Comparison of Hemilaminectomy and Mini-Hemilaminectomy in Dogs with Thoracolumbar Intervertebral Disc Extrusion using Computed Tomography and Magnetic Resonance Imaging: An Anatomical and Radiological Study

By

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ABSTRACT

COMPARISON OF HEMILAMINECTOMY AND MINI-HEMILAMINECTOMY IN DOGS WITH THORACOLUMBAR INTERVERTEBRAL DISC EXTRUSION USING COMPUTED TOMOGRAPHY AND MAGNETIC RESONANCE IMAGING: AN ANATOMICAL AND RADIOLOGICAL STUDY

Jonathan Huska
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This thesis is an investigation of the access provided to the vertebral canal in dogs by the hemilaminectomy and mini-hemilaminectomy surgical techniques using computed tomography (CT), and the completeness of evacuating extruded material in dogs with intervertebral disc (IVD) extrusion using magnetic resonance imaging (MRI).

Hemilaminectomy and mini-hemilaminectomy were performed on opposite sides of the spine at T11-T12, T13-L1, and L2-L3 in 10 cadavers. Measurements of the vertebral canal height, defect height, and any dorsal and ventral remnants of the vertebral arch were obtained by CT. A covariate analysis was used to compare measurements with the surgical technique, surgical site, and side of the vertebral column.

Defect height was greater with hemilaminectomy due to a smaller dorsal lamina remnant. There was no statistical difference in the height of the ventral remnant, or with surgical site.

Nineteen prospectively recruited dogs with suspected IVD extrusion were randomly assigned to hemilaminectomy (10 dogs) or mini-hemilaminectomy (9 dogs) groups. Intervertebral disc extrusion was identified pre-operatively with MRI and later confirmed
surgically, and immediate post-operative MRI was performed at the surgical site. The volume of extruded IVD material pre- and post-operative was calculated from transverse T2 images.

Although residual IVD material was present in post-operative images from all dogs in the hemilaminectomy group and only 4 in the mini-hemilaminectomy group, there was no statistically significant difference between the proportionate volumes of material removed by either technique. The median residual volume with hemilaminectomy was 13.6% (confidence interval: 7.8 – 23.6%), and with mini-hemilaminectomy was 7.7% (4.3 – 13.8%).

The results of this study confirm that the difference in the defect height between techniques is related to the removal of the articular processes creating a larger defect along the dorsal vertebral canal, while no difference in access to the ventral canal was observed. No effect of vertebral site was detected suggesting neither procedure provides an advantage over the other due to location of the lesion along the thoracolumbar spine. Residual extruded IVD material occurs with both techniques; while no statistical difference was noted, a larger population should be examined.
ACKNOWLEDGEMENTS

I would first like to express my gratitude towards my advisory committee; Drs Gaitero, Brisson, Nykamp, and Thomason. Dr. Gaitero provided mentorship and training, supporting both my residency training, DVSc program, and struggles. Dr. Brisson’s clinical experience and insight were paramount to the project, as well as Dr. Thomason’s experience as a graduate program mentor. While Dr. Nykamp was an invaluable clinical and academic resource, she gave me the desired direction and organization to guide me through the past 3 years.

Any research project would be a waste without competent statistical analysis and for this I have to thank Dr. Sears, especially for the immense amount of time spent bringing it down to my level of understanding. Jennifer Collins, Carolyn Bennett, Alice Daw, and Sue Kinsella provided technical support and the foundation to starting the project. Their patience and kindness are appreciated beyond words.

Most important of all is my family. I would like to thank my parents, Nancy and Eugene, who have believed in me and pushed me to further heights since the beginning, and my in-laws, May and Rick Brennan, for their consistent encouragement. However, none of this would be possible or have any worth if it were not for my beautiful wife and best friend, Stephanie, and love of my life, Carter. This is for you both.

Lastly I need to forever convey my gratefulness to the late Dr. Roberto Poma. Roberto sparked and maintained my initial interest in neurology, but of more significance showed so many of us the importance of family, friends, and life. His memory will always hold a place in my heart.
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**CHAPTER I**

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DECLARATION OF WORK PERFORMED

I declare that with the exception of the items indicated below, all the work reported in this thesis was performed by me.

Hemilaminectomy procedures were carried out in both cadavers and clinical cases by Dr. Luis Gaithero. Mini-hemilaminectomy procedures were carried out in both cadavers and clinical cases by Dr. Brigitte Brisson. Computed tomography was performed with the help of Carolyn Bennett, and MRI with Alice Daw. Statistical analysis was performed by William Sears.
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LIST OF ABBREVIATIONS

AF: Annulus Fibrosus
CI: Confidence Interval
CT: Computed Tomography
ICC: Interclass Correlation
IVD: Intervertebral Disc
IVDD: Intervertebral Disc Disease
MRI: Magnetic Resonance Imaging
NP: Nucleus Pulposus
TZ: Perinuclear Transitional Zone
INTRODUCTION

Neurological diseases frequently require surgical intervention. Access to the vertebral canal is needed in neurosurgical conditions such as intervertebral disc (IVD) herniation, exploratory surgical procedures and resection of neoplastic lesions, granulomas, cysts, and hematomas. During spinal neurosurgery, decompression involves removal of a portion of the vertebral bone and/or removal of space-occupying masses to alleviate ongoing compression of the spinal cord and nerve roots.

Intervertebral disc herniation is the most common cause of spinal cord dysfunction in dogs, particularly chondrodystrophic breeds, with the thoracolumbar spine being most commonly affected. Due to unique anatomic features, such as the intercapital ligament from T1–T10, over 85% of thoracolumbar extrusions occur between the T11-L3 intervertebral disc spaces. Spinal cord decompression through removal of the extruded disc material after gaining access to the vertebral canal is the treatment of choice for dogs showing neurological deficits and/or persistent or recurrent spinal pain.

The two most common decompressive surgical procedures used for the thoracolumbar spine, hemilaminectomy and mini-hemilaminectomy, differ by their approach and access to the vertebral canal, and the amount of bone removed. Hemilaminectomy requires removal of one half of the vertebral arch, including the lamina, pedicle, and the articular processes on one side of the vertebrae, and it is typically performed through a dorsal approach to the spine. Mini-hemilaminectomy extends over the same length as the hemilaminectomy but preserves the articular processes by removing the pedicles adjacent to the intervertebral foramen but not the lamina, therefore removing the portion of the vertebral arch ventral to the articular processes. It is typically performed through a lateral or dorsolateral approach.
Both procedures show similarly high success rates, defined as return to ambulatory function, in dogs suffering clinical signs secondary to IVD herniation with intact sensory function, although no direct comparison of the access window created by each procedure has been made. Specifically, the area of the vertebral canal accessed and the height of the lamina that is removed through these two procedures has not been accurately described. The exact location of the compression has to be considered and should guide the pre-surgical decision-making process; ideally, the extent of the bone window to be created should be decided based on the location of the material to be evacuated. However, it is also true that many surgeons frequently refer to described guidelines to create a “standard” hemilaminectomy or mini-hemilaminectomy defect to approach the majority of intervertebral disc extrusions other than in non-routine cases. As a general guideline, hemilaminectomy is indicated when the spinal cord is compressed by lesions in the lateral, dorsolateral, or ventrolateral aspects of the vertebral canal, and mini-hemilaminectomy in lesions confined to the lateral and ventrolateral aspects. Nevertheless, since information regarding specific dimensions and access provided by those two standard procedures is still missing, more specific indications are unknown.

Other factors should also be considered and mini-hemilaminectomies are preferred over hemilaminectomies in people. Proposed benefits for creating a smaller window (removing less bone) are decreased soft tissue dissection, decreased surgical time, and a possible reduced impact on the regional biomechanical function and stability in vitro (particularly since articular processes are preserved), therefore reduced post-operative morbidity. However, mini-hemilaminectomy may sacrifice access to the dorsal and dorsolateral vertebral canal and a potentially greater tendency for hemorrhage when working around the foramen could further decrease exposure. Moreover, a lateral approach to the spine is commonly utilized with mini-hemilaminectomy, which would require repositioning the patient if bilateral decompression was
required. Although this has not been a documented issue with hemilaminectomy, spinal instability could be a concern if the hemilaminectomy is extended more than three consecutive articulations, if a bilateral procedure is required or in active large-breed dogs where the number of consecutive hemilaminectomies that can be performed in one patient is potentially limited.

Although success rates ranging from 83 – 100% are commonly reported in dogs with intact nociception, lack of functional recovery and continued deterioration can occur despite surgical decompression. Potential causes for lack of recovery include progressive spinal cord necrosis (myelomalacia), inadequate decompression, further extrusion of IVD material at the surgical site or from another IVD, iatrogenic spinal cord injury, spinal column instability, compressive hematoma formation, and infection of the surgical site. Of particular relevance is to define what is considered a successful clinical recovery in those dogs: a patient recovering ambulatory function and not suffering further neurological status deterioration. Therefore, a wide range of neurological grades can be included in what is classified as a successful recovery, from a patient showing significant paresis and ataxia despite retaining the ability to walk, to patients showing a complete recovery and no neurological deficits. Actually, the perceived completeness of material evacuation at the time of surgery by an experienced surgeon does not exclude the potential for residual material to be present. Indeed, post-operative imaging has identified residual IVD material in both symptomatic and asymptomatic patients after decompression via hemilaminectomy; no such accounts have been published with the mini-hemilaminectomy technique. This provides an interesting avenue for investigation as any potential to improve evacuation of IVD material, whether that is more inherent with one technique than another, could lead to further improvement in post-operative recovery.

The first objectives of this study were to describe standardized anatomical limits of each technique using computed tomography (CT) and report any observed differences in the access
provided to the vertebral canal that could be considered during pre-surgical planning. The second objective was to determine the completeness of evacuating extruded IVD material with both the hemilaminectomy and mini-hemilaminectomy, and report any differences between techniques.

It was hypothesized that the window created by hemilaminectomy and mini-hemilaminectomy would differ, and that this difference would be primarily due to the retention of bone dorsal to the intervertebral foramen with mini-hemilaminectomy. It was also hypothesized that residual material would be present with both procedures, and that this difference would not be significant despite the previously hypothesized variation between the bone windows created with each technique.
CHAPTER I - GENERAL LITERATURE REVIEW

I. INTERVERTEBRAL DISC DISEASE

Anatomy of the Vertebrae and Vertebral Column

The vertebral column serves to protect and support the spinal cord, and to transfer propulsive movement generated by the limbs through the rest of the body (Evans 1993). In the dog the vertebral column consists of approximately 50 individual vertebrae, divided into 5 segments: cervical, thoracic, lumbar, sacral, and coccygeal (or caudal). Each vertebra is typically abbreviated by the first letter of the segment and its number. The vertebral formula in the dog is C7 T13 L7 S3 Cd20, with the 3 sacral segments being fused, and the number of caudal vertebrae being variable. The overall shape of each vertebra can vary considerably, however they all consist of a body, vertebral arch, and additional processes (Evans 1993). The vertebral body is located ventrally and abuts the IVD. The vertebral arch consists of pedicles (lateral) and lamina (dorsal), which along with the vertebral body form a continuous ring around the spinal cord. Multiple processes exist for muscular and ligamentous attachments, such as the transverse, spinous, accessory, mammillary, and articular processes. The articular processes, or articular facets, articulate with those of adjacent vertebrae to form bilateral synovial joints (Evans 1993). The junction between the caudal thoracic and cranial lumbar vertebrae has been demonstrated to be an area of high-motion and torsion in the dog (Slijper 1946).

The vertebral column is further supported by the epaxial muscles and multiple ligaments, including the ventral and dorsal longitudinal ligaments, which pass longitudinally along their respective aspects of the vertebral bodies, and fuse with each IVD (Evans 1993). Two
other ligaments that are associated with the IVD are the ligament of the head of the rib and the intercapital ligament, the latter of which extends from the head of one rib, across the dorsal aspect of the IVD to the opposite rib head (King & Smith 1955). This ligament is present with the second to tenth pair of ribs, though it has been documented as absent from the tenth pair of ribs in some dogs (Hansen 1952).

**Anatomy and Embryonic Development of the Intervertebral Disc**

In the early embryo the notochord is present as a cylindrical mass of cells with a sheath of mesoderm (Evans 1993). The mesoderm can be functionally divided into clusters of cells destined to form similar tissues, called somites. Of these, the sclerotomes undergo chondrification, eventually giving rise to the vertebrae and the AF (Evans 1993). This all but obliterates the notochord, leaving only a central core between each vertebra, which persists as the NP. Notochordal cells, characterized microscopically by densely packed glycogen within their cytoplasm, can be found as clusters of cells within the immature NP but decreases with age in most species (Hunter, Matyas, & Duncan 2004; Trout, Buckwalter, Moore, *et al* 1982). In chondrodystrophic dogs this change appears to be complete by about the age of skeletal maturity, 12 months, but they can persist for greater than 2 years in non-chondrodystrophic dogs (Hansen 1952; Hunter, Matyas, & Duncan 2004). The gradual loss of notochordal cells may be due to their differentiation into other cell types, such as chondrocytes, or actual cell death (Butler 1989).

With the exception of C1-C2 and the fused sacral vertebrae, an IVD is located between the bodies of each vertebra, totalling 26 between C1 to the sacrum (Evans 1993; Hansen 1952; Hoerlein 1978a). The IVD vary in shape and size according to their location within the vertebral column. Dallman *et al* (1991) demonstrated that the widest IVDs were those of the cervical and
lumbar region, specifically the C4-C5, C5-C6, and L2-L3. However, despite this varying morphology, each IVD is identical in its composition. This consists of an outer, fibrous ring, the annulus fibrosus (AF); a central, amorphous, gelatinous substance, the nucleus pulposus (NP); and cartilaginous endplates.

The AF is composed of primarily Type 1 collagen which is produced and maintained by fibrocytes interspersed within it (Hansen 1952). Moving towards the innermost limits, the fibrocytes become more numerous and a gradual increase in the concentration of Type 2 collagen is reported (Ghosh, Bushell, Taylor, et al. 1977; Hansen 1952; Silva, Farias, & Torres 1991). The collagen itself is organized into parallel fibrous bundles which form sheets of microscopically distinct layers, called lamellae. The individual lamellae are void of intracellular connections (Inoue 1981), which allow them to slide freely across each other during biomechanical loading (Bray & Burbidge 1998a). There are approximately fifteen to thirty-eight layers of distinct lamellae in humans (Marchand & Ahmed 1990), and possibly a similar number in dogs (Johnson, da Costa, & Allen 2010). In a transverse section the lamellae completely encircle the NP as concentric rings. With age the lamellae become increasingly interrupted, most often in the dorsolateral aspects (Marchand & Ahmed 1990). The lamellae attached to and span the adjacent vertebrae and cartilaginous endplates, in a roughly oblique orientation which alternates directions amongst subsequent layers (Inoue 1981). The longitudinal ligaments intertwine with the peripheral lamella of AF on its dorsal and ventral aspects, but no lateral constraints are present (Hoerlein 1978a). As the AF approaches the NP, a TZ of fibrocartilage is encountered, where an increase in the cellular elements and transition to Type 2 collagen is described (Ghosh, Bushell, Taylor, et al. 1977, Hansen 1952; Silva, Farias, & Torres 1991). The AF is thickest ventrally, sometimes up to three times thicker than dorsally (Johnson, da Costa, & Allen 2010), which means that the NP is always eccentrically positioned, especially in the
cervical and lumbar regions (Evans 1993; Hoerlein 1978a). In the young dog the NP is a gelatinous substance, and is composed of approximately 80% water (Hansen 1952; Hoerlein 1978a). Water is attracted via an osmotic gradient established by large, negatively charged proteoglycans within the NP matrix, of which the primary glycosaminoglycans are chondroitin-6-sulfate, keratan sulfate, and hyaluronic acid (Bray & Burbidge 1998a). This combination of ground substance and water creates a hydroelastic cushion. It has been shown that alterations in the proportions of glycosaminoglycans occur with age in dogs, with an overall increase in keratan sulfate and a decrease in chondroitin-6-sulfate, leading to a reduction in the water binding capacity of the NP (Gosh, Taylor, Braund, et al 1976a; Ghosh, Taylor, & Braund 1977).

Cells within the NP, predominantly chondrocytes in the young dog, are typically arranged in clusters, or ‘nests’, separated by a lattice of Type 2 collagen (Hansen 1952). With advancing age, fibrocytes and intermediate mesenchymal cells outnumber chondrocytes, and though many cells display a morphology consistent with degeneration, the overall number of cells increases. In Hansen’s (1952) study of IVD disease, a 50% probability of finding a change to a more fibroid NP was demonstrated by age 6 in non-chondrodystrophic dogs. This appears to represent a normal, degenerative aging process.

As only the outer portion of the IVD is supplied with blood vessels (Forsythe & Ghoshal 1984), nutrition to the inner aspect of the IVD must occur via diffusion of substances through vascular channels located in the thinner, central portion of the cartilaginous end plates (Maroudas, Stockwell, Nachemson, et al 1975; Niinimaki, Parviainen, Ruohonen, et al 2006; Urban, Holm, Maroudas, et al 1977). These vascular channels are evident in the canine IVD (Hansen 1952) and even drain directly into the bone marrow spaces of the vertebral bodies (Crock & Goldwasser 1984). Innervation of the canine IVD has been demonstrated, but is limited
to the peripheral three layers of the AF (Forsythe & Ghoshal 1984; Willenegger, Friess, Lang, et al 2005).

Definitions

Intervertebral disc (IVD) disease refers to the degenerative process affecting the intervertebral discs of both dogs and humans, which can lead to neurological dysfunction through herniation of the degenerated disc material resulting compression and injury to the spinal cord. Macroscopic and histopathological post-mortem studies performed by Hansen (Hansen 1952) lead to further sub-division of IVD disease into Type 1 and Type 2 herniations.

Hansen Type 1 herniation, also know as IVD extrusion, is characterized by chondroid metaplasia of the gelatinous nucleus pulposus (NP) with transformation to hyaline cartilage and mineralization. This process results in a general loss of its hydroelastic properties and ability to withstand pressure that can cause the rupture of the annulus fibrosus (AF) and herniation of calcified NP into the vertebral canal (Hansen 1952) in the form of IVD extrusion. NP that is extruded dorsally into the vertebral canal is further sub-divided by some authors into non-dispersed and dispersed extrusions. Non-dispersed material has contact with the IVD, whereas dispersed material has little to no contact with the site of extrusion (Besalti, Ozak, Pekcan, et al 2005; Besalti, Pekcan, Sirin, et al 2006). Funkquist (1962d) was the first to make such a distinction and considered dispersed extrusions as Funkquist Type III extrusions, though these categories are seldom used clinically, as no significant association between pre-operative or post-operative neurological status has been shown (Besalti, Ozak, Pekcan, et al 2005).

Type 2 IVD herniation or IVD protrusion, is best described as fibrous collagenization (fibrous metaplasia) of the NP with concurrent degeneration, damage and weakening of the AF. This can cause protrusion of the IVD into the canal, but often without complete rupture of the
AF. While the fibrous metaplasia that occurs with Type 2 IVD disease appears similar to the normal aging process of the IVD, it is speculated that an inciting factor such as trauma accelerates the degeneration (Hansen 1952).

Although the terms Hansen Type 1 or Type 2 IVD herniations, and IVD extrusion or protrusion are generally used interchangeably as synonyms within the literature, IVD extrusion and protrusion are the currently preferred nomenclature.

Trauma can also place enough pressure onto a non-degenerate IVD to cause rupture of the AF with explosion of an otherwise normal NP into the vertebral canal (Hansen 1952; Griffiths 1970). If the NP has not undergone degenerative changes, it diffuses within the epidural fat without a persistent focus of compression (Sanders, Bagley, & Gavin 2002). This process has also been referred to as traumatic disc prolapse (Hansen 1952), disc explosion (Griffiths 1970), Type 3 IVD disease, and acute non-compressive NP extrusion (Sanders, Bagley, & Gavin 2002). The focus of this study is with Hansen Type 1 IVD herniation or extrusion.

Chondrodystrophic or chondrodystrophoid refers to breeds in which abnormal endochondral ossification has occurred, resulting in skeletal abnormalities typically characterized by shorten limbs (Hansen 1952). Hansen (1952) discusses ‘chondrodystrophia’ and the premature halt of ossification occurring primarily in the diaphyses of the long bones. Much phenotypic variation exists, resulting in ‘true’ chondrodystrophic breeds being poorly defined, and likely there is substantial overlap amongst and within breeds (Braund, Ghosh, Taylor, et al 1975; Hansen 1952; Jensen & Christensen 2000). Confirmed chondrodystrophic breeds include the Dachshund, Pekingese, French Bulldog, and Beagle (Hansen 1952; Braund, Ghosh, Taylor, et al 1975).
Pathogenesis of Intervertebral Disc Degeneration

In 1896, Dexler was the first to describe compression of the spinal cord leading to paraplegia in a dog due to what he considered a cartilaginous outgrowth of the intervertebral disc. The condition was named Enchondrosis Intervertebralis for many years, and it was not until Tillmans, in 1939, that the condition was speculated to be due to protruded intervertebral disc material (Vaughan 1958). Histopathological studies by Hansen (1952) further confirmed this and described two distinct entities of IVD degeneration: a fibrous metaplasia and a chondroid metaplasia.

Fibrous metaplasia can occur in any breed, and is characterized by invasion of the NP with collagen fibrils, produced by metabolically active cells within the TZ. As the collagen invasion becomes more extensive and progresses deeper into center of the NP, it is divided into distinct lobules. A concurrent degeneration is also seen within the AF itself. With progressive degeneration of the NP and proliferation of fibrocartilage, the overall fibrous component of the IVD increases, the NP becomes indistinguishable from the AF, and chondroitin sulfate and water content decreases, leading to altered biomechanical properties of the IVD. Changes tend to peak at 7 years of age with Hansen (1952) reporting fibroid degeneration in the NP of non-chondrodystrophic dogs in 54.5%, 63.6%, and 54.5% of cervical, thoracic, and lumbar IVD, respectively.

