen; internal, intraforaminal, and external zones. The internal ligaments were commonly found in the inferior aspect of the medial portion of the foramen. They were broad ligaments attaching to the posterolateral aspect of the intervertebral disc and anterior surface of the superior articular facet. These attachments gave the ligaments an obliquely running course inferiorly and posterior. In its course the internal ligament bridges across the top of the superior vertebral notch, thereby converting it into a sub-compartment in the lower foraminal canal. Veins were commonly noted to be running through this sub-compartment (1).

The intraforaminal ligaments ran in three typical distributions. The first type traveled from the root of the pedicle to the inferior border the same vertebral body. The recurrent meningeal nerve and a branch of the spinal artery were observed within the compartment formed by this ligament. A second distribution was the attachment to the angle between the posterior end of the pedicle and the root of the transverse process extending to the postero-lateral surface of the same vertebral body. These attachments create an antero-superior compartment through which a large branch of the segmental artery was observed to travel in all specimens examined (1).

The last intraforaminal ligament noted was a strong, transversely oriented band originating from the anterior upper portion of the superior articular facet and attaching to the postero-lateral surface of the vertebra above. The exiting spinal nerve was noted to lye directly overtop this ligament in all specimens (1).

The external ligaments all had a common attachment to the root of the transverse process. From this position the bands ran in a superior, inferior, and transverse direction. All bands were seen to insert into the vertebral bodies at the same level and the level below. These three external ligaments have also been called the superior, middle, and inferior corporotransverse ligaments. The position of these ligaments creates multiple sub-compartments just external to the foramen. A large central compartment was seen encasing the exiting ventral rami. Anterior and superior to this central compartment are two smaller openings through which the spinal artery, recurrent meningeal nerve and a small branch of the segmental artery travel. Inferior to the ventral rami foramen are typically two or more small compartments through which veins were seen traversing. In the posterior aspect of the external foramen exist superior and inferior compartments. The superior compartment contained the medial division of posterior primary ramus and branches of the lumbar artery and vein. The inferior tunnel transmitted the lateral division of the posterior ramus and branches of the segmental artery and veins (1).

Kuofi et al (1) were able to establish the consistent presence of ligaments within the immediate region of the lumbar intervertebral foramen. Based on topographical mapping of the ligaments it was possible to conclude, in contradiction to earlier reports, that these ligaments are not responsible for entrapment of the spinal nerve resulting in radicular pain symptoms (6). In fact, the orientation of the ligaments precludes compression of the nerve root during dynamic alteration of the foramen. The presence of thick bands forming the compartments through which the vascular supply travels also denotes a protective role for these ligaments (1).

## BOUNDARIES OF THE NEURAL FORAMEN

The boundaries of the lumbar foramen contain not only osseous structures, but also have ligamentous structures that aide in defining its borders. These foramens are also unique because two joints form part of their boundaries. This arrangement allows the foramen to dynamically change its configuration according to movements of the trunk. Under normal conditions, these dynamic changes are easily tolerated by the neurovascular structures that run through them without any compromise of the neurovascular components. The boundaries of the intervertebral foramen have not been well defined. Different authors have chosen separate and distinct classifications to describe the foramen (11-13). Crock (11) in 1981 has described the intervertebral foramen as a single sagittal slice through the narrowest portion of the nerve root canal. Lee et al (12) in 1988 divided the foramen into three zones: lateral recess zone, midzone, and the exit zone. We have chosen a more generalized anatomic approach here to allow for a comprehensive description of the foraminal area.