In dogs, chondroid metaplasia of the NP is particularly common, although not limited to, chondrodystrophic breeds. It has also been described in chondrodystrophic human dwarfs (Bray & Burbidge 1998b; Hansen 1952; Jansen & Christensen 2000). While the initial changes are similar to those of non-chondrodystrophoid dog, they occur very early and progress very rapidly, with Hansen (1952) documenting chondroid changes to the NP in the thoracic spine of 79.5% of chondrodystrophic breeds between 2-9 months of age, and calcified IVD in at least 41%. Unlike
fibrous metaplasia, the degenerative changes associated with chondroid metaplasia affect IVD throughout the entire spine simultaneously. Ghosh et al (1977) documented the collagen content of the NP to be approximately 12 times that of proteoglycans in the chondystrophoid dog at birth. The proportion of collagen increases to 25% of the NP by 11 months of age, at all levels of the spine (Gosh 1977). In contrast, the collagen content in the NP of non-chondrodystrophic breeds averages 5% until middle age (Ghosh 1976a). Type X collagen, expressed by hypertrophic chondrocytes in the growth plate, is believed to be a key molecule in endochondral ossification (Reichenberger, Aigner, von der Mark, et al 1991), and has reported in both aged and degenerative IVD in humans (Roberts, Bains, Kwan, et al 1998). A significant increase in the relative expression of type X collagen was demonstrated in the degenerative, extruded NP of Dachshunds (11%) compared to Beagle NP controls (5.4%) (Itoh, Asou, Hara, et al 2008). The predominant proteoglycan also shifts from chondroitin sulfate to keratan sulfate at 2 years of age in the chondrodystrophoid dog, approximately 3 to 4 years earlier than the non-chondrodystrophoid dog (Ghosh 1977). This is suspected to be due to the replacement of mesenchymal cells within the NP with chondrocyte-type cells, and begins in the TZ. Proliferation of chondrocytes results in the NP gradually taking on the appearance of cartilage, with no observable lesion in the AF. Grossly, the distinction between the AF and NP becomes less distinct, and the mucoid NP transforms from a gelatinous substances that exudes moisture from its cut surface, to a grayish-white or grayish-yellow cartilaginous tissue. The ultimate result is partial or complete calcification of the center of the NP, which occurs most frequently in the thoracic region (Hansen 1952; Horlein 1953a; Jensen 2001; Jensen & Arnbjerg 2001; Jensen, Beck, Christensen, et al 2008; Stigen 1991; Stigen & Kolbjornsen 2007).

It is very likely that the degenerative changes occurring with chondroid metaplasia of the NP lead to a self-perpetuating cycle of further degeneration and altered biomechanics. As
previously discussed, nutrition to the avascular IVD is highly dependent on diffusion and osmotic
gradient (Crock & Goldwasser 1984; Forsythe & Ghoshal 1984; Maroudas, Stockwell,  
al 1977), and would be reduced by an increase in collagen content of the IVD, and segmentation  
of the NP by fibrocartilage. The osmotic gradient established by the negatively-charged  
proteoglycans is reduced by an overall loss of proteoglycans and a shift to predominantly  
dermatan sulfate (Bray & Burbridge 1998b; Gosh, Taylor, Braund, et al 1976b; Gosh, Taylor &  
Braund 1977). And while poor differentiation of the IVD is the inherent problem in  
chondrodystrophoid dogs, further differentiation of mesenchymal cells into chondrocytes would  
undoubtedly exacerbate dysfunction of the NP. Moreover, mechanical stresses can induce  
differentiation of mesenchymal cells, with compressive forces favouring chondrocyte production  
(Scapinelli & Little 1970).

Progressive degeneration of the NP impairs the normal hydroelastic function of the IVD  
(Ghosh, Taylor & Braund 1977; Hansen 1959; Hendry 1958), causing a greater proportion of  
compressive forces to be distributed to the AF (Bray & Burbidge 1998, Hoerlein 1978a). Type 1  
collagen, the primary constituent of the AF, is capable of withstanding torsional forces but not  
compression (Brickley-Parsons & Glimcher 1984). Annular tears develop, in the inner layer of the  
AF due to degenerative changes and in the outer layer due to traumatic forces, which can lead  
to complete rupture of the AF with extrusion of the degenerate NP through all layers of the AF.  
Extrusion of NP can occur in all directions (Hansen 1952); however, due to the eccentric position  
of the NP, extrusions occur more frequently in a dorsal direction, either through or lateral to the  
dorsal longitudinal ligament (Hansen 1952; Hansen 1959; King & Smith 1955; Marchand &  
Acute Spinal Cord Injury

IVD extrusions into the vertebral canal can impact the spinal cord with significant force, and cause continued compression of the parenchyma with associated vascular compromise. Hemorrhage is common (Hansen 1952; Hoerlein 1953a; Royal, Chigerwe, Coates, et al 2009; Thacher 1989; Vaughan 1958). Laceration of the paired ventral venous sinuses can occur leading to extensive hemorrhage and proportionally greater compression than the extruded material itself (Macias, McKee, May, et al 2002; Olby, Munana, Sharp, et al 2000; Tartarelli, Baroni & Borghi 2005). The extruded material itself is histologically identical to degenerate NP, and is typically dominated by acellular necrosis with varying degrees of calcification (Hansen 1952; Royal, Chigerwe, Coates, et al 2009; Vaughan 1958). In the subacute phase the histological picture is similar, with the addition of an inflammatory reaction (Hansen 1952; Hoerlein 1953a; Royal, Chigerwe, Coates, et al 2009). Chronic extruded material becomes densely surrounded by fibrous tissue, with the predominant cells being fibroblasts and large mononuclear cells.

Acute trauma to the spinal cord, either exogenous or endogenous, results in a complex pathophysiological mechanism of primary and secondary injury. Primary injury represents the initial mechanical damage to the spinal cord and is sub-divided into four morphological types: impact plus persistent compression, impact alone with transient compression, distraction, and laceration/transaction (Oyinbo 2011). IVD extrusion’s primary injury is characterized by two components: the acute impact and the persistent spinal cord compression, with vascular impairment being the hallmark effect creating a source for the development of secondary injuries. The severity of the primary injury determines the majority of a patient’s initial neurological dysfunction, and in the case of IVD extrusion is directly correlated to the velocity of the impact (Tarlov & Klinger 1954a,b), but in itself is self-limiting. It is the cascade of secondary
mechanisms following the primary injury that can become more deleterious to the patient’s function, which are often self-propagating and perpetuating to each other. To date, there are approximately 25 identified mechanisms of secondary injury (Tator, McCormick, Piepmeier, et al 1998); however, an in-depth discussion of all 25 mechanisms is beyond the scope of this review.

Secondary mechanisms continue into and dominate the sub-acute phase. A key event in this phase is inflammation, which can persist for months following spinal cord injury (Fehlings & Nguyen 2010). Recruitment of leukocytes and activation of resident microglial cells is essential for the removal of tissue debris, and possibly the release of neuroprotective agents, but is complicated by the release of cytotoxic agents and further pro-inflammatory cytokines. Other prominent mechanisms of secondary injury include rises in extracellular concentrations of glutamate (McAdoo, Xu, Robak, et al 1999; Olby, Sharp, Munana, et al 1999), formation of reactive oxygen and nitrogen species and induction of apoptotic cell death (Brown & Hall 1992; Xu, Chi, Xu, et al 2005), and intracellular accumulation of calcium (Simon, Sharif, Tan, et al 2009; Xu, Chi, Xu, et al 2005).

While the pathogenesis is complex, the end result is neurological dysfunction due to neuronal loss, disruption of axonoplasmic flow, direct damage to the myelin sheaths, and demyelination from oligodendrocyte injury. Neuronal necrosis results in permanent loss of neurons, with phagocytosis by astrocytes and the formation of a glial scar or cystic cavity (Olby & Blakemore 1996).

With severe spinal cord injury, a hemorrhagic necrosis and liquefaction of the parenchyma, termed myelomalacia, can develop. The exact mechanisms remain to be elucidated, but post mortem examinations indicate severe vascular stasis with edema and ensuing ischemia (Funkquist 1962c; Griffiths 1972; Hansen 1952; Hoerlein 1953a; Vaughan 1958), possibly associated with vasoactive substances released during the subacute phase of
injury (Griffiths 1972; Tator & Fehlings 1991). While myelomalacia can be focal, up to 10% of
dogs with absent nociception (the ability to perceive pain) will develop a diffuse form over a
period of 1 – 2 weeks (Griffiths 1972; Olby, Levine, Harris, et al 2003; Scott & McKee 1999).
Termed ‘ascending syndrome’, ‘ascending spinal cord necrosis’, ‘ascending-descending
myelomalacia’, or ‘progressive myelomalacia’, it is characterized by continued cranial and caudal
progression of hemorrhagic spinal cord necrosis. The development of ascending myelomalacia
always results in euthanasia, often due to uncontrolled spinal pain or progressive, ascending
spinal cord dysfunction such as respiratory paralysis (Scott and McKee 1999; Olby, Levine,

**Epidemiology**

Priester (1976) reported statistics on 8117 cases of IVD disease from 13 hospitals across
North America, spanning over 1 decade (1964-1974). His conclusions indicated a crude hospital
rate of 23 new cases of IVD herniation per 1 000 dogs per year (2.3%), consistent with earlier
reports (Hoerlein 1952). Hansen’s (1952) findings suggested a significantly higher prevalence of
IVD extrusion in some canine small breeds he considered chondrodystrophic due to altered
endochondral ossification, the Dachshund and French Bulldog, with 39 of 43 IVD extrusions
occurring in those two breeds. Later studies have confirmed this higher occurrence of IVD
extrusion in chondrodystrophic small breed dogs when compared with large non-
chondrodystrophic breeds (Gage 1975; Goggin, Li, & Franti 1970; Priester 1976).

Since then, the Beagle and other high-risk breeds showing similar morphological
characteristics have been added to the classification of chondrodystrophic (Braund, Ghosh,
in the cervical compared to thoracolumbar spine. Interestingly, it was recently shown by Itoh et
al (2008) that 34.8% of cases involving the cervical spine were Beagles, being the most over-represented breed in that group.

While the Dachshund was the most over-represented breed in Hansen’s study, this has also been documented by others, representing from 50 – 75% of all cases (Ball, McGuire, Swaim, et al 1982; Brisson, Holmberg, Parent, et al 2011; Brown, Helphrey, and Prata 1977; Gage 1975; Goggin, Li, & Franti 1970; Knecht 1972; Necas 1999; Olby, Levine, Harris, et al 2003; Priester 1976). Out of the 8117 dogs with IVD disease analysed by Priester (1976), 3898 (47%) were Dachshunds. Relative risk was estimated at 9.9; Goggin et al (1970) found a similar result amongst 645 cases of IVD disease, and determined that Dachshunds were 12.6 times more likely to develop IVD disease. It has been estimated that approximately 1 in 4 – 5 Dachshunds (20-25%) are likely to develop clinical signs of IVD disease within their lifetime (Ball, McGuire, Swaim, et al 1982; Priester 1976).

In a study by Ito et al (2008), the 3 most commonly affected breeds were the Dachshund, Beagle, and Shih Tzu. When comparing a subset of data from these 3 breeds a significant association was found between an older age of onset and multiple IVD extrusions in the Shih Tzu compared with the Dachshund and Beagle (Ito, Hara, Yoshimi, et al 2008). This provides an example of how the multifactorial genesis of IVD disease, particular genetic background and anatomical conformation may differ amongst breeds.

It must also be taken into consideration that IVD extrusion can occur in non-chondrodystrophic dogs, with Macias et al (2002) reporting 62 of 99 large breed dogs (greater than 20 kg) with thoracolumbar IVD disease as having IVD extrusion, and a much higher observation by Cudia and Duval (1997) of 57 out of 62 large breed dogs with thoracolumbar IVD disease. The Cocker Spaniel is not a chondrodystrophic breed but in some reports can represent up to 25% of intervertebral disc extrusion cases (Ferreira, Correia, Jaggy, et al 2002). These are
not in agreement with Hansen’s findings and could possibly reflect the population of dogs studied, but more likely represent a progression in the recognition and diagnosis of IVD disease over the span of 5 decades.

The occurrence of IVD extrusion peaks at 3 to 5 years of age in chondrodystrophic breeds and 6 to 8 years of age in non-chondrodystrophic breeds (Brown, Helphrey, & Prata 1977; Cudia & Duval 1997; Gage 1975; Knecht 1972; Macias, McKee, May, et al 2002; Preister 1976), consistent with the difference in the peak age of incidence of degenerative changes noted by Hansen (1952).

**Clinical Presentation and Neuroanatomical Localization**

Neurological dysfunction associated with IVD extrusion occurs due to acute spinal cord injury, as previously discussed, and is dependent on the severity of contusion, rate and degree of continued compression, and neuroanatomical location of the lesion (Olby, Levine, Harris, et al 2003; Scott & McKee 1999; Tarlov & Klinger 1954a,b).


One explanation for this observation would be the high degree of motion that occurs at the thoracolumbar junction in dogs (Slijper 1946), which could place greater forces on the IVD.
Moreover, the ratio of vertebral canal to spinal cord diameter is larger in the cervical spine and caudal lumbar spine compared to the thoracic spine (Evans 1993). The reduced physical space in the vertebral canal for extruded material results in greater mass effect on the thoracic spinal cord. Also, as previously discussed, the presence of the intercapital ligament from T2-T9/T10 likely provides a significant protective function against dorsal extrusion of NP (Hansen 1952; King & Smith 1955), though IVD extrusions (Gilmore 1983; Liptak, Watt, Thomson, et al 1999; Wilkens, Selcer, Adams, et al 1996) and protrusions have occasionally been reported at this location (Gaitero & Anor 2009; Jaderlund, Hansson, Narfstrom, et al 2002).

The severity of neurological dysfunction as a result of any extradural compression progresses through a course of well documented clinical signs (Scott 1997; Scott and McKee 1999). Spinal hyperesthesia is usually the first clinical sign. As there are no nociceptive fibers (general somatic afferent fibres) supplying the spinal cord itself, pain likely results from nerve root or meningeal compression/inflammation and physical damage to the outer layer of the AF and the dorsal longitudinal ligament (de Lahunta & Glass 2009; Forsythe & Goshal 1984). Axons located superficially, as in the ventral funiculus, should intuitively be more prone to the initial physical insult, as they are the first layer in the path of impact. Larger, more heavily myelinated axons are also very susceptible to injury. This is likely due to their reliance on myelin sheaths for adequate conductance and possibly because oligodendrocytes myelinating large axons may have higher metabolic requirements and be more susceptible to ischemia (Smith & Jeffrey 2006). Thus, it seems logical that the larger and more superficial ascending tracts within the dorsal funiculus are easily affected, resulting in proprioceptive deficits and ataxia, with more severe lesions required to produce deficits in the descending motor tracts of the ventral and lateral funiculi. This phenomenon is related to the usual progression of neurological deterioration from spinal pain as the initial clinical signs, progressing to proprioceptive deficits.
and ataxia, and eventually resulting in motor deficits (paresis). This also explains why the loss of
nociception is the final step in neurological deterioration and its association with a worse
as these small non-myelinated fibers lie in the propriospinal and spinoreticular tracts, located
centrally in the white matter, close to the gray matter (de Lahunta & Glass 2009).

Given the propensity for thoracolumbar extrusions to occur between T11 and L2, the
majority of patients present with clinical signs of upper motor neuron (UMN) paresis affecting
the pelvic limbs, as the lower motor neurons (LMN) at these sites innervate axial muscles and
therefore do not result in appreciable clinical signs (de Lahunta & Glass 2009). The influence of
the UMN on the LMN is primarily inhibitor, and thus a lesion in the UMN typically results in
increased muscle tone, spasticity, and hypereflexia in the affected limbs. On the other hand,
compression of the spinal segments located in the lumbosacral intumescence would result in
clinical signs of LMN dysfunction, such as flaccid muscle tone and loss of spinal reflexes in the
pelvic limbs. IVD extrusions involving the lumbar intumescence associated to LMNs clinical signs
in the pelvic limbs have historically been given a worse outcome; however, recent studies do not
support this (Dhupa, Glickman & Waters 1999; Olby, Levine, Harris, et al. 2003; Ruddle, Allen,

IVD extrusion is often lateralized to some degree (Besalti, Ozak, Pekcans, et al. 2005;
Naude, Lambrechts, Wagner, et al. 2008), and as such, many patients will present with varying
degrees of asymmetry in their neurological deficits (Black 1988; Brown, Helphrey, & Prata 1977;
Schulz, Walker, Moon, et al. 1998; Yovich, Read, & Eger 1994). However, neurological deficits do
not consistently occur ipsilateral to the compression, and a substantial proportion of patients
with contralateral deficits has been documented, ranging from 14 – 39% of those with
thoracolumbar IVD herniation (Bos, Brisson, Holmberg, et al 2007; Brown, Helphrey, & Prata 1977; Schulz, Walker, Moon, et al 1998; Smith, Newell, Budsberg, et al 1997; Tanaka, Nakayama, & Takase 2004; Yovich, Read, & Eger 1994). This likely occurs due to contrecoup injury, but could also be due to the formation of hemorrhage or inflammation (Olby, Dyce, & Houlton 1994).

**Treatment and Prognosis**

Treatment options for acute IVD extrusion are generally divided into medical, or conservative, and surgical management. Conservative management consists of strict cage rest for at least 4 – 6 weeks to allow potential fibrosis of the avascular AF and prevent further extrusion of NP (Wilcox 1965; Davies & Sharp 1983). Analgesics are recommended and used as necessary (Levine, Levine, Johnson, et al 2007; Mann, Wagner-Mann, Dunphy, et al 2007). However, one study determined that the duration of cage rest did not have an impact on success rate (Levine, Levine, Johnson, et al 2007). Success rate in ambulatory dogs managed conservatively ranges from 56 – 100% (Davies & Sharp 1983; Funkquist 1978; Levine, Levine, Johnson, et al 2007; Mann, Wagner-Mann, Dunphy, et al 2007; Wilcox 1965), while in non-ambulatory dogs is lower, at approximately 0-50% (Davies & Sharp 1983; Funkquist 1962c; Levine, Levine, Johnson, et al 2007; Wilcox 1965). In all of those studies success was determined as a return to ambulation, though residual deficits may have been present; in fact Davies and Sharp (1983) report an overall rate of residual ataxia in 13% of dogs deemed to be successfully treated, and 18% of owners reported chronic back pain in their dogs (Levine, Levine, Johnson, et al 2007). From this data, there is a general recommendation to reserve conservative management for ambulatory dogs with minimal or no neurological deficits, and to expect a recurrence of clinical signs in approximately half of those patients. It must also be considered that progression of the deterioration can be rapid, causing a once ambulatory patient to
become non-ambulatory. Conservative treatment in patients with absent nociception is not recommended as results are poor, with no dogs recovering function in 2 reports (Levine, Levine, Johnson, et al 2007; Schulman & Lippincott 1987) and only in 7% of dogs in another study (Davies & Sharp 1983).

Surgical procedures described in more detail in section II) essentially involve the removal of a portion of the vertebral lamina and/or pedicles to provide access to the vertebral canal, and evacuation of any compressive material such as extruded NP and hemorrhage. The overall goal is to alleviate the source of neurological deterioration as a result of spinal cord compression while preventing further development of secondary mechanisms, remove a potential source of inflammation, and possibly restore vascular dynamics to the spinal cord (Carlson, Gordon, Oliff, et al 2003). Decompressive procedures alone are often not sufficient to provide decompression if extruded material (either disc or hemorrhage) is not removed (Doppman & Girton 1976; McKee 1992). Early surgical decompression with removal of extruded material is a widely accepted treatment for most dogs with progressive, severe, or recurrent neurological deficits and/or spinal hyperesthesia (Funkquist 1962c, 1970; Hoerlein 1978b; Prata 1981; Schulman & Lippincott 1987; Scott 1997).

The prognosis for recovery after surgical management, defined as a return to ambulation, in dogs with intact nociception is considered favourable ranging 82-100% (Besalti, Ozak, Pekcan, et al 2005; Black 1998; Dhupa, Glickman, Waters, et al 1999; Funkquist 1970; Jeffery 1998; Kazakos, Polizopoulou, Patsikas, et al 2005; Lubbe & Verstraete 1994; Macias, McKee, May, et al 2002; Necas 1999; Scott 1997; Sukhiani, Parent, Atilola et al 1996; Yovich, Read, & Eger 1994). When focusing on the larger case series, the prognosis for these dogs changes little, but is likely a more accurate assessment at approximately 83 – 96% (Brisson, Moffatt, Swayne, et al 2004; Davis & Brown 2002; Ferreira, Correia, & Jaggy 2002; Funkquist...
A prospective study by Bush et al. (2007) actually reported 100% of 51 non-ambulatory, small-breed dogs with intact nociception to be ambulatory by 6 weeks post-operative. Also of note, a report on 99 cases of thoracolumbar IVD extrusion in large breed, non-chondrodystrophic dogs found a slightly smaller success rate of 86% in dogs with intact nociception (Macias, Mckee, May, et al. 2002).

determined that dogs with intact nociception prior to surgery were at least 1.7 times more likely to recovery ambulatory function than those without.

The reasons behind this variability have been a topic of debate with particular interest being invested into other, potentially more reliable, prognostic indicators. One proposed factor for such variability is the subjective nature and limitations intrinsically associated to the neurological examination and functional scoring scales, with some investigators pursuing the development and validation of more detailed scoring systems (Levine, Levine, Budke, et al 2009; Olby, Derisio, Munana, et al 2001). While too complex to be used in the daily clinical practice, the main goal is to establish treatment outcomes for research studies with improved accuracy (Olby, Derisio, Munana, et al 2001). Currently most veterinarians employ a modification of the Frankel Scale developed for humans (Frankel HL, Hancock DO, Hyslop G, et al 1969), usually allowing for assessment of voluntary motor function, ambulatory status, and presence or absence of nociception, although significant variability exists (Sharp & Wheeler 2005; Levine, Levine, Budke, et al 2009).