When looking outward through the intervertebral foramen from the spinal canal the foramen takes on the appearance of an oval, round, or inverted teardrop-shaped window (14). The roof of the intervertebral foramen is the inferior aspect of the vertebral notch of the pedicle of the superior vertebra (1), the ligamentum flavum at its outer free edge (11), and posteriorly lays the pars interarticularis and the zygapophysial joint. The floor of the nerve root canal is the superior vertebral notch of the pedicle of the inferior vertebra (1), postero-inferior margin of the superior vertebral body (11), the intervertebral disc, and the postero-superior margin of the inferior vertebral body. Multiple structures are involved in bounding the anterior aspect of the foramen. They include the posterior aspect of the adjacent vertebral bodies, the intervertebral disc, lateral expansion of the posterior longitudinal ligament, and the anterior longitudinal venous sinus. Posteriorly, the foramen is bounded by the superior and inferior articular process of the facet joint at the same level as the foramen, and the lateral prolongation of the ligamentum flavum. The medial canal border contains the dural sleeve. The lateral boundary is a fascial sheet and overlying psoas muscle (1). A distal and proximal oval perforation is seen in the fascia. The distal perforation houses the nerve root, and the smaller proximal perforation regularly have blood vessels traversing through them (1). The height of the foramen is dependent upon the vertical height of the corresponding intervertebral disc. With aging there is a natural tendency toward disc degeneration and loss of disc height. This decrease in disc height has direct anatomic consequences to the area of the foramen and resultant availability of space for neurovascular structures to pass. Direct cadaveric measurements of lumbar foraminal heights have varied from 11-19 mm (15, 16). Magnusson (16) also reported on foraminal width measurements of the lumbar spine. An average measurement of 7mm was reported from the front to the back of the foramen. Measurement of the foraminal canal by three-dimensional computed tomography (3DCT) has been attempted. Unfortunately, comparative studies using cadaveric specimens have shown the 3DCT to be an unreliable study to quantify the dimensions of the lumbar foramen (17).
Magnetic resonance imaging has also been performed in healthy subjects to measure normal values for the height of the intervertebral foramen (18). In one study, twenty male volunteers with no history of back pain or radiculopathy underwent magnetic resonance imaging (MRI). The height of the intervertebral foramen was measured between the inferior margin of the pedicle of the upper vertebra and the superior margin of the pedicle of the lower pedicle in two hundred and thirty-three levels, L1-L2 to L4-L5. The mean heights of the foramen were reported as follows: L1-L2, 17.1+/- 2mm; L2-L3, 18.4+/- 1.7mm; L3-L4, 18.1+/- 1.5mm; and L4-L5, 17.1 +/- 3.6mm (18). No comparison was made in that study to cadaveric or radiographic measurements. However, prior cadaveric studies have noted the lumbar foramens to have pedicle-to-pedicle heights varying from 11-19 mm (15, 16). The mean widths and heights of the pedicles of the L1 through L5 vertebra were also measured. The mean pedicle widths were seen to increase from the L2 to the L5 level. The pedicle heights appeared to remain relatively unchanged from level to level (18).

## THE NERVE ROOT CANAL

The true anatomic nerve root canal initially arises from the lateral aspect of the dural sac and travels through the neural lumbar foramen. At each level, anywhere from two to six anterior and posterior roots converge in the thecal sac to form anterior and posterior roots (19). Extensions of the dural sheath encase all nerve roots as they depart from the thecal sac. In the lumbar spine the nerve roots regularly exit the thecal sac approximately one segmental level above their respective foraminal canal (20). They take an oblique course downwards and laterally toward the intervertebral foramen. This oblique angle has modest differences based upon the lumbar level in question. In the upper lumbar nerve roots their orientation is more at a right angle to the dural sac than the distal nerve roots (21). This right angle makes the intraspinal portions of the upper nerve roots very short. In fact, in the upper lumbar area the thecal sac lies against the medial wall of the pedicles, therefore the nerve roots exit immediately into the intervertebral foramen (11). Distal to the L3 vertebral body level the dural sac is seen to taper progressively. The distal nerve roots are seen to exit from the thecal sac at more oblique angles after the L3 level. Bose and Balasubramaniam (22), in 1984, demonstrated a gradual decrease in the angle of inclination through the L1-2 through L5-S1 levels. This finding was later disputed by Cohen et al (23) who noted no change in the angle of inclination from the exiting nerve roots in the L1 through L5 nerve roots, but did note a significant drop-off in the angle of inclination at the S1 level. A more recent morphometric study using MRI to analyze angle of inclination from exiting nerve roots noted the L1 nerve to have a greater angle of departure from the thecal sac than all other lumbar nerve roots. In addition, the S1 root had a significantly smaller take-off angle than the other lumbar roots (18). All previous studies have demonstrated that the intra spinal course of the lumbosacral nerve roots is successively longer for each caudal level encountered (18, 22, 23). Epidural fat surrounds each nerve root throughout their course to the intervertebral foramen (11). Just prior to its entrance to the neural foramen the lumbar roots fit into an osseous groove at the medial base of the pedicle (19). This groove may be more pronounced at the level of the fifth lumbar vertebral foramen secondary to a more trefoil shape of the spinal canal (24). The term lateral recess has been used to describe this well-defined area. Verbiest (25) in 1954 was first to note that narrowing of this groove, or lateral recess stenosis, could cause radicular leg pain in patients. As the nerve root slides under the medial edge of the pedicle it takes an inferior and oblique direction away from the pedicle (19). At this point the nerve roots are located within the neural foramen, and they commonly combine to form the spinal nerve. Just prior to the formation of the spinal nerve a small enlargement of the dorsal root is noted. This enlargement is called the dorsal root ganglion (DRG), which contains the cell bodies of sensory neurons. The DRG location in perspective to the foramen can be quite variable. However, there are some general trends that are consistently reproduced in anatomical studies. The majority of DRG's in the lumbar levels are located within the anatomic boundaries of the intervertebral foramen (18, 22, 23). Most commonly, the position of DRG within the foramen is located directly beneath the foramen (22). Only at the S1 level is this rule not applicable. Studies have reported that the S1 DRG exist within the spinal canal approximately 80% of the time (18, 26). This intraspinal placement places the S1 DRG at increased risk of injury from disc herniations or degenerative changes of the L5-S1 intervertebral disc (18). In the foramen, nerve roots typically occupy approximately 30% of the available foraminal area (27), but numbers as high as 50% have been reported (28). As the spinal nerve reaches the foraminal outlet it curves around antero-laterally the base of the subjacent pedicle and transverse process. Around this exit zone of the foramen the spinal nerve divides into primary anterior and posterior rami. Just outside the foramen the primary rami run between the deep layers of the psoas muscle and the vertebral column (19). Within the psoas muscle the lumbar nerves coalesce into trunks that run down vertically along the surface of the junctional area between the body and the pedicle of the lumbar spine (29).

The nerve roots have two areas of fixation to surrounding structures. The first area of fixation occurs at the neck of the nerve root sheath as it exits the dural sac. The fibrous attachments were located both ventrally and dorsally on the neck of the nerve root sheath, with both bands attaching to the periosteum of the subjacent pedicle. The second area of fixation occurred at the lateral aspect of the foramen. These fibrous expansions are attached to both pedicles superiorly and inferiorly to the nerve root (30). Avulsions are commonly noted to occur at these two areas of fixation. The average rupture force in one study for roots of the L1-L4 level was 7.25 kg, 13 kg for the L5, and 11.5 for the S1 nerve root (30).

## VASCULAR SUPPLY OF THE NERVE ROOT AND DRG

The vascular supply to the lumbar nerve roots will be briefly discussed here. For a more detailed description the reader is referred to a prior publication by these authors (31). A more detailed look at the vascular supply of the dorsal root ganglion (DRG) will be presented here. Blood supply to the lumbar spinal nerve roots occurs proximally from branches of the longitudinal vessels of the conus medullaris. These vessels only travel a few centimeters along the rootlets before terminating (32). The posterior (or dorsal) nerve roots receive their vascular supply via the dorsolateral longitudinal spinal arterial system. This system is an extension of the vasa corona that forms a plexiform, interrupted network of vessels that is always in close proximity to the posterior rootlets. The ventral roots each receive a direct branch from the nearest vasa corona (32).

The remaining proximal portions of the nerve roots receive blood supply via the dorsal and ventral proximal radicular arteries (33). These blood vessels are derived from the dorsal longitudinal spinal artery and accessory anterolateral artery, respectively. The proximal radicular arteries enter the nerve root and follow the length of the nerve distally to anastomose with the distal radicular artery (33). Their entrance into the proximal nerve roots occurs slightly distal to the roots exit from the spinal cord. This delay in contact is most likely due to proximal regions of the nerve root already receiving vascular supply from the dorsal and anterior longitudinal vessels. As the proximal radicular artery enters the nerve root it follows along with one of the main fascicular bundles. A number of collateral branches occur directly off of the main radicular artery. These smaller branches tend to form parallel courses along other nerve root fascicles (32). Precapillary branching from these long running parallel vessels give supply to the subdivisions of fiber bundles not directly overlying the radicular arteries. These branches are unique in that they are coiled shaped. Coiling of these precapillary vessels has been noted to endow these vessels with a resistance to compression during flexion and extension moments of the spine, thereby preventing ischemia to nerve root fascicles (32).

The distal radicular artery branches from the lumbar artery at the level of the intervertebral foramen. It then divides into two branches, one entering each dorsal and ventral root. At this point it travels both proximal and distally along the length of the nerve roots giving it blood supply (34). As the distal radicular artery travels proximally it forms numerous arteriovenous anastomoses with neighboring veins (35).

There are two venous systems involved in drainage of the lumbar nerve roots, which are divided into proximal and distal radicular venous systems. The distal radicular veins drain into the lumbar vein at the level of the intervertebral foramen. The proximal radicular veins drain into the spinal cord venous plexuses (34). They have been documented to return via the vasa corona and then pass proximally in the anterior and posterior longitudinal veins of the cord (34). It has been demonstrated that the veins are similar to nerve root arteries in they have a variable location and number in the nerve root (33). The major veins of the nerve root demonstrate a more similar morphology and arrangement to those of the central nervous system. Their walls are comparatively thin and lack a tunica media. In contrast to peripheral nerves, nerve roots tend to have fewer numbers of veins and tend toward a more spiraling course through the deeper portions of the nerve root (32). The vascular supply of the DRG was first investigated by Bergmann and Alexander (36) in 1941. They used pen and ink drawings to depict the macro-vascular flow to the DRG. Microscopic cross-sections were illustrated by photomicrographs of the intraganglionic vasculature. Their findings were later supported by Day (37) in 1964. However, Day was only able to publish photographs of a limited number of lumbosacral DRG's. In 1973, Somogyi et al (38) also demonstrated similar drawings to Bergmann and Alexander of the T6 and L4 DRG's.