The variability in functional scoring, further limited by the few grades described, makes comparisons between studies difficult. For instance, some authors describe different scoring for dogs with superficial pain sensation and those with deep pain sensation (Jeffery 1998). This has been subjected to scrutiny and assessed as being too subjective and unreliable (de Lahunta & Glass 2009). Another example is how Muir et al (1995) grouped dogs with absent motor function but intact nociception in only one limb into the same category as dogs with absent motor function and intact nociception in both limbs. Most studies also do not define how the presence of nociception was assessed. De Lahunta and Glass (2009) recommend the use of forceps if digital pressure is inconclusive. Although this tends to be common practice it may not be universally applied. Scott and McKee (1999) went as far as using bone forceps or water pump
pliers if digital pressure was insufficient to elicit a reproducible response. Similar concerns rise with the assessment of other neurological tests. Olby et al (2004) mentioned the recovery of proprioceptive placing tests to be too variable to take into consideration, with some dogs having absent placing but good motor function, and dogs with poor motor function having adequate placing. A recent study found the cutaneous trunci reflex assessment to be an accurate predictor in determining the prognosis for development of ascending myelomalacia with no dog showing static or caudal progression developing myelomalacia (Muguet-Chanoit, Olby, Lim, et al 2012). Another inherent problem is the lack of sufficient numbers of dogs with absent nociception in some studies, often resulting in return to ambulatory function in 100% of the dogs including in some reports (Black 1988; Dhupa, Glickman, Waters, et al 1999; Kazakos, Polizopoulou, Patsikas, et al 2005; Lubbe & Verstreate 1994; Macias, McKee, May, et al 2002; Muir, Johnson, Manley, et al 1995; Schulman & Lippincott 1987; Scott 1997; Yovich, Read, Eger et al 1994). Power analysis, using a more advanced functional scoring scale, determined that approximately 150 dogs would be required in each functional group to have a 95% chance of detecting a 20% improvement in function (Olby, Harris, Burr, et al 2004).

Another criticism, mainly towards older literature, has been the lack of long-term follow-up in some studies. Olby et al (2003) demonstrated that in dogs with absent nociception that recovered motor function, the mean time to ambulation was 7 weeks, with 3 dogs (8%) requiring greater than 12 weeks. While the minimum follow-up in most studies is 12 weeks (Funkquist 1970; Kazakos, Polizopoulou, Patsikas, et al 2005; Loughin, Dewey, Ringwood, et al 2005; Olby, Levine, Harris, et al 2003; Ruddle, Allen, Schertel, et al 2006; Scott & McKee 1999), others report short-term follow-up or have variable lengths for individual patients (Dhupa, Glickman, & Waters 1999; Knecht 1970; Laitinen & Puerto 2005; Muir, Johnson, Manley, et al 1995; Macias, McKee, May, et al 2002). Both Olby et al (2003) and Ruddle et al (2006) reported
approximately 60% of these dogs were ambulatory at 4 weeks. This is comparative to results from Scott and McKee (1999), who also noted in their population that 20 of the 21 dogs who regained ambulatory ability had regained nociception by 2 weeks post-operative. Conversely, only 1 of 6 dogs with absent nociception at 2 weeks post-operative regained function (Scott & McKee 1999). Laitinen and Puerto (2005) also found recovery of nociception by 2 weeks post-operative to be a good prognostic indicator.

Another confounding factor limiting many studies is the use of owner questionnaires or telephone follow-up (Besalti, Ozak, Pekcan, et al 2005; Brisson, Moffatt, Swayne, et al 2011; Bush, Tiches, Kamprad, et al 2007; Davis & Brown 2002; Duval, Dewey, Roberts, et al 1996; Macias, McKee, May, et al 2002; Olby, Levine, Harris, et al 2003). While the degree of function required of most dogs to be household pets is satisfactory, residual deficits have been reported in 25-41% of dogs (Penning, Platt, Dennis, et al 2006; Scott 1997; Olby, Levine, Harris, et al 2003). Thus, it may be unrealistic to rely on owners to identify subtle changes that may influence treatment protocols, provide prognostic indicators, or identify relapse.

Other variables investigated as potential prognostic factors include the nature of the extrusion itself (degree of compression, rate of extrusion, duration of compression), the hemorrhagic component of the compression, site of extrusion, spinal cord swelling (and associated imaging characteristics), administration of corticosteroids, further extrusion of NP post-operative, and insufficient removal of extruded NP (residual material) following surgery.

Concussive injury to the spinal cord can induce secondary mechanisms of damage independently of compression (Sparrey, Choo, Liu, et al 2008); therefore the severity of a patient’s clinical signs can be due entirely to concussion, even with little evidence of compression. In contrast, a slowly compressive lesion can theoretically induce less damage initially. Interestingly, it has been demonstrated that the degree of spinal cord compression
present at the time of diagnosis, is not correlated with the severity of clinical signs or outcome
(Besalti, Pekcan, Sirin, et al 2006; Boekhoff, Flieshardt, Ensinger, et al 2011; Levine, Fosgate,
Boekhoff et al (2011) identified a statistically significant association between longer duration of
clinical signs in paraplegic dogs with larger spinal cord compressions, and suggested that injuries
that are primarily compressive can induce damage at a slower rate than concussive injuries.

Most studies have not been able to demonstrate a relationship between rate of onset of
clinical signs and outcome (Funkquist 1962a; Ito, Matsunaga, Jeffery, et al 2005; Kazakos,
Penning, Platt, Dennis, et al 2006; Scott 1997). However, in one study 50% of the dogs that
became paraplegic within 24 hours had a successful outcome compared to 90% that developed
clinical signs over 48 hours in another study (Scott & McKee 1999) and another report also
demonstrated a significant influence of the rate of onset of clinical signs on the clinical post-
operative outcome (Ferreira, Correia, & Jaggy 2002). Duration of the compression has been
suggested to affect the outcome, since prolonged compressions could further potentiate
secondary injury mechanisms (Brown & Hall 1992; Carlson, Gorden, Oliff, et al 2003; Griffiths
1975; Tarlov & Klinger 1954a). Knecht (1972) reported that a delay in decompressive surgery did
not appear to affect ambulatory dogs, but was devastating for the paraplegic dogs with absent
nociception, similarly to a study by Duval et al (1996) where a similar inverse relationship for
loss of nociception, with a higher success rate in the less than 12 hour group, compared to the
12 – 24 and 24 – 48 hour groups was reported. Those studies mentioned difficulty in accurately
determining when nociception was lost, having to rely on history and medical records. Two
other reports have similar results suggesting an indication to perform decompressive surgery
within 12 hours of a dog losing nociception (Laitinen & Puerto 2005; Loughin, Dewey, Ringwood,
et al 2005). However, not all studies have not been able to identify this same association (Ito, Matsunaga, Jeffery, et al 2005; Kazakos, Polizopoulou, Patsikas, et al 2005; Olby, Levine, Harris, et al 2003).

Regarding anatomical location of the compression, although Dhupa et al (1999) observed a mean return to ambulation of 12 days for dogs with LMN signs compared to 7 days in dogs with UMN signs, no association between ability to walk and anatomical location of the injury has been found in larger studies (Olby et al 2003; Ruddle, Allen, Schertel, et al 2006).

Venous sinus hemorrhage associated with IVD extrusion can cause diffuse spinal pain, peracute compression leading to rapid deterioration, and can elicit an inflammatory response, however the presence, location, and extent of epidural hemorrhage alone does not appear to be associated with a poor prognosis (Macias, McKee, May et al 2002; Loughin, Dewey, Ringwood, et al 2005; Mateo, Lorenzo, Foradada, et al 2011; Tartarelli, Baroni, & Borghi 2005; Thacher 1989).

Macroscopic swelling of the spinal cord can occur secondary to trauma, but alone does not seem to indicate irreversible damage. Indeed Loughin et al (2005) reported that subjective spinal cord swelling noted at the time of surgery did not impact functional recovery as 70% of those dogs observed to have gross evidence of spinal cord swelling at surgery returned to ambulatory status. Another study described the use of a myelographic swelling ratio as an indicator of poor prognosis in dogs with absent nociception, observing a sensitivity of 74% and specificity of 61% (Duval, Dewey, Roberts, et al 1996). However, those authors acknowledged that the technique for myelography could cause erroneous results, with a delay in obtaining radiographs create an appearance of spinal cord swelling, and later studies were unable to reproduce those results (Scott & McKee 1999).

MRI allows identification of changes within the spinal cord parenchyma following acute spinal cord injury that may provide useful prognostic information. Three retrospective case
series have investigated thoracolumbar IVD extrusion in dogs and MRI as a prognostic tool, each with evidence that the presence and longitudinal extent of hyperintensity within the spinal cord on T2-weighted images has a negative impact on functional outcome and is significantly correlated with the degree of neurological dysfunction (Boekhoff, Flieshardt, Ensinger, et al 2011; Ito, Matsunaga, Jeffery, et al 2005; Levine, Fosgate, Rushing, et al 2009).

Durotomy is a surgical technique initially recommended by some authors to grossly inspect the spinal cord parenchyma for signs of myelomalacia, such as softening or liquefaction, and to allow further decompression (Duval, Dewey, Roberts, et al 1996; Parker 1975a; Scott 1997; Scott & McKee 1999). Durotomy has been found to have no significant impact on functional outcome and no value as an indicator of myelomalacia (Duval, Dewey, Roberts, et al 1996; Loughin, Dewey, Ringwood, et al 2005; Salisbury & Cook 1988).

The use of corticosteroids in management of acute spinal cord injury is still controversial in both human and veterinary medicine and beyond the scope of this chapter. There has been no documented benefit with the use of a high-dose methylprednisolone sodium succinate protocol suggested in human medicine (Boekhoff, Flieshardt, Ensinger, et al 2011; Carlson, Gorden, Nakazawa, et al 2003; Davis & Brown 2002; Levine, Levine, Johnson, et al 2007; Levine, Levine, Boozer, et al 2008; Ruddie, Allen, Schertel, et al 2006), and adverse effects are common (Hanson, Bostwick, Twedt, et al 1997; Levine, Levine, Johnson, et al 2007; Levine, Levine, Boozer, et al 2008). However, one study found a decreased rate of recurrence in ambulatory dogs managed conservatively with a non-steroidal anti-inflammatory drug or MPSS compared to other corticosteroids (Mann, Wagner-Mann, Dunphy, et al 2007). Considering the likelihood of adverse effects associated to high doses of corticosteroids in dogs (Hanson, Bostwick, Twedt et al 1997; Levine, Levine, Boozer et al 2008), rigorous studies are required to justify their administration in dogs with acute spinal trauma, including IVD extrusions.
Inadequate surgical decompression due to ineffective removal of extruded material from the vertebral canal can result in a failed or incomplete post-operative recovery (Dhupa, Glickman, Waters, et al 1999; Forterre, Gorgas, Dickomeit, et al 2010), and is likely the factor that can be most easily and efficiently influenced by our intervention. A recent study found that of the 5.8% of dogs with lack of improvement in the early post-operative period, 70% were due to residual material confirmed via MRI and re-operative surgery (Forterre, Gorgas, Dickomeit, et al 2010). Poor evacuation of residual material from the vertebral canal can result from the surgery being performed at the wrong site (Forterre, Gorgas, Dickomeit, et al 2010), the wrong side (Dhupa, Glickman, Waters, et al 1999; Schulz, Walker, Moon, et al 1998), material being inadvertently pushed to the contralateral side of the vertebral canal or further cranially/cadually (Forterre, Gorgas, Dickomeit, et al 2010), inability to remove bilaterally located material with a unilateral surgical approach (Forterre, Konar, Spreng, et al 2008; Forterre, Gorgas, Dickomeit, et al 2010), and inability to effectively remove material from the appropriate surgical site (Dhupa, Glickman, Waters, et al 1999; Forterre, Gorgas, Dickomeit, et al 2010; Roach, Thomas, Weh, et al 2012). Inaccurate imaging can lead to improper lesion localization, a problem more commonly related to myelography than CT-myelography or MRI (Bos, Brisson, Nykamp, et al 2012; Forterre, Gorgas, Dickomeit, et al 2010; Schulz, Walker, Moon, et al 1998). It is expected that any surgical technique will be limited by expertise and human error, with inexperienced surgeons more likely to approach the wrong surgical site, make an inadequate surgical exposure, or underestimate the degree of material removal (Funkquist 1970; Forterre, Gorgas, Dickomeit, et al 2010). However, Loughin et al (2005) determined that there was no appreciable difference in the success rate between appropriately trained individuals (neurology intern, surgery resident, board-certified surgeon, and board-certified neurologist), and actually,
underestimation of disc removal has been documented with experienced surgeons (Forterre, Gorgas, Dickomeit, et al 2010; Roach, Thomas, Weh, et al 2012).

It is evident then that our ability to predict a functional recovery and intervene is limited by our current understanding of the pathogenesis of acute spinal cord injury. Even in patients with a seemingly good prognosis an unexpected outcome can occur. However, the opposite is true also; the fact that a population of dogs with absent nociception regain function would suggest that absence of nociception alone is not a definite indication of a transverse myelopathy (Olby, Levine, Harris, et al 2003). For those patients that, despite treatment, continue to deteriorate, do not recover function, or this recovery is incomplete, the potential causes can be: continued progression of secondary spinal cord injury, venous hemorrhage causing compression, residual NP causing compression from inadequate decompression or further herniation, diffuse myelomalacia, iatrogenic surgical trauma or instability, and extrusion at another IVD (Sharp & Wheeler 2005). Residual extruded material is likely present in many asymptomatic dogs. Residual material was present in only 1 of 19 dogs undergoing immediate post-operative MRI following hemilaminectomy in one study, and that dog recovered uneventfully (Forterre, Konar, Spreng, et al 2008). A recent prospective study performed post-operative CT studies in dogs undergoing hemilaminectomies, and determined that residual extruded material was present in 100% of cases, though this did not seem to affect functional outcome (Roach, Thomas, Weh, et al 2012). Limitations were the use of CT to identify residual material and long-term outcome, defined as ambulation with urination, being assessed only through phone interviews with the clients without a proper neurological examination. The mean percentage of material removed at surgery was 50.3% (range: 2.6 – 155.8%), suggesting that visualization of extruded material often underestimates the extent, and is likely hindered by the unilateral nature of the laminectomy window (Roach, Thomas, Weh, et al 2012). Considering the
complex mechanisms of spinal cord injury and the influence of impact velocity compared to sustained compression, it is not surprising clinical improvement can still happen despite an incomplete removal of extruded material. However, the goal of that study did not include an accurate assessment of residual deficits and further studies are required to investigate the long-term follow up with adequate neurological examinations.

Therefore, residual NP would appear to be an interesting area of investigation, due to the increasing availability to perform post-operative imaging and quantitative assessment, and given the potential association with human error and technical skill. Evacuation of extruded material is physically limited by the surgical approach, requiring accurate pre-operative planning and an increase in our knowledge of any potential limitation. Moreover, it is important to note again that a successful clinical recovery is generally limited to the ability to regain the ability to ambulate. Therefore, a wide range of neurological grades can be included in the broad range of successful recovery, from a patient showing significant paresis and ataxia despite retaining the ability to walk, to patients showing a complete recovery and no neurological deficits. Whether an incomplete recovery despite regaining the ability to walk in some patients after decompressive surgery for IVD extrusion is due to the presence of residual material or not remains to be elucidated. However, if residual material is responsible for an incomplete recovery, a question arises whether one surgical technique could be more successful than another.

**Diagnosis**

Accurate antemortem diagnosis and anatomical localization require diagnostic imaging, with subsequent confirmation of the presence of extruded material at the time of surgery. While a thorough history, physical and neurological examinations are essential, clinical signs
alone are inaccurate for surgical planning (Schulz, Walker, Moon, et al 1998; Smith, Newell, Budsberg, et al 1997). However, imaging findings must be correlated with the neurological assessment, as asymptomatic IVD herniations in conjunction with the primary extrusion are not uncommon (Hansen 1952; Jensen & Arnbjerg 2001). The accuracy of the imaging modality being utilized is an important consideration, as this can affect the ability to differentiate symptomatic from asymptomatic lesions, and heavily influences planning for surgical site, approach, and technique (Sharp & Wheeler 2005).

Conventional spinal radiographs can rule out severe fractures, luxations, aggressive bone lesions, and demonstrate changes consistent with IVD degeneration, but alone are unreliable for a diagnosis of IVD extrusion and fraught with interobserver variation (Lamb 2002). Radiographic detection of intervertebral disc extrusion requires significant IVD mineralization to be present (Stigen & Kolbjornsen 2007). When compared to surgical findings, radiographs had an accuracy of only 32 - 72% in identifying the correct site of extrusion (Kirberger, Roos, & Lubbe 1992; Lamb 2002; Olby, Dyce, & Houlton 1994). While performing a study evaluating myelography and CT, radiographs had a mean sensitivity of 94.7% compared to surgery when identifying the site of thoracolumbar IVD extrusion (Hecht, Thomas, Marioni-Henry, et al 2009); the use of digital radiographs may have accounted for this increased sensitivity, but the authors cautioned that determining lateralization of material would not have been possible using radiographs alone. Moreover, given the high likelihood of finding radiographic signs of IVD degeneration in asymptomatic animals of high risk breeds (Jensen & Arnbjerg 2001), possibly at more than 1 site, interpretation would prove difficult. A recent retrospective investigation in Dachshunds found that just as many extrusions occurred at IVD with radiographic evidence of mineralization as those that were undetectable (Rohdin, Jeserevic, Viitmaa, et al 2010), whereas
a recent prospective study of small breed dogs found none of the 65 mineralized IVD
corresponded with the site of extrusion (Bos, Brisson, Nykamp, et al 2012).

Myelography refers to the injection of a radio-opaque contrast medium into the
subarachnoid space with the purpose of delineating the margins of the spinal cord on
radiographs. It is a better assessment of compression, but can be confounded by spinal cord
swelling, extensive epidural hemorrhage, accidental injection into the epidural space, and
multiple compressive lesions (Dennison, Drees, Rylander, et al 2010; Gibbons, Macias, De
longitudinal lesion localization ranged considerably from 40 to 97% (Black 1988; Olby, Dyce, &
Houlton 1994), however more recent studies suggest a narrower range of approximately 74-
94.7% (Dennison, Drees, Rylander, et al 2010; Hecht, Thomas, Marioni-Henry, et al 2009; Israel,
often reported as less accurate, especially when compared to other modalities, with sensitivity
for lateral localization ranging from 49 – 83%, although this accuracy can be greatly improved
with the combination ventrodorsal and oblique views (Black 1988; Bos, Brisson, Holmberg, et al
1997; Tanaka, Nakayama, & Takase 2004). Myelography is technically demanding and invasive,
requiring puncture of the lumbar or cervical cisterns and administration of contrast medium into
the subarachnoid space with its intrinsic potential complications to consider, as neurological
status deterioration, seizures, meningitis, cardiorespiratory imbalances, subarachnoid and/or
epidural hemorrhage (Barone, Ziemer, Shofer, et al 2002; Carroll, Keene, & Forrest 1997; Israel,
The utility of CT and MR imaging will be discussed later in section III. Briefly, CT has the advantage of obtaining multiple thin slices, rapidly, and with excellent spatial resolution (the ability to discern two objects as separate) (Tidwell & Jones 1999). Sensitivity for identifying extruded material with CT alone ranges from 81.8 – 100%, but is heavily influenced by the degree of mineralization and can be difficult to distinguish from hemorrhage (Dennison, Drees, Rylander, et al 2010; Hecht, Thomas, Marioni-Henry, et al 2009; Israel, Levine, Kerwin, et al 2009; Newcomb, Arble, Roschat, et al 2012; Olby, Munana, Sharp, et al 2000). CT can be combined with myelography; the ability to obtain transverse images and reformatted images with CT and detect relatively low concentrations of contrast medium in the subarachnoid space improves the diagnostic quality, however the risks associated with myelography still remain. Currently, MRI is considered the gold standard for diagnostic imaging in IVD disease, providing excellent tissue contrast resolution, images in multiple planes, and a lesion localization sensitivity of 100% (Bos, Brisson, Nykamp, et al 2012; Naude, Lembrechts, Wagner, et al 2008; Tidwell & Jones 1999).
II. SURGICAL TECHNIQUE

Surgical Treatment for Intervertebral Disc Disease

Olsson (1951) first proposed IVD fenestration as a therapeutic method to relieve ‘dynamic compression’ and stabilize the spine, as well as offering a prophylactic benefit by removing further NP and creating a lateral window for further extrusion. Seemann (1968) suggested fenestration be performed concurrently with laminectomy, as laminectomy provided no prophylactic effect, and described a lateral muscle-separating approach that would allow access to adjacent IVD. Funkquist also observed that the rate of recurrence was nearly identical for dorsal laminectomy and conservative management, and also advised concurrent fenestration to prevent further herniation at the site of extrusion (Funkquist 1970).

Reported advantages of the fenestration technique were a prophylactic effect (Funkquist 1962c; Hoerlein 1978a), minimal invasiveness, and less reliance on imaging and specialized surgical equipment (Olsson 1951; Butterworth & Denny 1991). Some studies were able to demonstrate high success rates of 88 – 96% (Butterworth & Denny 1991; Davies & Sharp 1983; Denny 1978; Flo & Brinker 1975), but despite this the technique came under early criticism. Prolonged recoveries similar to those seen in conservatively managed cases were reported (Butterworth & Denny 1991; Davies & Sharp 1983; Funkquist 1978), and its inability to provide decompression was felt by some as a justification to avoid it as a sole method of treatment (Funkquist 1978; Hoerlein 1978a,b). Fenestration was then recognized as not suitable for treatment in dogs with absent nociception (Butterworth & Denny 1991; Hoerlein 1978a), and in some reports the majority of dogs treated were already ambulatory at the time of treatment and may have responded to conservative management alone (Butterworth & Denny 1991).
After Greene’s (1952) initial laminectomy description, Funkquist (1962a,c,d, 1970) published several articles describing her work on dorsal laminectomy in normal and experimental dogs. Dorsal laminectomy refers to the removal of the spinous processes, dorsal laminae, and variable amounts of the articular processes and pedicles, over at least 2 consecutive vertebrae (Toombs & Waters 2003). There are 4 variations of the dorsal laminectomy. Funkquist type A is characterized by removal of the articular processes bilaterally, with reduction of the pedicles bilaterally to approximately the middle of their dorsoventral height (Hoerlein 1978a). Funkquist type B laminectomy conserves the pedicles and the majority of the caudal articular processes (Funkquist 1962d). Modified dorsal laminectomy removes the caudal articular processes, leaves the cranial articular processes intact, and can be augmented with removal of the medial aspect of the pedicles bilaterally (Trotter 1974). Modified deep dorsal laminectomy includes removal of the articular processes and the entire pedicle bilaterally (Trotter, Brasmer, & de Lahunta 1975). The thoracolumbar spine is accessed through a dorsal midline approach for dorsal laminectomy (Coates, Hoffman, & Dewey 2003).

The initial Funkquist type A technique resulted in significant compression secondary to scar formation (laminectomy membrane), and the Funkquist type B technique was adopted. However, it was recognized that with the more limited Funkquist type B approach, significant manipulation of the spinal cord was required, as many IVD extrusions are within the ventral confines of the vertebral canal (Funkquist 1962a,c,d). By preserving the majority of the articular processes the laminectomy could be extended across many adjacent vertebrae (Hoerlein 1978a), and a modified approach was soon reported which described under-cutting of the pedicle on the medial aspect to better approach ventrally located material (Trotter 1974). Evidence became available to support the need for removal of extruded NP, which created some concern that simply creating a bone window with a dorsal laminectomy would not provide
adequate decompression as residual material often remained within the canal after the dorsal laminectomy technique (Bitteto & Thacher 1987; Doppman & Girton 1976; McKee 1992).

Success rates of approximately 80 – 89% were being documented with dorsal laminectomy (Brown, Helphrey, & Prata 1977; Funkquist 1970; Gambardella 1980), but the hemilaminectomy technique reported by Redding (1952) was also being utilized with equal success (Hoerlein 1952, 1956; Knecht 1972; Schulman & Lippincott 1987), and a report by Hoerlein (1978b) found more veterinarians were performing hemilaminectomies with concurrent IVD fenestration. Hemilaminectomy requires the removal of the entire vertebral arch unilaterally, over the site of interest. The pedicle, articular processes, and lamina are removed to the base of the spinous process, and to the ventral limit of the vertebral canal (Redding 1951; Schulman & Lippincott 1987). The spinous process, vertebral body, and contralateral vertebral arch are preserved with the cranial and caudal limits usually spanning to, but not including, the base of the adjacent articular processes (Redding 1951; Schulman & Lippincott 1987; Sharp & Wheeler 2005). A dorsolateral approach to the thoracolumbar spine is recommended, although a lateral muscle-separation approach can be utilized (Hoerlein 1978a).

Prior to the availability of advanced imaging Prata (1981) observed that there was no statistical difference in the lateralization of extruded NP to the right or left, so concluded that hemilaminectomy would fail to expose the compression 50% of the time. Two cadaveric investigations were later published that revealed the dorsal laminectomy to be the most destabilizing of the techniques and that it may even lead to increased pressure within the disc due to the altered biomechanics which could create a predisposition to IVD extrusion at the adjacent sites (Shires, Waldron, Hedlund, et al 1991; Smith & Walter 1988). This promoted interested into comparing the success rates; McKee (1992) found a higher post-operative recurrence with dorsal laminectomy compared to hemilaminectomy and concurrent
fenestration, though it isn’t clear if this was due to fenestration in the hemilaminectomy group
or residual compressions in the dorsal laminectomy group. In addition, extruded NP was only
recovered from 40% of the dogs in the dorsal laminectomy group (McKee 1992). Muir et al
(1995) did not report a difference in long-term outcome between 96 dogs receiving either
hemilaminectomy or dorsal laminectomy but significantly worse neurological scores were noted
in the immediate post-operative period with the dorsal laminectomy group. The authors of this
study proposed that early post-operative deterioration likely occurred because of aggressive
manipulation of the spinal cord rather than residual disc material since extruded NP was
removed in 96% of dogs that received dorsal laminectomy (McKee 1992; Muir, Johnson, Manley,
et al 1995).

Further reports of excellent success with the hemilaminectomy technique were
published (Dhupa, Glickman, Waters, et al 1999; Ferreira, Correia, & Jaggy 2002; Macias, McKee,
May, et al 2002; Necas 1999; Scott 1997), including successful outcomes in dogs with absent
nociception (Anderson, Lippincott, & Gill 1991; Necas 1999; Scott & McKee 1999), and reported
use of dorsal laminectomy in the thoracolumbar spine declined.

It had been already recognized in human medicine that lateral and anterior approaches
to the spine where favourable as they required significantly less spinal cord manipulation (Fidler
& Goedhart 1984; Hulme 1960) when Braund et al (1976) reported a lateral approach to the
thoracolumbar spine, similar to Seemann’s (1968) lateral muscle-separation for fenestration,
with a lateral decompressive technique. The ‘lateral’ or ‘modified lateral decompressive
technique’ (Black 1988; Bitetto & Thacher 1987; Braund, Taylor, Ghosh, et al 1976; Yovich, Read,
& Eger 1994) has been more commonly referred to as the ‘mini-hemilaminectomy’, but also the
‘extended foraminotomy’ (McCartney 1997) or ‘pediculectomy’ (Brisson, Moffatt, Swayne, et al
A mini-hemilaminectomy removes the bone forming the pedicle adjacent to the intervertebral foramen cranially and caudally, including removal of the accessory processes. While most descriptions indicate that care should be taken to preserve the articular processes (Bitetto & Thacher 1987; Black 1988; Braund, Taylor, Ghosh, et al 1976; Jeffery 1988; Lubbe & Verstreate 1994; Yovich, Read, & Eger 1994), some also describe the dorsal limit as being dorsal to the accessory process (Jeffery 1988; Lubbe & Verstreate 1994). It is likely that in at least certain areas of the spine, such as the cranial lumbar vertebrae, this would involve some invasion of the ventral aspect of the articular process. It has been suggested that ‘mini-hemilaminectomy’ is a misnomer, as only pedicular bone is removed and the dorsal lamina and articular processes are preserved (Lubbe & Verstreate 1994). However, in the initial report by Braund et al (1976) it is suggested that the amount of bone removed is determined by the individual case, and thus the location of the extruded NP.

Braund et al (1976) cited that a mini-hemilaminectomy would result in less manipulation of the spinal cord, decreased surgical time, significantly less bone removal, and suspected that the decompressive effect would be similar to hemilaminectomy based on similar craniocaudal extents (Braund, Taylor, Ghosh, et al 1976). They noted that the technique had been performed successfully at their institution in a clinical trial of 20 dogs. Bitetto & Thacher (1987) evaluated the success of this technique in 8 dogs, but preferred a dorsolateral approach to the spine as they felt it would allow easier removal of additional bone should the lateral technique be insufficient. Long-term outcome was 100% successful (Bitetto & Thacher, 1987), with identical results reported shortly thereafter by Black (1988) and Jeffery (1988), in 39 and 7 dogs, respectively. All 3 three studies reported a decreased surgical time and a rapid return to recovery, but it should be noted that of 54 dogs only 1 had absent nociception (Black 1988). Further reports indicated recovery rates of over 90% using the dorsolateral approach for mini-

Partial pedicullectomy refers to the removal of pedicular bone from the middle of the vertebrae, sparing the pedicular bone adjacent to the intervertebral foramen (McCartney 1997), using either a dorsolateral or lateral approach. A primary advantage of the technique cited by McCartney (1997) is that it avoids the blood vessel associated with the attachment of the longissimus tendon, and the spinal nerve and vessels. While the technique is fast, spares the articular processes, and offers good access to the vertebral canal at the mid-body of the vertebrae, access to the vertebral canal is limited by the smaller window, which could increase the risk for residual material, and access to the intervertebral disc is more difficult (McCartney 1997; Sharp & Wheeler 2005). Indeed McCartney (1997) reported that of 27 dogs treated with partial pedicullectomy, 8 (29%) required extension of the technique to a mini-hemilaminectomy, as extruded material could not be sufficiently removed from around the intervertebral foramen.

Of the more recently described techniques, lateral or partial lateral corpectomy is achieved by creating a lateral slot in two adjacent vertebral bodies, centered on the intervertebral disc (Flegel, Boettcher, Ludewig, et al 2011; Moissonnier, Meheust, & Carozzo 2004). The limits of the lateral slot are ideally ¼ the length of both the cranial and caudal vertebral bodies, dorsal ½ of the vertebral body height, and ½ to ⅔ the depth of the vertebral body, and aligned perpendicular to the long-axis of the spine in the frontal plane. A dorsal, dorsolateral, or lateral approach to the spine can be performed (Moissonnier, Meheust, & Carozzo 2004).

The initial goal described for the partial lateral corpectomy was to minimize iatrogenic spinal cord trauma in cases of IVD protrusion and chronic (>3 weeks) IVD extrusions, which are located primarily in the ventral vertebral canal and can require substantial manipulation to
remove fibrous or adhered material (Flegel, Boettcher, Ludewig, et al. 2011; Moissonnier, Meheust, & Carozzo 2004). There are no published studies specifically evaluating the utility of the technique for acute IVD extrusions in dogs. Moissonnier et al (2004) report no significant complications in 15 dogs, with only 1 developing a seroma at the incision site, and all dogs improving post-operative. However, Flegel et al (2011) described incomplete decompression in 9% of partial lateral corpectomies (5 out of 60), all of which were located in the thoracic spine, immediate post-operative revision of the initial surgery in 19% of the procedures, and high technical difficulty. Other reported limitations of the technique are a lack of spinal cord visualization, inability to access compressions located laterally, and possible requirement for rib head exarticulation or rib resection to improve access in the thoracic spine (Flegel, Boettcher, Ludewig, et al. 2011; Moissonnier, Meheust, & Carozzo 2004). Moissonnier et al (2004) suggested the addition of a hemilaminectomy to improve visualization of the lateral vertebral canal in some cases, however a recent cadaver study identified an exacerbation of spinal instability compared to that a single partial corpectomy procedure (Reves, Burki, Ferguson, et al. 2012).

Success Rates and Limitations – Hemilaminectomy and Mini-hemilaminectomy

a direct comparison would be difficult, and no studies have been performed comparing the techniques. In all likelihood, the high success rate between both techniques has lessened the urge for a direct comparison.

As the articular processes are preserved and a minimal amount of lamina removed, it could be expected that a mini-hemilaminectomy would theoretically have less effect on the biomechanical properties of the spinal column, and could be extended across many adjacent vertebrae without an inherent effect on stability. The only published report in dogs assessing spinal stability following mini-hemilaminectomy compared lumbar spines with unilateral hemilaminectomy and concomitant fenestration, unilateral mini-hemilaminectomy and concomitant fenestration, fenestration alone, and unaltered controls, all under lateral bending; however, the authors did not provide a detailed description for any of the techniques (Hill, Lubbe, & Guthrie 2000). All surgical groups demonstrated significant alterations in stability when compared to the control group, with hemilaminectomy and concomitant fenestration having the greatest effect. Although mini-hemilaminectomy with fenestration had the least destabilizing effects, the difference compared to hemilaminectomy was not statistically significant (Hill, Lubbe, & Guthrie 2000).

The clinical relevance of these biomechanical studies can be debated for multiple reasons: the vertebral segments being assessed often differ; studies are often not comparing similar or multiple planes of loading; all studies have been performed in vitro without the combined effects of paravertebral musculature; and chondrodystrophic dogs are rarely included. Multisegmental vertebral units, composed of 3 or more consecutive vertebrae, are considered necessary to evaluate the biomechanical effects over several vertebrae and likely represent a more physiological conditions, but have only been evaluated in the more recent studies (Corse, Renberg, & Friss 2002; Hill, Lubbe, & Guthrie 2000; Smolders, Kingma, Bergknut,
et al 2012). Most published studies will concede that their chosen method of biomechanical testing is an over-simplification (Corse, Renberg, & Friss 2002; Hill, Lubbe, & Guthrie 2000). Lateral bending appears to adequately represent the contribution of the articular processes to spinal stability, as tensile forces to the dorsal vertebral compartment are maintained by the dorsal spinous, interspinous, and supraspinous ligaments (Hill, Lubbe, & Guthrie 2000; Smith & Walter 1988), and rotational stability is primarily provided by the IVD (Shires, Waldron, Hedlund, et al 1991; Smolders, Kingma, Bergknut, et al 2012). However, the canine spine has the most range of motion in extension and flexion (Smith & Walter 1988), an important mechanism in loading of the spine during locomotion, which is not considered in some studies. Though not assessed in dogs in vivo, the stability of the spine is likely also enhanced by the action of paravertebral muscles, as documented in humans (Wilke, Wolf, Claes, et al 1995).

The important contribution of the IVD to the stability of the spinal column is well-recognized (Hill, Lubbe, & Guthrie 2000; Schulz, Waldron, Grant, et al 1996; Shires, Waldron, Hedlund, et al 1991; Smolders, Kingma, Bergknut, et al 2012), with IVD fenestration the single most destabilizing factor in the report from Hill et al (2000). This should be considered when attempting to compare results between studies, especially as the extent of the incision into the AF may have an impact (Hill, Lubbe, & Guthrie 2000).

It was not until recently that the effect of chondrodystrophic IVD degeneration on spinal stability was investigated. Smolders et al (2012) compared multisegmental vertebral units from chondrodystrophic and non-chondrodystrophic dogs, and found a significantly increased range of motion in axial rotation compared to non-chondrodystrophic spinal columns. When surgically altered by fenestration and removal of the NP, range of motion was significantly worsened in the chondrodystrophic spines (Smolders, Kingma, Bergknut, et al 2012). These results call into question previous studies, as the study population is often healthy, non-chondrodystrophic dogs.
Despite this information, there are no confirmed cases of clinical failure due to instability from a unilateral hemilaminectomy or mini-hemilaminectomy, and clinical success following multiple adjacent hemilaminectomies has been reported in the literature (Tartarelli, Baroni, & Borghi 2005). A case of subluxation has been documented after a dog received bilateral mini-hemilaminectomy, bilateral pediculectomy, and fenestration (Arthurs 2009).

**Surgical Considerations for Prognosis**

Though the prognosis for return of ambulatory function for dogs with intact nociception is good with surgical decompression, it is not perfect, with many dogs retaining permanent deficits. Again, a successful recovery is considered if the patient regains the ability to ambulate, so many patients with a partial or incomplete recovery are included under the broad classification as success. There are several reasons for an incomplete recovery but it is unknown whether some of them could be more frequently associated to one surgical technique over another. Therefore, any particular aspect of the surgical technique that could alter the recovery should be investigated to promote as complete of a recovery as possible. Does preservation of the articular processes offer any advantage over removal, such as retained vertebral stability or reduced tissue trauma? Is the extent of bone removal correlated with long-term prognosis? Could excess bone removal cause detrimental effects to the healing spinal cord, or conversely, does increased bone removal result in increased decompression or significantly better access to extruded material? What effect can the heat and vibration produced by the use of a drill have on the spinal cord? And of importance, how effective is the evacuation of compressive material with surgery (Sharp & Wheeler 2005)? While it is expected that surgical expertise has some
influence, could removal of extruded material also be limited by the surgical approach? And if so, at what point is residual material considered clinically relevant?

To the date, no investigations into the differences between hemilaminectomy and mini-hemilaminectomy have been made, nor to the potential clinical impact of potential differences. With reports of similar success rates, these 2 techniques are the most frequently performed for the thoracolumbar spine, representing opposite ends of the spectrum of bone removal.
III.  ADVANCED IMAGING

As discussed previously, advanced diagnostic imaging is required for diagnosis, accurate lesion localization, and pre-surgical planning, with potential limited implications towards prognosis. MR imaging will be discussed further, but has been shown to be the most accurate pre-operative modality for intervertebral disc disease. Which modality is best suited for post-operative imaging however, revolves greatly around the clinical question, and is the basis for the following discussion.

Computed Tomography

Tomography is the depiction of a section of the patient free from superimposition of overlaying structures (Tidwell & Jones 1999). As conventional radiographs represent variations in tissue absorption of x-rays in a linear direction, physical structures are superimposed. Computed Tomography (CT) transmits x-rays through the patient, around a single axis of rotation, to detectors; the data is processed by a computer and creates the image as a slice, free of superimposition. The level of x-ray attenuation by a tissue can be measured and is expressed by a standard unit, the Hounsfield unit (HU), with zero being the attenuation of pure water (Tidwell & Jones 1999). CT has the advantage of obtaining thin slices, rapidly, with excellent spatial resolution (Tidwell & Jones 1999). Transverse images can be reformatted into other planes, and was shown to improve lesion localization accuracy prior to surgery (King, Jones, Rossmeisl Jr, et al 2009), though image quality may deteriorate (da Costa & Samii 2010). Bone detail is better on CT than soft tissue, with the normal spinal cord appearing of intermediate attenuation (mean 31 HU), contrasted laterally by hypoattenuating epidural fat, with notable less epidural fat over the vertebral bodies (Olby, Munana, Sharp, et al 2000).
Most CT units are capable of obtaining slices with thicknesses as thin as 0.625 – 1.5 mm. This reduces partial volume averaging and, when coupled with algorithms that apply edge-enhancing filters, and manipulation of window levels post-scanning to a wide window for high contrast structures, provides excellent spatial resolution of bone with measurements accurate within millimetres (Tidwell & Jones 1999). The boney anatomy of the vertebral column is depicted in great detail, including the laminae, pedicles, foramina, and articular processes. Cortical bone is best described as thin with uniformly high density, whereas cancellous bone tends to have a lacy or honeycomb appearance (Tidwell & Jones 1999). The bone detail provided by increased spatial resolution with CT is superior to conventional radiographs, which are subjected to superimposition of overlying tissues, and lack the ability to be obtained in transverse planes or with 3D reconstruction, as well as MRI, where the amount of data within the field of view is related to the degree of noise and often limits slice thickness to 2 – 3 mm (da Costa & Samii 2010; Tidwell & Jones 1999).

While spatial resolution is an advantage of CT when compared to MRI contrast resolution (the ability to identify separate tissues) is generally inferior. This is of particular importance in the vertebral column, where distinguishing between tissues such as the spinal cord parenchyma and vertebral ligaments often relies on contrast provided by the very hypodense epidural fat, which can be problematic if not present in adequate quantities (Tidwell & Jones 1999). Obtaining CT scans using a soft tissue algorithm and manipulating the images with a narrow window can enhance the detail of soft tissues, but rarely to that of MRI (da Costa & Samii 2010; Tidwell & Jones 1999). CT is also limited to acquiring images in the transverse plane, with further planes requiring computerized reconstruction that can result in a diminished image quality (da Costa & Samii 2010). While the rapid speed with which images can be acquired through CT offers a significant advantage for clinical patients, such as decreased anesthetic time.
or the ability to provide imaging under sedation and a reduction in motion artifacts, it is also accompanied by a greater dose of radiation to the patient when compared with conventional radiographs, and MRI, which does not emit ionized radiation (Tidwell & Jones 1999).

**Computed Tomography and Intervertebral Disc Disease**

CT images can be acquired after a myelogram as this can improve lateral localization, small volumes of contrast medium can be identified that otherwise may not be visible on radiographs, and the improved contrast resolution allows detection of mineralized NP and hemorrhage within the vertebral canal (Robertson & Thrall 2011). CT as the sole diagnostic modality avoids the adverse effects associated with myelography and requires less time, thus decreasing the length of time under anaesthesia (Olby, Munana, Sharp, et al 2000). The capability to identify mineralized NP and hemorrhage has been established through a case series that described the CT characteristics of 23 dogs with surgically confirmed thoracolumbar IVD extrusions (Olby, Munana, Sharp, et al 2000). They identified 3 groups of findings; acutely extruded, mineralized NP; acute extrusion of NP with hemorrhage; and chronic, mineralized NP. The first group of dogs had an acute onset of clinical signs, and a heterogenous, hyperattenuating (mean 219 HU) extradural mass was identified causing severe spinal cord compression, which was confirmed at surgery to be calcified NP. The second group of dogs also presented for an acute onset of clinical signs, and were found to have herniated material causing less compression, extending over multiple vertebral spaces, that was only slightly distinguishable from the spinal cord (mean 59 HU). This was confirmed at surgery to be mineralized NP admixed with hemorrhage. Spinal cord compression in both groups of dogs was characterized by loss of the hypoattenuating epidural space. The third group of dogs had a chronic history of less severe clinical signs, and the extruded NP was described as extremely
hyperattenuating (mean 745 HU) and more homogenous. One of these dogs had undergone a previous dorsal laminectomy, and residual IVD material was identified (Olby, Munana, Sharp, et al 2000).

Other studies have compared the sensitivity of CT to myelography and/or CT-myelography, for the identification of IVD extrusions in the thoracolumbar spine. A large retrospective study evaluated CT and myelography in 182 dogs of varying breed (Israel, Levine, Kerwin, et al 2009). Both methods had similar sensitivities, 81.8% for CT and 83.6% for myelography, though CT was statistically more sensitive at identifying lesions in chronically affected dogs and myelography was more sensitive for dogs weighing less than 5 kg (Israel, Levine, Kerwin, et al 2009). The increased sensitivity for smaller dogs is likely related to the higher incidence of chronic lesions in large breed dogs. Though the population of dogs was large, the two groups were disproportionate, they were enrolled by clinician’s preference for modality, and few dogs had both modalities performed. A lesion localization sensitivity of 94.7 – 100% and a lateralization sensitivity of 85.3 – 87.4%, depending on CT modality, were described in a prospective study of 19 dogs (Hecht, Thomas, Marioni-Henry, et al 2009). Each dog had both CT modalities performed as well as a myelogram, and sensitivities were similar between groups, leading the authors to conclude that CT is a reliable method in chondrodystrophic dogs with acute IVD extrusions (Hecht, Thomas, Marioni-Henry, et al 2009). Another prospective study compared 4 modalities, CT, CT angiography, myelography, and CT-myelogram, in dogs with cervical and thoracolumbar myelopathies (Dennison, Drees, Rylander, et al 2010). Conventional CT alone was capable of identifying all mineralized IVD extrusions, though it was not able to identify the associated spinal cord swelling noted with the other modalities, and was insufficient for identifying non-mineralized IVD extrusions. Overall sensitivity of conventional CT, which included multiple intradural and intramedullary lesions, decreased by 20% when mineralized
IVD extrusions were excluded; therefore CT was deemed insufficient in non-chondrodystrophic breeds (Dennison, Drees, Rylander, et al 2010).

The aforementioned studies compared results of imaging modalities to surgical findings, and this has been called into question by some authors for a high degree of bias, and inability to circumferentially explore the entire canal with standard laminectomy techniques (Naude, Lambrechts, Wagner, et al 2008; Schulz, Walker, Moon, et al 1998). Newcomb et al (2012) recently performed a prospective, blinded comparison of CT and myelography in 30 dogs, using CT-myelogram as the reference standard. Dogs were of various breeds, though predominantly chondrodystrophic, and only one patient had a lesion outside of the thoracolumbar spine. CT was found to be more sensitive than myelogram with a longitudinal and lateral localization accuracy of 91 and 94%, compared to 64 and 74%, and had less inter-observer variability (Newcomb, Arble, Roschat, et al 2012).