More recently, Parke and Whalen (39) in 2002 examined the arterial supply of three human perinatal cadavers, one adult rabbit, and venous injections of vertebral segmental tissues of two adult human anatomic cadavers. After injection of India Ink into the perinatal cadavers, transilluminated microphotographs were taken of the DRGs. These photographs supported previous findings of vascular supply throughout all levels tested (36-38).

The vascular supply to the DRG consists of a two primary plexuses, one superficial and one deep into the substance of the DRG. The two plexuses are connected via fine, centripetally running, anastomotic channels. Both internal and peripheral plexuses of arteries are derived from distal and proximal polar arteries. Epidural branches of the intersegmental vertebral arteries feed these polar arteries. The intersegmental radicular arteries are branches from the larger and epi-spinal segmental arteries distally, and from the anterior and posterior spinal arteries centrally. This basic vascular pattern is seen throughout all vertebral levels, and also supported by previous works (36-39). Nutrient arteries have also been noted to directly branch off the spinal segmental artery and give blood supply to the DRG (40). In comparison to the nerve root, the DRG has more abundant intrinsic vascular supply. A reason for this increased vascular supply is most likely due to cellular elements that exist within the DRG (40). A dense network of continuous and fenestrated capillaries is seen surrounding the parenchymal cells of the DRG (40). A superficial periganglionic venous plexus is noted surrounding the DRG. Multiple anastomotic channels are seen connecting the parenchyma of the DRG to the periganglionic plexus (39).

The importance of the DRG is evidenced by the intricate arterial supply that surrounds and invests this structure. In addition, blood flow volume to the DRG has been measured. Hachiya et al (41, 42) in 1989-1990 examined the blood flow volume of the DRG in the dog. In their studies an electrochemically generated hydrogen washout method was used with a tissue blood flow meter. They found the absolute blood flow volume of the dorsal nerve root to be an average of 26.9 ml/min/100g, whereas the blood flow of the DRG of the dog was an average of 56.1

ml/min/100g. These studies demonstrated about twice as much blood flow volume in the DRG as compared to the nerve root. In comparison to other nervous structures, the DRG's blood flow was similar to that of the gray matter of the spinal cord (43). The peripheral nerve blood flow is slightly less than that to the DRG, 47.9 versus 56.1 ml/min/100g respectively (42, 44). White matter blood flow is approximately five times less than that to the DRG, 11.5 versus 56.1 ml/min/100g respectively (42, 45).

A number of studies have been performed to evaluate the effects of mechanical compression on blood flow in the DRG (42, 46). In all studies the DRG blood flow was reduced by compression of the nerve root proximal and distal to the DRG. In contrast, the flow volume in the ganglion decreased by 40-45% by compression on the distal side of the ganglion as compared to 10-15% decrease by compression proximal to the ganglion. A reason for this significant drop in flow by clamping of the spinal nerve distal to the DRG is secondary to concomitant clamping of the segmental artery through which direct nutrient arteries to the DRG branch (40). A delay in return of normal blood flow was also noted when the nerve root was compressed proximal to the DRG. This phenomenon is believed to be due to a disturbance in the normal pulsatile flowing of the cerebrospinal fluid (41, 42). Experiments have demonstrated that spinal nerve roots derive nutrients not only from the vascular supply, but also via diffusion from the cerebrospinal fluid (47). If this cerebrospinal flow is critical for normal function of the DRG, then any disturbance in its flow will have an adverse effect on the vascular supply. Similar results have also been noted to occur in experiments of blood flow in the spinal cord (15).

## CONCLUSION

The intervertebral foramen continues to be a poorly defined region of the spinal canal. However, its general anatomic boundaries aid us in describing the structures that exist within the foramen. The presence of ligaments in the foramen has been documented by numerous studies. These ligaments have been shown to play an organizational as well as protective role within the foramen. Normal parameters of foraminal height have been well documented by cadaveric and radiographic studies. This height is critical to allow safe passage of vital neurovascular structures to and from the spinal canal. Compromise of these neurovascular structures in the foramen is frequently responsible for the radicular pain patterns seen in elderly patients.

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