Based on these findings, most authors agree that conventional CT is at least comparable with myelography for the localization of IVD extrusions in chondrodystrophoid dogs, though it is should be undertaken with the acceptance that an additional myelogram may be required (da Costa & Samii 2010; Dennis, Drees, Rylander, et al 2010; Hecht, Thomas, Marioni-Henry, et al 2009; Israel, Levine, Kerwin, et al 2009; Newcomb, Arble, Roschat et al 2012; Olby, Munana, Sharp, et al 2000; Robertson & Thrall 2011). In the post-operative case, the excellent spatial resolution and superior bone detail (Tidwell & Jones 1999) would provide accurate assessment of boney margins, being particularly useful when examining the limits of laminectomy removal. However, its utility is restricted by the difficulty in differentiating extruded material from hemorrhage (Olby, Munana, Sharp, et al 2000; Roach, Thomas, Weh, et al 2012), reliance on reconstruction of images in planes other than the transverse with associated loss of image quality, and poor contrast resolution to delineate the spinal cord parenchyma from non-
mineralized NP without the aid of a myelogram (Dennison, Drees, Rylander, et al 2010; Olby, Munana, Sharp, et al 2000; Tidwell & Jones 1999). As some degree of hemorrhage within the vertebral canal is common in the period immediately post-operative, CT would not be the ideal imaging modality to accurately assess residual material. This is evident in the study by Roach et al (2012), in which the authors attributed residual volumes of greater than 100% as being due to an inability to differentiate hemorrhage from extruded material.

**Magnetic Resonance Imaging**

Magnetic resonance imaging (MRI) is also tomographic, as it produces images of tissue planes without superimposition from other tissues (Tidwell & Jones 1999). MR images are created by aligning the magnetic spin of protons within tissues using a magnetic field, and applying a radiofrequency to disrupt the alignment. The protons return to the original alignment and spin based on relaxation rates, termed T1 and T2 relaxation, and by doing so produce radio signals that can be received and processed by a computer (da Costa & Samii 2010; Tidwell & Jones 1999). Tissue contrast on the images is a function of different rates of relaxation amongst tissues. Different imaging sequences accentuate the T1 and T2 characteristics of tissues to generate images with different tissue contrast.

The superior degree of contrast resolution provided by MRI is beyond that of conventional radiographs and CT imaging. Manipulation of the various imaging characteristics of tissues allows the multiple anatomical structures within the vertebral column to be distinguished, including the supporting ligamentous structures, synovial joints, bone marrow, nerve roots, spinal cord parenchyma, cerebrospinal fluid, epidural fat, and the layers of the IVD (Tidwell & Jones 1999). Similarly, this also allows a high sensitivity and relatively high specificity for identification of pathological changes within the vertebral column, including inflammation,
edema, neoplastic changes, hemorrhage, and ischemia (Tidwell & Jones 1999). In addition to superior contrast resolution, the ability to obtain images in virtually any anatomic plane with no loss in image quality is a significant advantage over CT (da Costa & Samii 2010; Tidwell & Jones 1999).

Spatial resolution is limited by an increase in noise accompanied with any increases in the amount of data within the field of view (da Costa & Samii; Tidwell & Jones 1999). This can present an issue in veterinary patients, as the relatively small diameter of vertebral column in most dogs and cats paired with slice thicknesses of 3 mm can make it impossible to accurately distinguish the borders of some tissues, especially when pathological changes are present (da Costa & Samii 2010; Tidwell & Jones 1999). Other disadvantages of MRI include lengthy image acquisition times and requirement for longer anesthetic time, interference of metallic objects on imaging quality, and the potentially detrimental effects of metallic implants to the patient (da Costa & Samii 2010).

Magnetic Resonance Imaging and Intervertebral Disc Disease

Sether et al (1990) were able to correlate anatomical findings of experimental and naturally occurring IVD in canine cadavers with MRI, and demonstrated a loss of the normal T2-weighted hyperintensity of the NP with fibrosis and calcification, as well as observing changes in the sclerotic vertebral bodies and cartilaginous end-plates with chronic degeneration. MR findings were also consistent for the healthy IVD, with a hypointense AF surrounding a well-demarcated NP of comparable hyperintensity as the CSF (Sether, Nguyen, Yu, et al 1990). The hyperintensity of the NP is believed to be due to the proteoglycan content, and not the water or collagen content (Besalti, Pekcan, Sirin, et al 2008). Besalti et al (2008) reviewed MR images from 69 dogs with thoracolumbar IVD disease, and were able to describe findings similar to the
classification scheme used during that time in humans. Four categories of IVD disease were observed: IVD degeneration, characterized by variable loss of hyperintensity of the NP, which corresponded to 3 grades of degeneration observed in humans; bulging of the IVD characterized by diffuse, symmetrical, uniform extension of the outer margin symmetrically; protrusion of the IVD, characterized by asymmetrical extension with focal disruption of the annulus; and IVD extrusion if the NP had herniated through all layers of the AF and was evident as a focal epidural mass (Besalti, Pekcan, Sirin, et al 2008). MRI also allowed identification of the borders of the extruded material, spinal cord, and other soft tissue structures of the spine (Besalti, Pekcan, Sirin, et al 2008). Extruded NP was identified as a low signal intensity within the epidural space on T1- and T2-weighted images, and could be characterized as dispersed if it was not associated with the affected IVD space and spread throughout the epidural space, or non-dispersed if it remained in contact with the affected IVD as a ‘button-like’ protrusion. However, epidural hemorrhage associated with IVD extrusion can result in a wide range of signal intensities, so a diagnosis of IVD extrusion should not rely on one pattern of signal intensity (Mateo, Lorenzo, Faradada, et al 2011).

A prospective study of 16 Dachshunds with thoracolumbar IVD extrusion found 100% sensitivity for longitudinal and lateral localization with MRI, using surgery as the comparison standard (Naude, Lembrechts, Wagner, et al 2008). It was also determined that MRI provided a good estimate of the cranial and caudal limits of extruded NP to assist with surgical planning, and found the T2-weighted images to be the most accurate for assessing extruded NP. Gallach et al (2011) determined that the ability to assess the site of IVD extrusion based on the T2-weighted sagittal images alone, when compared to assessment of the entire MRI study, was approximately 90%, and of those incorrectly localized 55% were actually at the adjacent IVD space. Intravenous contrast is commonly used during MR imaging, as increased permeability of
the blood-spinal cord barrier can be identified by the presence of contrast within the spinal cord parenchyma. This is common with pathological conditions resulting in inflammation, and especially neovascularization of neoplasia, however, varying patterns of contrast enhancement are frequently observed with the extruded NP and should be taken into consideration (Freeman, Platt, Kent, et al 2012).

MRI offers superior contrast resolution of soft tissue structures, is extremely sensitive, can differentiate various categories of compressions, is available in multiple planes of section, can identify and differentiate hemorrhage, and has been shown to identify pathological changes within the spinal cord that can be associated with prognosis (Boekhoff, Flieshardt, Ensinger, et al 2011; da Costa & Samii 2010; Ito, Matsunaga, Jeffery, et al 2005; Levine, Fosgate, Rushing, et al 2009; Okada, Kitawaga, Ito, et al 2010; Platt, McConnell, Bestbier, et al 2006; Tidwell & Jones 1999). Of specific interest in the post-operative patient is the ability to differentiate hemorrhage from extruded NP, based on signal intensity and gradient echo and T2* characteristics (Mateo, Lorenzo, Faradada, et al 2011; Tidwell & Jones 1999). When attempting to quantify compressive material, MR has the advantage of providing better distinction of material from spinal cord parenchyma, better delineation of spinal cord parenchyma, and is not subject to the loss of image quality in other planes as is CT imaging. Unfortunately spatial resolution is reduced, with images slices being no thinner than 3.0 mm, contributing to volume averaging and in some inaccuracy to measurements. Despite this, MRI is the ideal modality to assess residual material as the superior contrast resolution allows accurate identification of extruded material and differentiation from hemorrhage and spinal cord parenchyma. Historically, MR imaging in the post-operative patient has been limited by availability, cost, increased anesthetic time, and limited information concerning the predictive value of identifying residual material.
It is evident that a gap exists in our current knowledge of IVD herniation, linking the pathogenesis and ability to accurately predict functional outcome. Despite greater than 83% of dogs with intact nociception recovering ambulatory function after surgical decompression (Bush, Tiches, Kamrad, et al 2007; Jeffery 1988; Lubbe & Verstraete 1994; Ruddle, Allen, Schertel, et al 2006), return to function is not guaranteed. With loss of ambulatory and urinary function often being devastating to the dog and owner, and few too many pre-operative predictors with an accurate sensitivity, it is therefore prudent that any factors which can be guided by our intervention be rigorously investigated.

Of these potential areas of investigation, the completeness of evacuating IVD material may be most under our control. The study by Roach et al (2012) was the first to report a large population of dogs with residual material using post-operative imaging, although this did not affect functional recovery. However, we must assume that some degree of residual material can affect recovery, as this has been previously reported (Dhupa, Glickman, Waters, et al 1999; Forterre, Gorgas, Dickomeit, et al 2010). Likely the volume of residual material, degree of residual spinal cord compression, and physiological state of the spinal cord parenchyma all influence the effect on recovery.

As the ability to evacuate extruded material is directly linked to the surgical approach and technique (Bitteto & Thacher 1987; Doppman & Girton 1976; Forterre, Gorgas, Dickomeit, et al 2010; Funkquist 1962a, c, d, 1970; McKee 1992), it would seem worthwhile to investigate any potential differences between the 2 most commonly utilized techniques for the thoracolumbar spine, hemilaminectomy and mini-hemilaminectomy. Hemilaminectomy should provide a greater window to visualize and access the vertebral canal, but there are known
benefits to patient morbidity associated with limited bone removal, as with mini-
hemilaminectomy (Bitetto & Thacher 1987; Braund, Taylor, Ghosh, et al 1976; Thome,
Zevgaridis, Leheta, et al 2005). How this may affect the surgeon’s ability to remove extruded
material has not been assessed in veterinary medicine. Indeed, Roach et al (2012) examined a
population consisting of entirely hemilaminectomies, and no large reports of post-operative
imaging following mini-hemilaminectomy have been published.

The first goal would be to describe the anatomical limits of each procedure, as this has
not been examined in a standardized manner, with only general descriptions of anatomical
landmarks being reported (Bitetto & Thacher 1987; Black 1988; Braund, Taylor, Ghosh, et al
1976; Jeffery 1988; Lubbe & Verstreate 1994; Yovich, Read, & Eger 1994). This could provide
insight into any physical limitations with either technique and give a better understanding to the
circumferential access available to the vertebral canal. As well, anatomical variation is present
amongst vertebrae, particularly between the thoracic and lumbar vertebrae, and this could
hinder the ability to conform to landmarks described for each technique. For this investigation,
CT is the best suited imaging modality, given the ability to create images with high bone detail
and spatial resolution (Tidwell & Jones 1999).

The second avenue of investigation would be to assess the completeness of evacuation
occurring with clinical cases receiving treatment via hemilaminectomy and mini-
hemilaminectomy. As post-operative imaging is not frequently performed, the true occurrence
of residual material is largely unknown, especially with the mini-hemilaminectomy technique.
While Roach et al (2012) reviewed a large population; this data may have been limited by their
use of CT, as even the authors suspected difficulty distinguishing extruded NP from post-
operative hemorrhage. Magnetic resonance imaging would seem the most appropriate modality
for this task due to its superior contrast resolution, ability to assess images in multiple planes
free of reconstruction techniques, and availability of sequences to assist in distinguishing hemorrhage (Tidwell & Jones 1999).


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CHAPTER II

Comparison of the access window created by hemilaminectomy and mini-hemilaminectomy in the thoracolumbar vertebral canal using computed tomography

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Keywords: Hemilaminectomy, Mini-hemilaminectomy, Intervertebral disc herniation, Computed tomography

Summary

Objectives: To describe standardized anatomical limits of each technique in the canine thoracolumbar spine, and report any observed differences in the access provided to the vertebral canal.

Methods: Hemilaminectomy and mini-hemilaminectomy were performed on opposite sides of the spine at T11-T12, T13-L1, and L2-L3 in 10 canine cadavers, and only mini-hemilaminectomies of the right-side in an 11th cadaver. Measurements of the vertebral canal height, defect height, and any dorsal and ventral remnants of the vertebral arch were obtained after computed tomography. Covariate analysis was used to compare measurements with surgical procedure, surgical site, and side of the vertebral column.

Results: Defect height was greater with hemilaminectomy due to a smaller dorsal remnant. As the height of the vertebral canal increased, the height of the defect actually decreased proportionally, and this was more prominent with mini-hemilaminectomy. A median of 7-20% of the vertebral canal height was not removed dorsally after mini-hemilaminectomy compared to 1-2% in hemilaminectomy. A 13-25% of the vertebral canal height was left ventrally in mini-hemilaminectomy and 11-27% by hemilaminectomy.

Clinical Significance: Potential for a restricted exposure of thoracolumbar lesions should be considered when located either in the ventral 11-27% of the canal height when performing either procedure or in the dorsal 7-20% of the canal height when a mini-hemilaminectomy is performed compared to the dorsal 1-2% height after hemilaminectomy. However, those findings are of limited clinical significance in most extrusions.
**Introduction**

Neurological diseases frequently require surgical intervention. Access to the vertebral canal is needed in neurosurgical conditions such as intervertebral disc (IVD) herniation, exploratory surgical procedures and resection of neoplastic lesions, granulomas, cysts, and hematomas. During spinal neurosurgery decompression involves removal of a portion of the vertebral bone and removal of space-occupying masses to alleviate ongoing compression of the spinal cord and nerve roots (1).

Intervertebral disc herniation is the most common cause of spinal cord dysfunction in dogs (1-3), particularly chondrodystrophic breeds, with the thoracolumbar spine most commonly affected (3-9). Due to unique anatomic features, such as presence of the intercapital ligament from T1 – T10, over 85% of thoracolumbar extrusions occur between the T11-L3 intervertebral disc spaces (10). Spinal cord decompression through removal of the extruded compressive disc material after gaining access to the vertebral canal is the treatment of choice for dogs showing neurological deficits and/or persistent or recurrent spinal pain, and with spinal cord compression identified on diagnostic imaging (1,2,10,11).

The two most common decompressive surgical procedures used for the thoracolumbar spine, hemilaminectomy and mini-hemilaminectomy (Fig 1), differ by their approach and access to the vertebral canal, and the amount of bone removed. Hemilaminectomy requires removal of one half of the vertebral arch, including the lamina, pedicle, and the articular processes on one side of the vertebrae, and it is typically performed through a dorsal approach to the spine (10,12-14). Mini-hemilaminectomy extends over the same length as the hemilaminectomy but preserves the articular processes by removing the pedicles adjacent to the intervertebral foramen but not the lamina. It is typically performed through a lateral or dorsolateral approach (10,12,15-20). This technique is also referred to by some authors as extended foraminotomy.
lateral spinal decompression (15-17,19), modified lateral hemilaminectomy (22), or pediculectomy (6,20). Proposed benefits for creating a smaller window are decreased soft tissue dissection, decreased surgical time, and a possible reduced impact on the regional biomechanical function and stability in vitro, particularly since articular processes are preserved, leading to less post-operative morbidity (10,12,15,20,23,24).

No direct comparison of the section of the vertebral canal accessed and the height of the lamina that is removed through these two surgical procedures has been accurately described. During pre-surgical planning, the exact location of the compression has to be considered and should guide the selection of a surgical approach. Ideally, the extent of the bone window to be created should be based on the location of the material to be evacuated. Nevertheless, many surgeons refer to described guidelines to create a “standard” hemilaminectomy or mini-hemilaminectomy defect to approach the vast majority of intervertebral disc extrusions and typically use one procedure over the other depending on preference and experience. Information regarding the exact anatomical landmarks of each procedure is available but is limited and variable (12-20). In the case of mini-hemilaminectomy, the dorsal limit of the defect is indicated only by stating that the diarthrodal joint is preserved (15-17,19,20), with only one report giving a more accurate boundary, that being the dorsal margin of the accessory process (18). However, removal of the accessory process has been also described (17,18). Generally, hemilaminectomy is indicated when the spinal cord is compressed by lesions in the lateral, dorsolateral, or ventrolateral aspects of the vertebral canal, while mini-hemilaminectomy in lesions confined to the lateral and ventrolateral aspects sacrificing access to the dorsal and dorsolateral canal (10,22).

Factors that could influence the ability to achieve the desired bone window, such as the longitudinal location within the thoracolumbar spine, should be considered during pre-surgical
planning; however few variables have been objectively assessed. For instance, if particular aspects of the thoracic vertebrae, such as the articulation with the rib head, visually or physically impede the ability to maintain anatomical landmarks during mini-hemilaminectomy, this could result in greater bone removal and negate the proposed advantages over a hemilaminectomy. While the goal of surgery is adequate removal of the compressive lesion, and this should be tailored to the individual patient (17), specific knowledge of these limits is required before any potential benefit can be conveyed.

Since specific quantitative data about the access provided by each of those two standard procedures is still missing, clear indications for either procedure cannot be made. For example, the benefit of creating a smaller surgical and bone window leading to less tissue dissection and less morbidity may not be outweighed by a decreased exposure and ability to remove the compressive lesion. For this reason, more accurate knowledge of the physical limits of each technique is necessary.

The objectives of this study were to describe standardized anatomical limits of each technique in the canine thoracolumbar spine and report any observed differences in the access provided to the thoracolumbar vertebral canal that could be considered during pre-surgical planning.

**Materials and Methods**

Eleven canine cadavers from animals euthanized for reasons unrelated to the study were utilized. The cadavers were obtained from a colony of research beagles and the study was approved by the University of Guelph Animal Use and Care Committee. Ten cadavers, weighing between 8 and 11 kg, had both hemilaminectomy and mini-hemilaminectomy procedures performed on opposite sides of the vertebral column at T11-T12, T13-L1, and L2-L3.
intervertebral sites. The side each procedure was performed on was alternated between cadavers to ensure an even number for the left and right sides. An eleventh cadaver had the mini-hemilaminectomy procedure performed on the right side, however the hemilaminectomies performed on the left side were one intervertebral site caudal to the areas of interest; only the data from the mini-hemilaminectomy were included in the analysis. All hemilaminectomies were performed by one surgeon (LG) and all mini-hemilaminectomies were performed by another surgeon (BB) with each surgeon using this procedure for routine clinical cases. Both techniques adhered to previous descriptions in the veterinary literature and clinical practice at our institution (10,12-14,16,17).

Hemilaminectomy was performed through a dorsal approach to the spinal column with the cadaver positioned in sternal recumbency (10,12-14). The dorsal midline incision was extended from T10 to L4, through the skin and subcutaneous tissues. A small incision through the thoracolumbar fascia and supraspinatous ligament was made just lateral to the spinous process of L4, on the side the hemilaminectomy was to be performed, and extended to T10 with Mayo scissors. Osteotomes were used for sharp dissection of the multifidus musculature at its insertion on the dorsal spinous processes. Correct orientation of the surgical sites was verified by visual identification of the rib heads and transverse processes of the lumbar vertebrae. The origin of the multifidus musculature to the articular processes and mamillary processes of T11-T12, T13-L1, and L2-L3 were released by sharp dissection with osteotomes, proceeding in a caudal to cranial direction around the facet. Lateral retraction was maintained with self-retaining Gelpi retractors, and the insertion of the longissimus musculature on the accessory process was incised. The articular processes were removed at the appropriate surgical sites with rongeurs. Hemilaminectomy was performed with a Hall’s pneumatic drill, with the margins being the base of the spinous process dorsally, ventral aspect of the intervertebral foramen.
ventrally, and the base of the adjacent articular facet both cranial and caudal. Only the outer margins were drilled, and once at the level of the periosteum the remaining vertebral arch was pulled away from the vertebral canal.

Mini-hemilaminectomy was performed through a dorsolateral approach with the cadaver positioned obliquely, midway between sternal and lateral recumbency with the affected side facing up (10,12,15,20). A skin incision was made approximately 2 cm lateral to dorsal midline, and extended from T10 to L4 through the subcutaneous fat and lumbo-dorsal fascia. The intermuscular plane ventral to the longissimus musculature was identified and bluntly dissected focally to allow palpation of the ribs and transverse processes of interest for identification of the correct surgical sites. Once the desired space identified, an incision was made through the longissimus muscles midway between the articular processes and the rib or transverse process using a #15 scalpel blade and the bony lamina identified. The lateral pedicles were cleared of soft tissues using a periosteal elevator and the tendinous attachment of the longissimus musculature was cauterized and sharply transected at the level of its insertion on the accessory process at each of the surgical sites exposing the desired intervertebral foramen. Any remaining soft tissue attachments were cleared off using a periosteal elevator and retraction was maintained with self-retaining Gelpi retractors during the procedure. Surgical exposure spanned a space dorsal to the level of the ribs or transverse processes, and ventral to the base of the articular facet. Cranially and caudally, the dissection extended to, but did not expose the adjacent intervertebral foramina. Mini-hemilaminectomy was performed using a Hall’s pneumatic drill. The accessory process that overlies the dorsal aspect of the foramen was first removed and this was used as the dorsal extent of the mini-hemilaminectomy. Ventral to this, the pedicle was drilled cranial and caudal to the intervertebral foramen over approximately 2/3 of the length of each vertebra. The ventral extent of the mini-hemilaminectomy was the
ventral aspect of the intervertebral foramen. Once exposed, the endosteum (inner periosteum) was removed using a 22 gauge needle with the tip bent at 90 degrees and a #11 scalpel blade to expose the vertebral canal over the entire length of the mini-hemilaminectomy.

The thoracolumbar spine was imaged in each cadaver with a helical computed tomography (CT) unit (1.25 mm slice thickness, 0.75 mm slice interval, small scan field of view, sharp reconstruction kernel, kV 120, mA 300). Scans were viewed and analyzed with DICOM viewing software (window width: 2400, window level: 400 Hounsfield units). Measurements were taken from the transverse slice most representative of the laminectomy defect, being the point of greatest defect height (Fig 2). The maximum height of the vertebral canal was measured (Fig 2, C) and a perpendicular line tool overlain. Defect height was defined as the length from the most dorsal and ventral limits of the remaining vertebral arch (Fig 2, D). A linear measurement was chosen to best represent the window created with each technique and provide a purely quantitative value. Further investigation of vertebral canal access would have been subjective, requiring interpretation of the surgeon’s line of site and the type of surgical instruments used to evacuate material.

To assess the relative dorsoventral position of the laminectomy window, the height of any remaining vertebral arch was measured, providing respective dorsal (Fig 2, A) and ventral markers (Fig 2, B). Dorsal and ventral remnants were defined as the height of the dorsal (lamina) and ventral (pedicle) aspects of the vertebral arch not removed during the laminectomy procedure. Therefore, complete unilateral access would be defined as 100% removal of one side of the vertebral arch, with no dorsal or ventral remnants. The dorsal and ventral remnants were measured at their maximum distance from the perpendicular line tool.

Four variables (vertebral canal, defect, dorsal remnant, and ventral remnant heights) were measured at each surgery site. A total number of 252 measurements were taken. Each
measurement was repeated and recorded 3 times, resulting in a total of 756 measurements.

Three-dimensional reconstructions were created and assessed subjectively for uniformity. All measurements were performed individually by a single reviewer (JH). All measurements were linear, reported in millimeters, and maintained parallel to the sagittal axis using angles reported by the software program. To control for variation in vertebral canal size, the measurements defect height, dorsal remnant, and ventral remnant were later expressed as percentages of the vertebral canal height at the site of measurement.

When it was observed that the articular processes had been invaded at a mini-hemilaminectomy site, the dorsoventral height of the articular processes was measured at its smallest point within the cranial and caudal boundaries of the mini-hemilaminectomy defect. Given the lack of contralateral articular processes due to concurrent hemilaminectomy, the ipsilateral articular processes of the immediately caudal intervertebral disc space served as a control; the articular processes height missing was expressed as a percent of the articular process height compared to the caudal control.

Statistical Analyses

The data was collected in the form of a split-plot design, with each animal receiving a particular technique (whole-plot factor) and being split into a 2-factor factorial with the 2 factors side and site (split-plot factors); also, there was sub-sampling, which allows a measure of repeatability to be assessed. Each animal constituted a random blocking variable, while technique, side and site are fixed effects variables. In addition, there was the covariate of canal height. The response measures may be related to this covariate. The covariate was entered into the model as a linear fixed effect as well as a quadratic effect. All 2-term interactions were
included (along with the covariate and quadratic covariate) in the model to start, and then non-
significant terms removed.

To analyze the data, a General Linear Mixed Model was employed using Proc Mixed in
SAS. To assess the ANOVA assumptions, the residuals were formally tested for normality using
the four tests offered by SAS (Proc UNIVARIATE): Shapiro-Wilk, Kolmogorov-Smirnov, Cramér-
von Mises and Anderson-Darling tests. Data for the ventral remnant measure fit normality, so a
log transformation with an added constant of 0.01 was applied. The residuals were also plotted
against the predicted values as well as all explanatory variables (animal, side, site, technique,
and canal height). A p-value of less than 0.05 was considered statistically significant.

Results

The observed differences in results varied with the covariate vertebral canal height. To
trend this difference estimated means were calculated for the smallest recorded vertebral canal
height (6.8 mm), the median canal height (7.9 mm), and the largest vertebral canal height (9.5
mm), with all reported results representing the estimated least squares means and confidence
interval (CI). Results are summarized in table 1.

For mini-hemilaminectomies, estimated mean defect height was 75% (71-79) of the
vertebral canal height at the smallest canal (6.8mm height), 67% (64-69) at the median canal
(7.9mm), and 58% (55-61) at the largest canal (9.5mm). For hemilaminectomies, estimated
mean defect height was 87% (83-91) of the canal at the smallest canal height, 81% (79-84) at the
median canal height, and 76% (72-79) at the largest canal. Therefore, about 58-75% (estimated
mean range) of the vertebral canal height was removed by mini-hemilaminectomies while 76-
87% by hemilaminectomies.
A statistically significant difference was observed in the laminectomy defect height between hemilaminectomy and mini-hemilaminectomy, and this was consistent at all vertebral canal heights. At the smallest canal height there was an estimated mean difference of 12% in defect height between surgical techniques (CI 4-20%; p < 0.0001), at the median canal height a 14% mean height difference (CI 10-20%; p < 0.0001), and at the largest vertebral canal height a 18% height difference (CI 11-24%; p < 0.0001). There was no effect of surgical site or side on defect height. However, the proportion of vertebral arch removed with both surgical techniques (defect height as a percentage of the vertebral canal height) significantly decreased with larger vertebral canals (p < 0.0001). This inverse relationship was greater for the mini-hemilaminectomy compared to the hemilaminectomy (p < 0.0001).

Dorsal remnant height (as estimated mean and CI) in the mini-hemilaminectomy group was 7% (5-10) of the vertebral canal height for the smallest canal height, 13% (12-15) in the median canal, and 20% (17-22) in the largest canal. In the hemilaminectomy group, dorsal remnant height was 1% (2-4) of the vertebral canal height for the smallest canal, 2% (0-3) in the median canal, and 2% (0-5) in the largest canal. Roughly, 7-20% of the vertebral canal height was not removed dorsally by mini-hemilaminectomy and 1-2% by hemilaminectomy. The difference observed in the height of the dorsal remnant between mini-hemilaminectomy and hemilaminectomy was also statistically significant at all vertebral canal heights (p < 0.0009 – 0.0001). No effect of surgical site or side was observed.

Regarding mini-hemilaminectomies, estimated ventral remnant height for the smallest, median, and largest vertebral canal heights were, respectively, 13% (10-17), 17% (14-22), and 25% (19-32) of the corresponding vertebral canal height. In the hemilaminectomies, ventral remnant heights were 11% (8-14), 14% (11-18), and 20% (15-27) of the vertebral canal height for, respectively, the smallest, median, and the largest canal height. Approximately, 13-25%
(estimated mean range) of the vertebral canal height was not removed ventrally by mini-hemilaminectomy and 11-27% by hemilaminectomy. The ventral remnant height difference was not statistically significant between surgical techniques, or surgery site, but was significantly different between the left and right side of the vertebral column. This observation was only significant with the smaller vertebral canal height (p = 0.0097), and not the median or largest canal height. For the smallest canal height the ventral remnant was larger on the left side compared to the right (1.09 mm or 16% of the vertebral canal height; CI: 0.75 – 1.43 mm, 11 – 21%).

In 18 of the 33 mini-hemilaminectomy sites (55%), the most ventral aspect of the articular processes was at least partially invaded. When the articular processes height at the mini-hemilaminectomy site was expressed as a percent of the articular processes height caudal to the procedure, a mean of 22% was removed with a range of 4-41%. Observations were too few to allow statistical analysis, however no obvious trends were observed between any of the remaining variables (vertebral canal height, intervertebral site, and vertebral column side), or the size of the cadaver, to account for the difference.

**Discussion**

While retrospective studies of both procedures show similar high clinical success rates (19,25-30), no direct comparison of the access window created by each procedure has been made. The results of this study showed that approximately 58-75% (estimated mean range) of the vertebral canal height was removed through minihemilaminectomy, while 76-87% was removed by hemilaminectomy. As expected, the larger defect created in a hemilaminectomy procedure was due to greater removal of bone dorsal to the intervertebral foramen (10,12), but no significant difference in the amount of bone removed ventrally was detected.
The difference in the amount of remnant vertebral arch over the dorsal vertebral canal between surgical techniques ranged from 6 to 18% of the vertebral canal height, or 0.43 – 1.62 mm, meaning that 7-20% of the vertebral canal height was not removed dorsally by mini-hemilaminectomy while 1-2% of the dorsal vertebral canal was left by hemilaminectomy. The clinical relevance of this finding has no significance for lesions located in the ventral, ventrolateral, or lateral vertebral canal, and likely of little significance for dorsolateral compressions considering most surgical instruments used to explore the vertebral canal have a curved tip with a length greater than 1 – 2 mm that can access this area. In contrast, access to the central dorsal and opposite dorsolateral vertebral canal would likely be impeded without substantial manipulation of the spinal cord. This is not often the case with most IVD herniations, as the majority are located in the ventral, ventrolateral, or lateral vertebral canal. Moreover, while greater removal of the vertebral arch with a hemilaminectomy could theoretically provide a more adequate physical window to relieve pressure to the spinal cord, it is well accepted that laminectomy alone without evacuation of the compressive lesion does not provide sufficient decompression (31,32). However, these results should still be considered during pre-surgical planning since visualization and access to lesions in the most dorsal 7-20% height of the vertebral canal could be more challenging with mini-hemilaminectomy compared to hemilaminectomy. That could be the case when dealing with intramedullary or intradural lesions, or even extradural non-disc associated lesions (neoplasia or synovial cyst) where exposure of the whole lesion is more necessary compared to purely acute disc extruded material to improve the ability to address them and to avoid further iatrogenic spinal trauma. Similarly, this greater exposure could also be desirable in more solid or chronic IVD extrusions with possible adhesion of disc material.
Although the authors expected that the ventral remnant height would be minimal or absent for both procedures, this measure ranged 13-25% of the vertebral canal height in minihemilaminectomies and 11-27% in hemilaminectomies, similar to and even exceeding the dorsal remnant height in the case of mini-hemilaminectomies. A potential explanation for those findings is that the measurement of vertebral canal height extends ventrally on midline to the dorsal surface of the vertebral body, and thus enters the vertebral gutter, including some aspect of vertebral body in the measurement when taken at the most lateral aspect of the vertebra. This would be especially true in the lumbar vertebrae where the dorsal surface of the body is slightly concave. This means that extending the laminectomy to the bottom of the canal would involve invasion of the rib head, transverse process and vertebral body in most cases.

Nevertheless, this finding needs to be kept in mind as material located in the most ventral 11-27% height of the vertebral canal could not be directly exposed with either surgical procedure, although it could likely be accessed with the appropriate instrumentation. Consequently, other procedures providing a better access to the ventral canal floor, such as partial lateral corpectomy, could be more desirable in chronic IVD protrusions, since those are frequently located in the ventral midline, and are typically associated with adhesions (33). Anecdotally, there is often a tendency for surgeons to create an excessively dorsal hemilaminectomy defect, resulting in a larger ventral remnant which can lead to incomplete evacuation of residual IVD material or even an inability to identify a ventral compression. This is likely to occur due to the more sternal positioning of the patient and dorsal approach to the vertebral column, and perceived notion of avoiding hemorrhage from laceration of the paired vertebral sinuses. Although this was not identified in our study, it must be taken into consideration during pre-surgical planning, as the majority of IVD extrusions are located in the ventral and ventrolateral
spinal canal, and such an approach would eliminate the advantages of performing a hemilaminectomy over a mini-hemilaminectomy.

Of particular interest is the finding of a decreasing overall defect height with increasing vertebral canal height, and that it was not equal between the two techniques. One theory for the disproportionate removal of bone with increasing vertebral canal height is that larger anatomy (size) provides a better visualization of anatomical limits, and that these limits are not as accurately adhered to with a smaller patient leading to more invasion of the ventral aspect of the articular facets during mini-hemilaminectomy. Another hypothesis is that larger dogs might have a disproportionately smaller amount of articular process overlying the dorsal aspect of the vertebral canal. Although no trends in the occurrence or proportion of articular process invasion were observed in relation to the size of dog or vertebral canal height that would support this, a larger population of cadavers with more size variations would likely to be required to identify such a difference. Though the exposure of the dorsal vertebral canal was proportionally greater in a larger dog with a hemilaminectomy technique in this study, this is of unknown clinical significance.

The remaining variables did not demonstrate a significant impact on exposure of the vertebral canal, and would therefore appear to have little effect on pre-surgical planning. No effect of intervertebral site was observed, suggesting that one procedure cannot be specifically recommended over the other at any one disc space along the thoracolumbar vertebral column.

The finding of an effect of the side the surgery was performed on was only identified for the ventral remnant of the smallest vertebral canal height; a greater number of cases may be required to further investigate a difference; however this is unlikely to be clinically significant. A subjective observation is that right-handed surgeons tend to be more comfortable with an approach to the left-side of the vertebral column. It is interesting that although both surgeons in
this study were right-handed, the left side actually had the larger ventral remnant. Perhaps the right side was over drilled along the ventral aspect due to having a different exposure or access. Alternatively, the angle obtained from the left sided approach may provide as good visualization through a smaller approach which could explain the difference.

While surgical time was not assessed in this study, the reduced requirement for soft tissue exposure and for bone removal with a mini-hemilaminectomy should reduce the overall surgical time and perhaps post-operative morbidity (10,12,20). Decreased bone removal is associated with lower morbidity in humans (23,24). In fact, mini-hemilaminectomies and other techniques such as microdiscectomy are preferred in people in order to limit the amount of bone removed where possible (34).

Formation of a laminectomy membrane, a constrictive, fibrotic scar that covers the previous laminectomy defect, is a reported cause of surgical failure in humans, though only rarely reported in dogs (35). An actual occurrence rate for laminectomy membrane formation in the thoracolumbar spine has not been documented in dogs, with only 3 confirmed cases following dorsal laminectomy (36). Formation of a laminectomy membrane has been associated with surgical techniques that remove large sections of the vertebral lamina exposing the spinal cord beyond the level of the bone. Given the smaller size of the mini-hemilaminectomy defect laminectomy membrane formation would theoretically be more likely to occur with a hemilaminectomy, especially with excessive removal of bone dorsally, although this has not been investigated and it does not appear to be a clinical problem (10). However, the potentially increased risk of laminectomy membrane formation is one of the reasons why many surgeons cover hemilaminectomy defects with a fat graft or gelatin sponge prior to surgical closure while mini-hemilaminectomy defects are left uncovered. Fat grafts and other materials left at the
laminectomy site have also been associated with spinal cord compression and have the potential to cause postoperative complications (35,37).

Another potential concern associated with larger bony defects created during hemilaminectomy is the potential for low grade spinal instability that could lead to higher morbidity (10). Overt spinal instability could be a concern if a hemilaminectomy is extended more than three consecutive articulations, if a bilateral procedure is required or in active large-breed dogs where the number of consecutive hemilaminectomies that can be performed in one patient is potentially very limited (1,38). Although the removal of articular processes has been shown to have minimal effects on lateral bending in normal dogs, a significant effect has been reported in rotation, especially when combined with disk fenestration (39-41). Moreover, hemilaminectomy results in a significant increase in vertebral range of motion (11%) with some authors suggesting that could result in adverse effects on a spinal cord that is already injured (42). These factors have been contemplated as being potentially more clinically relevant in large-breed dogs and could be associated with a reportedly higher morbidity and lower surgical success compared to small-breed dogs (43,44). For that reason, preserving as much of the articular processes as possible through a mini-hemilaminectomy procedure would be particularly desirable in large-breed dogs.

Although a significantly smaller amount of dorsal remnant was identified with the hemilaminectomy technique, 55% of the mini-hemilaminectomies in this study had some degree of invasion of the base of the articular processes. While the majority of reports describing the mini-hemilaminectomy technique state that care is taken to preserve the articular processes (15,16,18-20), to the author’s knowledge no study has assessed the ability of this technique to spare their involvement entirely. Some descriptions include the dorsal limit of the mini-hemilaminectomy window being just dorsal to the accessory process (21), which would suggest
that at least a portion of the articular processes would be inevitably encroached, at least in a small dog. In fact some authors suggest removal of vertebral arch dorsal to the intervertebral foramen should vary according to the location of extruded material with each individual case (17); thus a mini-hemilaminectomy is likely to encroach on the base of the articular processes in some cases and the effect of such an invasion on stability is not known. Regardless, none of the mini-hemilaminectomies extended beyond the level of the hemilaminectomies in this study. Unfortunately, measurements of the articular processes required use of the adjacent segments for controls and may not have been entirely accurate, therefore the degree of invasion could have been over or underestimated. Pre-operative imaging would have allowed more accurate assessment but was unavailable.

One of the main limitations of this study was the involvement of only 2 surgeons, each performing different techniques as per their clinical practice. Limiting each surgeon to 1 technique was chosen to prevent inadequate or inappropriate vertebral canal exposure from surgeons attempting a technique they were not as familiar or comfortable with. However, we cannot argue that these results are not a direct comparison of the two surgeons in question. Ideally this variable would be removed by including more surgeons, but would require a much larger number of cadavers.

The Hawthorne effect, a well described phenomenon in human literature, is suggested to occur when a study participant’s behavior and results are altered by their awareness of being monitored or included in a study, and may even have more influence on outcome measures than the placebo effect (45,46). As neither of the surgeons in our study were blinded to the inclusion of cadavers, and randomization did not occur, we cannot exclude the influence this may have had on the laminectomy created.
In addition, the procedures were performed on cadavers in a controlled environment, and did not take into account variation provided by clinical cases in a clinical scenario such as the location and extent or herniated disc material, hemorrhage and the presence of a normal spinal cord; the purpose of the study was to document the access to the vertebral canal for both surgical techniques, and report any observed differences that may contribute to pre-surgical planning. A prospective study utilizing clinical cases would be necessary to assess post-operative morbidity and potential influence of intra-operative hemorrhage on visualization. Cadavers were chosen to provide greater control over anatomical variability, allowing multiple surgical sites to be assessed bilaterally along the longitudinal axis of the vertebral column in a single dog.

An additional limitation of this study may have been the choice of using the transverse image with the greatest defect height for measurements, as this could have resulted in underestimation of dorsal and ventral remnants, and subsequent overestimation of defect height. However, 3D reconstructions were evaluated and determined the laminectomy windows to be relatively consistent in height across their length.

In conclusion, this study described the anatomical limits provided by hemilaminectomy and mini-hemilaminectomy techniques in the thoracolumbar spine. The study found that removal of the dorsal vertebral arch was significantly different between techniques, and actually decreased disproportionately with increasing vertebral canal height, while a difference in the degree of removal of the most ventral vertebral arch was not found. A potential limited exposure and visualization of thoracolumbar lesions located in the dorsal 7-20% of the spinal height after mini-hemilaminectomy compared to the dorsal 1-2% after hemilaminectomy, and a restricted exposure of the most ventral 11-27% vertebral canal height after either of the two procedures should be considered. However, the difference in the exposure of the most dorsal
vertebral canal is of unknown clinical significance, and probably little in the case of most acute
disc extrusions. To the authors’ knowledge this is the first report of such findings.
Footnotes

a. LightSpeed Quadslice Helical Scanner, General Electric, Milwaukee, WI, USA

b. Advantage Workstation, version 4.2, General Electric, Milwaukee, WI, USA

c. SAS, version 9.2, SAS Institute Inc., Cary, NC, USA
References


32. McKee WM. Comparison of hemilaminectomy (with concomitant disc fenestration) and dorsal laminectomy for the treatment of thoracolumbar disc protrusion in dogs. Vet Record 1992; 130:296-300.


Figure 1. 3D reconstruction from a CT of a canine thoracolumbar spine demonstrating left-sided hemilaminectomies (A) and right-sided mini-hemilaminectomies (B) at T11-T12, T13-L1, and L2-L3.
**Figure 2.** Transverse CT image at the point of greatest dorsoventral defect height for a right-sided mini-hemilaminectomy at T11-T12. Measurements demonstrated are dorsal remnant (A), ventral remnant (B), vertebral canal height (C), and defect height (D). A concurrent left-sided hemilaminectomy has also been performed.
Table 1. Estimated differences and confidence interval for defect height and dorsal remnant height between techniques. Results are presented in mm and as percentage of the height of the vertebral canal. Mini-hemi = mini-hemilaminectomy, Hemi = hemilaminectomy.

<table>
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<th>Vertebral Canal Height (mm)</th>
<th>Defect Height (mm)</th>
<th>Dorsal Remnant (mm)</th>
<th>Ventral Remnant (mm)</th>
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<tr>
<td></td>
<td>Mini-hemi</td>
<td>Hemi</td>
<td>Mini-hemi</td>
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<td>6.8</td>
<td>5.12 (4.86-5.39)</td>
<td>5.91 (5.64-6.17)</td>
<td>0.50 (0.33-0.68)</td>
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<td>75% (71-79)</td>
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<td>7% (5-10)</td>
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<td>7.9</td>
<td>5.28 (5.09-5.47)</td>
<td>6.42 (6.23-6.62)</td>
<td>1.05 (0.94-1.17)</td>
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<td>81% (79-84)</td>
<td>13% (12-15)</td>
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<tr>
<td>9.5</td>
<td>5.51 (5.18-5.84)</td>
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<td>58% (55-61)</td>
<td>76% (72-79)</td>
<td>20% (17-22)</td>
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CHAPTER III

COMPARISON OF RESIDUAL DISC MATERIAL FOLLOWING HEMILAMINECTOMY AND MINI-HEMILAMINECTOMY IN DOGS WITH THORACOLUMBAR DISC EXTRUSION THROUGH MAGNETIC RESONANCE IMAGING

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This manuscript represents a portion of a thesis submitted by Dr Huska to the University of Guelph Department of Clinical Studies as partial fulfillment of the requirements for a Doctor of Veterinary Science degree.

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The authors would like to acknowledge Jennifer Collins and Alice Daw for their technical assistance, and Roberto Poma for his clinical insight.
**Objectives:** To investigate the presence of residual material following surgical decompression in spontaneous canine thoracolumbar intervertebral disc (IVD) extrusion, and compare findings between hemilaminectomy and mini-hemilaminectomy.

**Animals:** Nineteen, prospectively recruited, client-owned dogs.

**Procedures:** Surgical decompression for thoracolumbar IVD extrusion was performed through hemilaminectomy or mini-hemilaminectomy. The volume of extruded IVD material within the vertebral canal and the proportion of residual material were determined using pre- and post-operative MRI. A covariate analysis was performed to compare measurements with the surgical technique, surgical site, and side of the vertebral column.

**Results:** Residual material was identified in 100% (10 of 10) of the hemilaminectomies and 44% of the mini-hemilaminectomies (4 of 9). The median estimated volume of residual material was 25.8 mm$^3$ (CI: 13.5 – 49.4 mm$^3$) with hemilaminectomy, and 9.3 mm$^3$ (CI: 4.7 – 18.4 mm$^3$) with mini-hemilaminectomy, or 13.6% and 7.7% of the pre-operative volume, respectively. This difference was not statistically significant.

**Conclusions and Clinical Relevance:** Residual material can be present after decompressive surgery with both the mini-hemilaminectomy and hemilaminectomy techniques.
Abbreviations

CI – Confidence Interval

CT – Computed Tomography

IVD – Intervertebral Disc

MRI – Magnetic Resonance Imaging

Introduction

Intervertebral disc extrusion is a common cause of progressive spinal cord dysfunction in dogs,1-3 particularly chondrodystrophic breeds,3-5 with 85% of cases affecting IVDs between T11-L3.1-9 Surgical decompression of the spinal cord through removal of extruded compressive IVD material is the treatment of choice for dogs with neurological deficits and/or persistent or recurrent back pain.1,2,9,10 A successful recovery, defined as return of ambulatory function, has been reported to range between 83 – 100% after surgical decompression in patients with intact nociception;11-14 however this is considerably less in dogs with absent nociception with most reports citing recovery rates less than 50%.13,15-19 Although the prognosis for return of ambulatory function in those dogs lacking nociception is guarded to poor, it can occur.20 However an incomplete recovery, being a lack of improvement or even progressive deterioration, has been reported in dogs with intact nociception in spite of apparently adequate surgical decompression.11-14,21 Potential causes for the latter include progressive myelomalacia,21,22 progression of secondary spinal cord injuries,23 iatrogenic spinal cord trauma,9 low-grade instability of the vertebral column,9 post-operative infection,24 formation of a compressive hematoma,21,25 further extrusion of IVD material,7,25 and inadequate evacuation of extruded IVD material.21,25
Successful clinical recovery is defined as a patient recovering ambulatory function and not suffering further neurological deterioration. Recovery therefore includes a wide range of neurological grades ranging from significant paresis and ataxia while retaining the ability to walk, to complete recovery with no neurological deficits. Since post-operative imaging studies are not routinely carried out after surgery, it is not possible to confirm whether an incomplete recovery is due to the presence of residual extruded material. It is widely accepted that even with accurate pre-surgical planning, surgery performed at the correct location, and the perceived completeness of evacuation by an experienced surgeon, residual material can still be present in the vertebral canal following decompressive surgery. In fact, a recent study identified residual material in all 40 dogs that recovered ambulatory function and were imaged after hemilaminectomy. This provides an interesting avenue for investigation as any potential to improve evacuation of extruded IVD material, whether that is more inherent with one particular surgical technique than another, could lead to further improvement in post-operative recovery.

Although no direct comparison has been made between hemilaminectomy and mini-hemilaminectomy, the two most common decompressive surgical procedures used for the thoracolumbar spine, retrospective studies show similar high success rates for return to ambulatory function in dogs with IVD herniation and intact sensory function. The two decompressive procedures differ by their approach and access to the vertebral canal. Hemilaminectomy requires removal of one half of the vertebral arch, including the lamina, pedicle, and the articular processes on one side of the vertebrae. Mini-hemilaminectomy extends over the same length as the hemilaminectomy but preserves the articular processes by removing the pedicles adjacent to the intervertebral foramen but not the lamina, therefore removing the portion of the vertebral arch ventral to the articular processes.
technique is also referred to by some authors as extended foraminotomy, lateral spinal decompression, modified lateral hemilaminectomy, or pediculectomy.

Proposed benefits of removing less bone with mini-hemilaminectomy are decreased soft tissue dissection, decreased surgical time, a possible reduced impact on the regional biomechanical function and spinal stability in vitro (particularly since the articular processes are preserved), and therefore reduced post-operative morbidity. In contrast, the smaller window created with the mini-hemilaminectomy may reduce access to the dorsal and dorsolateral vertebral canal and could lead to a potentially greater tendency for hemorrhage when working around the foramen that could further decrease exposure. The effect this may have on the ability to evacuate extruded IVD material has not being investigated yet. Moreover, there are no published reports with post-operative imaging documenting the incidence of residual material following mini-hemilaminectomy.

The objectives of this study were to investigate through MRI the presence of residual material in dogs suffering spontaneous thoracolumbar IVD extrusion after surgical decompression, and compare the completeness of evacuation of extruded IVD material between two surgical techniques, hemilaminectomy and mini-hemilaminectomy. It was hypothesized that residual material would be present with both procedures, and that this difference would not be significant.

Materials and Methods

Dogs with spontaneous thoracolumbar (T10-L3) IVD extrusion diagnosed on MRI were prospectively recruited and assigned to hemilaminectomy or mini-hemilaminectomy surgery group based on surgeon (BB, LG) availability, without randomization. A post-surgical MRI was performed within 24 hours of surgery. Informed client consent was obtained, and the study was
approved by the Animal Care Committee of the University of Guelph. Visual confirmation of the presence of extruded IVD material at the surgical site was required for patients to be included. Exclusion criteria were presence of previously identified neurological disease and deficits unrelated to the present episode, and/or orthopedic disease. Neurological examination was performed immediately prior to surgery, within 72 hours following surgery, and at 4 – 6 and 12 – 16 week rechecks. The pelvic limbs were each graded based on a previously validated modified version of the Texas Spinal Cord Injury Scale (Table 1).42

All hemilaminectomies were performed by one surgeon (LG) and all mini-hemilaminectomies were performed by another surgeon (BB) with each surgeon being familiar with this procedure as it was their procedure of choice for routine clinical cases. Both techniques adhered to previous descriptions in the veterinary literature and to clinical practice at our institution.9,30-33 Fenestration of the affected IVD was performed in all cases.

Hemilaminectomy was performed through a dorsal approach to the spinal column with the dog positioned in sternal recumbency.9,30-37 Osteotomes were used for sharp dissection of the multifidus musculature at its insertion on the spinous processes and the origin of the multifidus musculature to the articular processes and mamillary processes; the articular processes were removed at the appropriate surgical site with rongeurs. Hemilaminectomy was performed with a Hall’s pneumatic drill, with the margins being the base of the spinous process dorsally, the ventral aspect of the intervertebral foramen ventrally, and the base of the adjacent articular facet both cranial and caudal. Prior to closure, absorbable gelatin sponge was routinely placed ventral to the spinal cord and covering the laminectomy defect in all cases.

Mini-hemilaminectomy was performed through a dorsolateral approach with the dog positioned obliquely.9,30,33,37 The intermuscular plane ventral to the longissimus musculature was identified and bluntly dissected to allow palpation of the ribs and transverse processes of
interest for identification of the correct surgical sites. Once the desired space identified, an incision was made through the longissimus muscles, the lateral pedicles were cleared of soft tissues using a periosteal elevator, and the tendinous attachment of the longissimus musculature was sharply transected at its insertion on the accessory process at the surgical site. Exposure was maintained by retracting soft tissues with Gelpi retractors. Mini-hemilaminectomy was performed using a Hall’s pneumatic drill. The accessory process that overlies the dorsal aspect of the foramen was first removed and it’s most dorsal margin was used to determine the dorsal extent of the mini-hemilaminectomy. Ventral to this, the pedicle was drilled cranial and caudal to the intervertebral foramen over approximately 2/3 of the length of each vertebra. The most ventral extent of the mini-hemilaminectomy was the ventral aspect of the intervertebral foramen. Absorbable gelatin sponge was placed ventral to the spinal cord in two cases to control sinus hemorrhage and was left in place post-operatively.

The following image sequences were obtained with a 1.5 Tesla MR unit while dogs were in dorsal recumbency: T1-weighted, T2-weighted, and T2* in the transverse plane, and T2-weighted and T2-weighted myelogram in the sagittal plane. Images in the transverse plane were obtained across the extent of the laminectomy defect with a 3.0 mm slice thickness and 0.2 mm slice gap. Sagittal images were obtained across the length of the thoracolumbar spine and the width of the vertebral column, with a 3.0 mm slice thickness and 0.2 mm slice gap. If residual material was noted within the vertebral canal extending past the cranial and caudal limits of the laminectomy defect on the post-operative sagittal images, further transverse sequences were obtained.

The MR was reviewed and analyzed with DICOM viewing software. Measurements were performed by 2 reviewers: a neurology resident (JH), and a board-certified veterinary radiologist (SN). Reviewers were blinded to patient and clinical information, though the surgical
technique could often be assumed based on the appearance of the defect on MRI, and pre- and post-operative images were easily distinguished. Measurements were not performed independently, with both reviewers assessing the images together and agreeing on a single appropriate measure. The cross-sectional area of material within the vertebral canal was measured on each T2-weighted transverse image using a free-hand tool (Fig 1), and reported in mm$^2$. The cross-sectional area was then multiplied by the slice thickness plus the slice gap (3.2 mm), with sum of these calculations represented the estimated volume of material within the vertebral canal, and reported in mm$^3$. Residual material represented the estimated volume of material within the vertebral canal post-operative. The ratio of residual material was assessed by dividing the estimated volume of material post-operative by the estimated volume of material pre-operative. The cross-sectional area of the vertebral canal was also recorded from the transverse slice with most evidence of spinal cord compression, and the cross-sectional area of the extruded material at this point was divided by the cross-sectional area of the vertebral canal. The proportion of material with characteristics of hemorrhage was visually graded and given a semi-quantitative score with 1 representing 100%, and 0 representing no evidence of hemorrhagic component. This was based on the identification of hypointense or signal void appearance to extruded material in T2* sequences. When it was observed that a mini-hemilaminectomy had invaded the articular processes, the extent of invasion was subjectively graded (0 = no invasion, 1 = mild invasion, 2 = moderate invasion, 3 = severe/hemilaminectomy).

Further data collected included the patient signalment (age, breed, sex), patient weight on admission, onset and duration of clinical signs, neurological status (on admission, immediately post-operative, and on recheck examinations) using a modified version of the Texas Spinal Cord Injury Scale, the surgical technique that was performed, surgical site, side of the
vertebral column where the surgery was performed, and the time elapsed between surgery and the post-operative MRI procedure.

Statistical Analyses

The data was collected in the form of a split-plot design, with each dog receiving a particular technique (whole-plot factor) and being split into a 2-factor factorial with the 2 factors surgical site and vertebral column side (split-plot factors). Sub-sampling was performed to allow a measure of repeatability. Each dog constituted a random blocking variable, while technique, site and side were fixed effects variables. In addition, covariates of weight, duration of clinical signs, elapsed time to post-operative imaging, and hemorrhage were included. For those dogs with residual material the degree of spinal cord compression, assessed by the ratio of cross-sectional area for material to vertebral canal, was also assessed. The covariates were entered into the model as a linear fixed effect as well as a quadratic effect. All 2-term interactions were included (along with the covariate and quadratic covariate) in the model to start, and then non-significant terms removed.

To analyze the data, a General Linear Mixed Model was employed using Proc Mixed in SAS. To assess the ANOVA assumptions, the residuals were formally tested for normality using the four tests offered by SAS (Proc UNIVARIATE): Shapiro-Wilk, Kolmogorov-Smirnov, Cramér-von Mises and Anderson-Darling tests. The residuals were also plotted against the predicted values as well as all explanatory variables (dog, technique, site, side) to check for possible outliers, assess for equality of variance or other potential problems. Transformation was performed as required based on residual analysis. A p-value of less than 0.05 was considered statistically significant.
Results

Nineteen dogs were included in the study, 10 in the hemilaminectomy group and 9 in the mini-hemilaminectomy group. Miniature Dachshunds were over-represented (11), with remaining dogs being Beagles (3), and 1 each of: Beagle/Collie cross, Cocker/Poodle cross, Shih Tzu/Poodle cross, Miniature Poodle, and Bassett Hound. Male and females were evenly distributed (10 males, 9 females), and no dogs were intact. The mean weight of dogs included in the study was 11 kg (range: 4.5 – 38), with a mean weight of 13.5 kg (range: 5.8 – 38) in the hemilaminectomy group and 8.1 kg (range: 4.5 – 15) in the mini-hemilaminectomy group. The difference in weight between surgical groups was not statistically significant (p = 0.1373).

Seventeen dogs weighed between 4.5 – 17 kg, with the Beagle/Collie cross and Bassett Hound weighing 21.8 and 38 kg, respectively. The most common site affected was T13-L1 (n=7), followed by T12-T13 (4), L1-L2 (3), L2-L3 (2), and T11-T12 (1). Two dogs, 1 in each surgical group, had extruded material extending beyond a single IVD site, requiring decompression of 2 adjacent sites. Eleven surgeries were performed on the left side of the vertebral column, 6 in the hemilaminectomy group and 5 in the mini-hemilaminectomy group, and 8 surgeries were performed on the right side, 4 in each group. Patient data is summarized in table 2.

The mean duration of clinical signs prior to surgery was 5.2 days (range: 1 – 30), with a mean of 6.5 days (range: 1 – 30) in the hemilaminectomy group and 3.7 days (range: 1 – 8) in the mini-hemilaminectomy group. The mean time between surgery and post-operative MRI technique was 4.8 hours (range: 0.5 – 18), with a mean of 5 hours (range: 0.5 – 17) for the hemilaminectomy group and 4.5 hours (range: 0.5 – 18) for the mini-hemilaminectomy group.

Data and results of statistical analysis for the degree of spinal cord compression, volume of extruded material, and proportion of material estimated to be due to hemorrhage are presented in table 3. Results of the statistical model are reported as median values, given the
presence of outliers skewing the mean values. Residual material was identified in 100% of the hemilaminectomies and 44% of the mini-hemilaminectomies. The median estimated volume of residual material was 25.8 mm$^3$ (CI: 13.5 – 49.4 mm$^3$, p < 0.0001) with hemilaminectomy, or 13.6% of the pre-operative volume (post- to pre-operative volume ratio of 0.14). The median estimated volume of residual material with mini-hemilaminectomy was 9.3 mm$^3$ (CI: 4.7 – 18.4 mm$^3$, p < 0.0001) with mini-hemilaminectomy, or 7.7% of the pre-operative volume (post- to pre-operative volume ratio of 0.08). The median estimated volume of residual material, regardless of surgical technique, was 10.4% (CI: 6.8 – 15.7, p < 0.0001), or a post- to pre-operative residual volume ratio of 0.10.

The ratio of pre- to post-operative volume was 7.4 (CI: 4.2 – 12.9, p < 0.0001) in the hemilaminectomy group, and 13 (CI: 7.3 – 23.4, p < 0.0001) in the mini-hemilaminectomy group. The difference in the ratio of median estimated pre to post-operative volume of material between mini-hemilaminectomy and hemilaminectomy was 1.8 (CI: 0.8 – 3.9), however this observed difference was not statistically significant (p = 0.1561). There was no effect of surgical site, or side of the vertebral column on the ratio of residual material, nor was there an observed effect of surgical technique on the degree of spinal compression (p > 0.20).

Patient weight and duration of clinical signs did not have a significant effect on the ratio of residual material (p > 0.20). Patient weight did have a significant effect on the average volume of material (p = 0.0475), with a 0.054 mm$^3$ increase in material for every 1 kg increase in weight. However, when the Bassett Hound (38 kg) from the hemilaminectomy group was removed from the data this effect became insignificant (p = 0.3450). Due to the large quantity of variables and small population size, the effect of time between surgery and post-operative imaging on the ratio of residual material, and the effect of pre-operative material volume on post-operative material volume could not be assessed.
The ventral aspect of the articular processes was at least partially invaded in all of the mini-hemilaminectomy sites, with 4 subjectively graded as moderate invasion and 5 as minimal invasion. An insufficient number of cases precluded statistical analysis, however there were no trends observed between the grade of articular processes invasion and the calculated ratio of residual material or any other variable assessed.

On initial presentation, neurological examination localized a lesion in the T3-L3 spinal cord segment in all patients. The mean neurological score on admission was 12.6 (range: 0 – 26), with a mean score of 12.2 (range: 4 – 20) for the hemilaminectomy group and 13 (range: 0 – 26) for the mini-hemilaminectomy group. Eight dogs were ambulatory paraparetic (4 in each surgical group), 6 dogs were non-ambulatory paraparetic (4 in the hemilaminectomy group, 2 mini-hemilaminectomy), and 5 dogs were paraplegic (2 hemilaminectomy, 3 mini-hemilaminectomy) 2 of which had absent nociception (1 in each surgical group). Five dogs experienced mild deterioration of 1 – 4 points in the immediate post-operative period; 2 in the hemilaminectomy group and 3 in the mini-hemilaminectomy group. However, all except 2 dogs improved and were ambulatory by the 4-6 week recheck examination. One dog included in the hemilaminectomy group was paraplegic with intact nociception on initial presentation and was euthanized at the referring veterinarian due to a lack of improvement 4-6 weeks post-operatively. One dog from the mini-hemilaminectomy group presented paraplegic with absent nociception, showed no improvement within 72 hours, but was lost to follow-up after discharge. On telephone conversation with the owner this dog was reported to have remained paraplegic 8 months post-operatively. Another dog in the mini-hemilaminectomy group was paraplegic with intact nociception on presentation had asymmetric motor function detected immediately post-operative, but also did not return for follow-up assessment. On telephone conversation with the
owner 8 months post-operative, the dog was reported to have returned to normal ambulatory function within 4-6 weeks of surgery.

In the 5 dogs showing a minor deterioration in their neurological score immediately post-operative, there were no trends subjectively observed between the occurrence of deterioration and the volume of residual material, with the 2 dogs in the hemilaminectomy group having residual volumes of 9.1% and 18%, and only 1 of the 3 dogs in the mini-hemilaminectomy group having residual material identified (27%). There were no trends observed with other variables (pre-operative volume, surgical site, side of vertebral column, weight, hemorrhage, degree of spinal compression, degree of articular process invasion). All 5 dogs had duration of clinical signs of at least 3 days prior to surgery; 1 dog in each surgical group had clinical signs for 8 days, while the remaining dogs had signs for 3 days.

Discussion

The results of our study confirm that residual material can be present with both hemilaminectomy and mini-hemilaminectomy techniques. Residual material was present with all dogs in the hemilaminectomy group (100%), and 4 (44%) dogs in the mini-hemilaminectomy group with a difference of 5.9% in the median estimated volume of residual material between surgical techniques but this was not statistically significant. The small size of the study population likely contributed to the lack of significance. Based on these results a power analysis indicated that 1561 dogs (781 in each group) would be required to detect a 70% difference in residual material between surgical techniques using this statistical model. The volume of residual compressive material may have also been over-estimated in the hemilaminectomy group by the use of absorbable gelatin sponge, which was only used in 2 dogs in the mini-hemilaminectomy group. This absorbable porcine gelatin sponge is often used to provide
hemostasis and prevent the formation of a compressive hematoma or a restrictive laminectomy membrane. While this material tends to be completely resorbed within 4-6 weeks, very little information exists on its magnetic resonance imaging signal characteristics and appearance, particularly over time while it is degraded and resorbed. On post-operative images obtained immediately after surgery (< 30 minutes) in the hemilaminectomy group, the gelatin sponge could easily be distinguished as a sharply demarcated, geometric shape with high T2-weighted signal (Fig 2). However, these imaging characteristics became much less defined in those patients that had images obtained 12 hours post-operatively; the material became heterogeneous, poorly demarcated, and difficult to distinguish from extruded IVD material (Fig 3). This may have had an effect on volume calculations, as the 3 dogs that had their post-operative MRI performed greater than 30 minutes post-operative (14.5, 15, and 17 hours) represented half of the dogs with residual volumes greater than 10% (14, 16 , and 32%).

Residual compressive material was not identified in either dog that had absorbable gelatin sponge used in the mini-hemilaminectomy group, although post-operative MRI was performed at 1 and 1.5 hours post-operatively. The influence of the elapsed time to post-operative MRI on the calculated residual volume was assessed but unfortunately could not be adequately fitted in the statistical model due to the small sample and could not reach statistical significance.

Although the observed difference in residual IVD material between hemilaminectomy and mini-hemilaminectomy was not found to be statistically significant, it must be cautioned that the results may be clinically significant. Both the mean residual:pre-operative volume and estimated median residual:pre-operative volume of extruded material in the hemilaminectomy group are almost double that of the mini-hemilaminectomy group. In fact, all dogs in the hemilaminectomy group had residual material identified post-operatively, whereas 5 dogs in the mini-hemilaminectomy were deemed to have complete evacuation of material. Despite possibly
over-estimating the volume of residual material due to absorbable gelatin sponge and an inability to identify a statistical significance, the clinical impact of hemilaminectomy evacuating only half of the extruded IVD material of a mini-hemilaminectomy needs to be considered, as the goal of surgical intervention is decompression of the spinal cord.

Few studies have assessed the occurrence of residual material following decompressive surgery for thoracolumbar IVD extrusion, and none involving the mini-hemilaminectomy technique. Post-operative imaging is most often performed in clinical patients showing complications during the recovery period, but it has not been until recently that post-operative CT was also performed in non-complicated patients. Given the few published studies, the exact clinical relevance of residual material in a recovering dog has yet to be determined.

In this study the mean residual volume was 11.5% with a range of 0 to 32.6%. This differed from the work of Roach et al (2012) who found a mean volume of residual material of approximately 50% on computed tomography, indicating that on average only half of the extruded material was removed, though their results had a wide range of 2.6 – 155.8%. A residual volume of greater than 100% was most likely due to complications such as further disc extrusion or post-operative hemorrhage. No dogs in our study had a residual volume of greater than 100%. Moreover, these two studies assessed the amount of residual material through different imaging modalities (CT vs MRI) and that factor should be taken into consideration when results are compared. Hemorrhage can have similar imaging characteristics on CT as mineralized extruded material, which can lead to over-estimation compared to the superior contrast resolution with MRI. However, neither imaging modality is particularly sensitive for distinguishing degenerate nucleus pulposus from annulus fibrosis. It is therefore
possible that estimates of residual extruded material may have included residual, non-compressive, annulus fibrosis.

The clinical significance of the difference in volume of residual material is an important question given the presence of residual material in dogs with normal post-operative recoveries.\textsuperscript{26,27} As the degree of spinal cord dysfunction depends not just on the compression itself but also on pathophysiological mechanisms that cannot be readily measured in clinical cases,\textsuperscript{23} the physical volume of residual material that can be clinically tolerated likely varies between individuals. Large volumes of compressive material can be tolerated by the spinal cord in the normal animal, provided the rate of extrusion and compression are slow, as well as the force of the initial impact.\textsuperscript{43,44} Unfortunately acute IVD extrusion can have a high velocity of impact, with the degree of neurological damage related more to concussive forces than compression. While sustained compression is a source of further vascular impairment to the spinal cord and secondary mechanisms of injury,\textsuperscript{23} it may have little influence on neurological impairment in patients with high velocity, low volume IVD extrusions.\textsuperscript{43,44} The impact of residual material on functional outcome in our study population is also largely unknown, as the lack of a larger sample size precluded any statistical analysis. Unfortunately, 2 dogs were lost to follow-up, 1 of which had absent nociception, and 1 paraplegic dog was euthanized for lack of improvement prior to the 4 – 6 week post-operative assessment. Dogs with absent nociception treated by surgical decompression for thoracolumbar IVD extrusion can require up to 13 weeks to recover ambulation,\textsuperscript{45} indicating the importance of long-term follow-up. In this study all dogs, excluding the 3 without long-term follow-up, had improved and were ambulatory by the 4 – 6 week assessment. The residual material encountered on post-operative imaging did not appear to affect function recovery, although a larger study population would be required for statistical analysis. The mild deterioration in neurological score observed immediately post-operative in 5
dogs did not appear to be specifically related to either surgical technique, such as spinal cord manipulation, or the presence of residual material. The differences between pre- and postoperative neurological scores could have been affected by anesthetic recovery and post-operative analgesics, or represent further deterioration, such as further vascular impairment to the spinal cord, which occurred after initial examination but prior to decompressive surgery.

In the two dogs that had a complicated recovery, 1 dog in the hemilaminectomy group presented paraplegic with intact nociception euthanized at 4-6 weeks post-operative due to a lack of improvement and another in the mini-hemilaminectomy group with absent nociception reported by the owner to have no recovery of function, residual material was identified on post-operative imaging. There were no subjectively observed trends amongst them. The dog in the mini-hemilaminectomy group had a residual volume of 21.9% while the dog in the hemilaminectomy group had only 5.6%. The dog in the hemilaminectomy group had the highest degree of residual compression (83% of the calculated pre-operative spinal compression) and the dog in the mini-hemilaminectomy group had the fourth highest (60% of the calculated pre-operative spinal compression). Both dogs also had a similar acute onset and rapid deterioration, with the duration of clinical signs being no greater than 24 hours. However, of the other 3 dogs to present paraplegic with intact nociception, all had a similar duration of clinical signs (2 with 1 day, 1 with 2 days), residual material identified on post-operative imaging (11, 18, and 32%), residual spinal compression present (19, 67, and 72% of calculated pre-operative compression), and all recovered ambulatory function (neurological grade of 25 and 28 on assessment by clinician, and the other reported by the owner).

Venous sinus hemorrhage associated with IVD extrusion is common. Intra-operative hemorrhage can occur with either hemilaminectomy or mini-hemilaminectomy and typically originates from the venous sinuses or spinal vessels and vessels of the muscular attachments to
the articular processes.\textsuperscript{30,39} The presence of hemorrhage itself is not associated with a poor prognosis, but can lead to formation of a post-operative compressive hematoma and result in a complicated recovery.\textsuperscript{46} In this study, hemorrhage was identified on pre-operative imaging in 8 out of 19 dogs (42%), but only observed on post-operative imaging in 2 dogs (11%). Both of the dogs with hemorrhage identified on post-operative imaging (100%) were in the hemilaminectomy group, as were 5 of the 8 dogs (63%) with hemorrhage identified on pre-operative imaging. While hemorrhage can have multiple characteristics on MRI, the accuracy of MRI to identify hemorrhage and the ability to distinguish it from other material within the vertebral canal is superior compared to computed tomography when using T2*(gradient echo) sequences.\textsuperscript{47} Due to the inherent characteristics of T2* sequences, as inferior resolution, and the often dispersed nature of hemorrhage within extruded material, circumferential measurements were deemed too inaccurate for consideration in this study. Despite the proportion of hemorrhage being a subjective measure, its presence had no effect on the volume of residual material between techniques.

An interesting finding in this study was the invasion of the ventral aspect of the articular facet in 100% of the mini-hemilaminectomy sites. While many reports for the mini-hemilaminectomy technique recommend preserving the articular processes,\textsuperscript{29,33,34,36,37} others suggest altering the dorsal limit of the laminectomy window based on the location of extruded material,\textsuperscript{36} and some indicate the removing the accessory process as the dorsal landmark which would suggest at least partial encroachment of the articular processes.\textsuperscript{38} The effect of partial removal of the articular process on vertebral column stability is unknown, although the extent of bone removal could influence the proposed benefits for decreased biomechanical instability with mini-hemilaminectomy. Certainly, the potential for a larger mini-hemilaminectomy window to have a positive influence on the ability to evacuate compressive material should be
considered when results of this study are assessed. Consideration must be given to the fact that
this was a subjective grading scheme, that none of the mini-hemilaminectomies extended near
the extent of a hemilaminectomy, and statistical analysis for trends was precluded by the small
study population. A previous study performed by the authors assessed post-operative CT images
obtained from cadavers after both hemilaminectomy and mini-hemilaminectomy techniques,
and described the dorsoventral dimensions of the window created in the vertebral arch
(unpublished results). As expected, hemilaminectomy resulted in a significantly larger window,
and this was determined to be due to relative sparing of the more dorsal aspect of the vertebral
lamina with the mini-hemilaminectomy technique. The size of the window decreased with
increasing vertebral canal height (increasing size of dog) regardless of technique, though the
difference was greater with the mini-hemilaminectomy. While the dimensions of the
laminectomy windows were not measured in the current study the smaller window of the mini-
hemilaminectomy did not appear to affect the ability to evacuate extruded material in the
clinical cases assessed here. Patient weight and signalment did not have a significant effect on
the volume of residual material. In the hemilaminectomy group the dogs with the three smallest
volumes of residual material were the 15 kg Beagle (5.1%), 16.7 kg Dachshund (5.6%), and 38 kg
Basset Hound (5.8%). Of the 4 dogs in the mini-hemilaminectomy group with residual material
identified, 2 were 4.5 kg Dachshunds (11.8 and 18.6%), 1 was a 9.2 kg Dachshund (22%), and the
other a 15 kg Beagle (27.3%). Although the greater volume of residual material in this subset
belonged to the 2 heavier dogs, it should be noted that all dogs without residual material were
greater than 5.8 kg, the heaviest weighing 12 kg. Additionally, the degree of invasion of the
articular processes with mini-hemilaminectomy did not appear to be exclusive to the dogs with
lower body weight. The size and limits of the bone window were not measured in clinical cases,
due to the lack of adequate spatial resolution with MRI.
A potential limitation of this study is related to the choice of imaging modalities. Magnetic resonance imaging was chosen for its superior contrast resolution, however spatial resolution is reduced compared to CT. Slice thickness and gap were included in the calculation of volume (3.2 mm) and may represent an over-estimation, especially in small dogs where volume averaging is more likely to occur. To the author’s knowledge there are no published studies investigating the accuracy of imaging when calculating extruded IVD material or even a reported standardized procedure to estimate it; however MRI is currently the gold standard for diagnosis of IVD extrusion due to its high sensitivity. While CT has superior spatial resolution and is often capable of slice thickness close to 1 mm, its more limited ability to distinguish hyperdense IVD material from hemorrhage can lead to a residual disc material over-estimation. A broadly used standardized technique to determine the volume of disc material through advanced imaging is still missing in veterinary medicine. Future studies comparing calculations performed via imaging and those taken in situ, as during post-mortem examination, are required.

The other limitation of this study was the inclusion of only 2 surgeons, each performing different techniques as per their routine clinical practice, and lack of randomization. We cannot definitively argue that the presented results are not a direct comparison of the surgeons in question. Ideally, this variable would be removed by introducing multiple surgeons and/or planning of the two surgeons to randomly alternate both surgical procedures. However, this is not possible with the limited population in this study, and lead to the choice of fewer surgeons to decrease operator variability. A separate surgeon was chosen for each technique to prevent inadequate evacuation of compressive material due to the limited experience of a surgeon utilizing a technique they were not familiar. It should also be noted that although the surgeons were not blinded to the patient’s inclusion in the study or the technique being utilized, they were blinded to the results of post-operative imaging while cases were still being included in the
study. This prevented the surgeons from making further corrections or adjustments to their technique, and is reflected in the data which does not show a trend for a decreasing residual volume related to the date of inclusion into the study.

The small sample (n=19) is another limitation to consider, as this prevented accurate analysis using the statistical model, often described as ‘over-fitting’ of results. For instance, when attempting to assess the influence of pre-operative material volume on post-operative volume (as perhaps larger volumes make it harder to complete evacuation), the statistical model estimates a potential post-operative volume of 9682 mm$^3$. Alone, the volume of pre-operative material trended towards an influence on post-operative volume, but the significance of this was greatly reduced when used in the quadratic model, as the degree of freedom were insufficient. A much larger study population would be required to detect further effects, but the size of the population would be heavily influenced by the clinical relevance of residual IVD material. For instance, to detect a difference in residual volume between surgical techniques of 20% with 80% power, 606 dogs would be required in each group. To detect a more conservative difference between techniques of 50% with a greater power of 90% would require only 165 dogs in each group. With the sample population in this study a difference of 70%, which would represent a large amount of residual material, could not be detected. Unfortunately, post-operative imaging in dogs with thoracolumbar IVD extrusion is often limited by the availability of imaging, cost, and increased anesthetic time. Since the number of similar studies is limited non-equivalent, this study was designed as a pilot study to provide guidelines in order to adequately design future research studies, as identifying limitations and contributing with useful information to perform power analysis to calculate the required sample population.

The Hawthorne effect, a well described phenomenon in human literature, is suggested to occur when a study participant’s behavior and results are altered by their
awareness of being monitored or included in a study, and may even have more influence on outcome measures than the placebo effect.\textsuperscript{49,50} As neither of the surgeons in our study were blinded to the inclusion of cases, and randomization did not occur, we cannot exclude the influence this may have had on the laminectomy created or the quality of extruded IVD material evacuation. However, both surgeons were blinded to the results of post-operative MR imaging in clinical patients, which may have prevent any additional steps being taken to improve their outcomes. When observing the residual:pre-operative IVD material volumes for each case in chronological order, one would expect a decreasing ratio over time either surgeon was adapting their technique based on post-operative imaging results, and this is not observed in our study.

In conclusion, this study identified residual material in dogs with thoracolumbar IVD extrusion that had undergone both hemilaminectomy and mini-hemilaminectomy, but no significant difference in the amount of residual material could be detected between both surgical techniques. Future consideration should be given to the use of absorbable gelatin sponge and its imaging characteristics, as well as the extent of the laminectomy defect created during mini-hemilaminectomy. While variability in the dorsal limits of the mini-hemilaminectomy is evident, the effect this has on vertebral column stability, patient morbidity, and the ability to remove compressive material from the vertebral canal requires more investigation. To the author’s knowledge this is the only published report of residual IVD material following mini-hemilaminectomy, and the first prospective study of residual material in non-complicated dogs using MRI.
Footnotes

a. Sigma Scanner, General Electric Medical Systems – Canada, Mississauga, ON

b. Surgifoam, ETHICON, Somerville, NJ

c. Advantage Workstation, version 4.2, General Electric, Milwaukee, WI

REFERENCES


32. Hoerlein BF. The treatment of intervertebral disc protrusions in the dog, in *Proceedings of the American Veterinary Medical Association* 1952;206.


**Figure 1.** Transverse, T2-weighted image of the lumbar spine. Free-hand measurement of the circumference of extruded material within the vertebral canal (1).
Figure 2. Transverse, T2-weighted image obtained 30 minutes post-operative. Note the linear, geometric hyperintensity in the ventral spinal canal.
Figure 3. Transverse, T2-weighted image obtained 900 minutes post-operative. Note the lack of defined borders and mixed intensity.
Table 1. Modified version of the Texas Spinal Cord Injury Score.

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Table 2. Patient data. * = mini-hemilaminectomy with absorbable gelatin sponge remaining at surgical site.

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<th>Surgical Site</th>
<th>Side of Surgery</th>
<th>Neurological Score</th>
<th>Residual Volume mm³(%)</th>
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<td>Hemi</td>
<td>T10-T12</td>
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<td>Right</td>
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Table 3. Results of statistical analysis. Range is given in brackets for mean results, and confidence interval is given in brackets for median results. P-value < 0.0001 for all median results.

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<th>Hemilaminectomy</th>
<th>Mini-hemilaminectomy</th>
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<td>Pre</td>
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<tr>
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<td>10.3 (3 – 17)</td>
<td>37.0 (20 – 67)</td>
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<td>Volume of Material (mm³)</td>
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<td>28.8 (6.4 – 70.4)</td>
<td>152.2 (32 – 413)</td>
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<td>Volume of Material (mm³)</td>
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<td>25.8 (13.5-49.4)</td>
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<td>Ratio of Material Pre:Post</td>
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<td>13.0 (7.3 – 23.4)</td>
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<tr>
<td>Volume Residual Material (%)</td>
<td>13.6 (7.8 – 23.6)</td>
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<td>Proportion of Material</td>
<td>12 (0 – 50)</td>
<td>5 (0 – 30)</td>
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Neurological diseases frequently require surgical intervention, with intervertebral disc (IVD) extrusions being the most common condition requiring access to the vertebral canal. During spinal neurosurgery, decompression involves removal of a portion of the vertebral bone and/or removal of space-occupying masses, such as extruded IVD material, to alleviate ongoing compression of the spinal cord and nerve roots. The 2 most common surgical techniques utilized to access the thoracolumbar vertebral canal in dogs, hemilaminectomy and mini-hemilaminectomy, differ by the size and location of the window created in the vertebral bone. Descriptions of both techniques in the literature often consist of vague anatomical landmarks with minimal standardization of their physical limits, making comparison of potential efficacy and morbidity related to the techniques difficult, if not impossible. Although both techniques have similar reported success rates for dogs with acute IVD extrusion, greater than 80% of non-ambulatory dogs with intact nociception recovering ambulation, no direct comparisons have been made between the two techniques.

Multiple theories have been proposed for complicated post-operative recoveries, defined as an absence of improvement or continued deterioration in neurological function, and is likely complicated by the poorly understood pathophysiology of acute spinal cord injury. One potential cause is inadequate evacuation of compressive IVD material following surgery resulting in residual compression post-operatively, as has been documented in individual cases of IVD extrusion. Unfortunately, few studies have assessed for the presence of residual material with post-operative imaging following decompressive surgery for IVD extrusion, and in fact those that have documented that residual material can be identified in both complicated and uncomplicated recoveries. Another confounding factor is the potential effect of the size and
location of the laminectomy window on the ability to evacuate compressive material, which is complicated by the lack of standardized descriptions and assessments for both hemilaminectomy and mini-hemilaminectomy. The goals of these studies were to describe standardize anatomical limits for each surgical technique, and describe any observed differences between techniques which may influence the ability to evacuate compressive material; and to determine the presence and volume of residual compressive material in dogs with IVD extrusion undergoing either surgical techniques, and assess for any differences that may influence the ability to evacuate compressive material.

A relatively homogeneous population of canine cadavers underwent both hemilaminectomy and mini-hemilaminectomy techniques at common sites of IVD extrusion in the thoracolumbar spine: T11-T12, T13-L1, and L2-3. Computed tomography (CT) was chosen as the imaging modality with which to measure the dorsoventral dimensions of the laminectomy windows, due to the superior spatial resolution and bone detail compared to conventional radiographs and magnetic resonance imaging (MRI). Measurements of the dorsoventral height of the defect, and the heights of the dorsal and ventral remnants of the vertebral arch were obtained and statistical analysis performed with the vertebral canal height as a covariate to control for the size of the cadavers. As expected, the hemilaminectomy resulted in a larger defect, with the difference in the mini-hemilaminectomy occurring due to its ventral position and thus retention of the more dorsal aspect of the lamina and articular processes. None of the other variables assessed had an effect on the defect size, suggesting that either technique could be utilized at any point along the thoracolumbar spine without sacrificing the ability to create the standardized laminectomy.

The difference in the defect height between techniques was no greater than 1.62 mm for dogs weighing 8 – 11 kg, and was related to creating a larger defect along the dorsal
vertebral canal, while no statistical difference in access to the ventral canal was observed, as expected. This finding is likely of limited clinical significance in most acute disc extrusions; however the clinical implications of this were not assessed. It should be considered that there is a potential for restricted exposure to a thoracolumbar lesion located either in the ventral 11-27% of the vertebral canal height when performing either procedure, or in the dorsal 7-20% of the vertebral canal height when a mini-hemilaminectomy is performed, compared to the dorsal 1-2% of the vertebral canal height with a hemilaminectomy.

An unexpected finding was the overall trend for decreasing defect height with increasing vertebral canal height (size of dog), which was greater with the mini-hemilaminectomy technique than the hemilaminectomy technique. A proposed theory for this finding is the ability to better respect anatomical landmarks in larger dogs where the anatomical constraints, such as the position of the accessory processes in relation to the articular processes, have less of an effect. This finding could impact the ability to effectively evacuate a compressive lesion in smaller dogs, especially with the mini-hemilaminectomy technique, and warrants further investigation with a larger population of dogs and greater variation in size. Consider the anatomical variation between a toy breed and giant breed dog. Greater physical limitations and less ability to visualize the vertebral canal in extremely small dogs could affect the completeness of evacuation of extruded material with either technique.

Of note was the observed invasion of the ventral aspect of the articular processes in 55% of the mini-hemilaminectomy sites. The small number of cases precluded statistical analysis; however this observation raises some questions, particularly related to the clinical scenario. Is the invasion of the articular processes more common with smaller dogs? Does this have a positive influence on the ability to remove compressive material, potentially biasing the efficacy of a mini-hemilaminectomy? And, what influence does this have on spinal stability?
While removal of an entire unilateral articular process does not significantly affect spinal stability, nor has it resulted in instability that is appreciable clinically, it could be misleading to perform bilateral or multiple consecutive mini-hemilaminectomies under the belief that it is less destabilizing than multiple hemilaminectomies, at least if the articular processes are being invaded. Additionally, a larger population may provide the ability to perform a statistical analysis with the exclusion of those cases that had articular facet invasion, as their inclusion may be causing significant over-estimation of the dorsoventral defect height with the mini-hemilaminectomy technique, provided this does not result in exclusion of all dogs within a particular weight range. Regardless, none of the mini-hemilaminectomy procedures extended to the level of a hemilaminectomy, and when determining the most appropriate technique for a clinical case, mini-hemilaminectomy must still be considered to remove less bone compared to hemilaminectomy.

Post-operative MRI identified residual material in clinical cases of thoracolumbar IVD extrusion with both surgical techniques, with an estimated median volume of residual material of 13.6% (CI: 7.8 – 23.6, p < 0.0001) in the hemilaminectomy group (in 100% of dogs) and 7.7% (CI: 4.3 – 13.8, p < 0.0001) in the mini-hemilaminectomy group (in 44% of dogs). However, a statistical difference was not detected, nor was there an association between any of the measured variables, though this could be affected by the sample size. In fact, a power analysis revealed that 165 dogs would be required in each group to detect a difference of 50% between techniques, with a power of 90%.

Regardless, all dogs regained ambulatory function with the exception of 2. One was euthanized at only 4-6 weeks post-operative for a lack of recovery, and 1 had absent nociception both pre and post-operatively and was lost to follow-up. This leads to the particularly relevant question of defining what is considered a successful clinical recovery in
dogs: a patient recovering ambulatory function and not suffering further neurological status deterioration. Therefore, a wide range of neurological grades can be included in what is classified as a successful recovery, from a patient showing significant paresis and ataxia despite retaining the ability to walk, to patients showing a complete recovery and no neurological deficits. This is further complicated by lack of routine post-operative imaging studies, hindering the ability to confirm whether a proportion of incomplete recoveries are due to the presence of residual extruded material. It is widely accepted that even with accurate pre-surgical planning, surgery performed at the correct location, and the perceived completeness of evacuation by an experienced surgeon, residual material can still be present in the vertebral canal, as has been recently documented in dogs with uncomplicated recoveries following hemilaminectomy.

Without post-operative imaging in both dogs with complicated and uncomplicated recoveries, it is also difficult to produce a quantitative analysis of the proportion of residual material that is clinically tolerable. What would seem to be large quantities of residual material have been identified in uncomplicated cases in the literature as well as this study, while the opposite has also been confirmed by this study. Recovery of neurological function is likely linked to the intricate pathophysiology of acute spinal cord injury, of which compression is only one factor. Concussive forces can lead to severe, irreversible spinal cord injury without the presence of compression, and is currently impossible to quantify in clinical patients, outside of an absence in nociception. Severe concussive injury may be more likely to result in a rapid progression of clinical signs, and was assessed in our study but was limited by the small population size.

The purpose of this study was to report the presence of residual extruded material, but also to provide guidelines to adequately design future research studies by identifying limitations and power calculations. An important consideration to this study is how the quantity of residual material is measured and thus the chosen imaging modality. While CT imaging has superior
spatial resolution allowing precise measurements, it can be difficult to distinguish extruded material from hemorrhage, a common result of the extrusion itself and surgical technique, leading to over-estimations residual material. Magnetic resonance imaging offers superior contrast resolution, and is therefore highly sensitive, but may also lend to over-estimation given the loss of spatial resolution and effect of volume averaging. In our study it was believed that hemorrhage could be easily distinguish with the use of T2* (gradient echo) sequences, and extruded material readily identified. Further comparison of estimates made with advanced imaging modalities and in situ material, such as at post-mortem examination, is required but not realistic in clinical patients.

The use of absorbable gelatin sponge, a material used for hemostasis, was difficult to distinguish from extruded material on post-operative MRI, especially with elapsed time. This could have resulted in over-estimation of residual material in the hemilaminectomy group. Currently, there is no data on the imaging characteristics of this material as it degrades and is absorbed. Until this information is described it is the authors’ recommendation to avoid its use if imaging is planned greater than 1 hour post-operative.

Given the lack of spatial resolution and bone detail with MRI, it was decided not to obtain post-operative measurements of the laminectomy window in the clinical cases, thus the CT findings acquired from the cadavers have not been assessed in a clinical scenario. However, if the trend towards decreasing laminectomy height with increasing patient size was also occurring in the clinical cases, it did not appear to have an effect on the ability to evacuate extruded material, as patient weight was not associated with the volume of residual material. Additionally, all mini-hemilaminectomy techniques invaded at least a minor portion of articular processes, consistent with the findings in the CT study. Again, none approached the level of a hemilaminectomy and no subjective trends in any variable were observed, though a larger
population of patients is required. The clinical significance of this finding has yet to be determined, and further biomechanical studies may be warranted, especially across multiple consecutive mini-hemilaminectomies.

In conclusion, these studies described standardized anatomical limits to both the hemilaminectomy and mini-hemilaminectomy technique, and identified residual material in dogs undergoing decompression for thoracolumbar IVD extrusion with either technique. There was no statistical difference observed in the quantity of residual material between techniques, and there was no effect observed by any of the variables assessed. However, these results must be interpreted with caution, as a larger sample size could be required to detect the observed difference in residual material, and other variables (ie: patient weight, duration of clinical signs) could prove to have a significant effect.
### APPENDIX

### I. COMPUTED TOMOGRAPHY MEASUREMENTS

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<th>Site</th>
<th>Side</th>
<th>Technique</th>
<th>Canal Height (mm)</th>
<th>Defect Height (mm)</th>
<th>Remnant Height (mm)</th>
<th>Facet Height (mm)</th>
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