Comparison of Two Minimally Invasive Approaches to the Thoracolumbar Spinal Canal in Dogs

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Submitted April 2012
Accepted September 2012

DOI:10.1111/j.1532-950X.2013.12098.x

Objective: To describe 2 minimally invasive approaches to the spinal canal for treatment of intervertebral disc disease and compare their efficacy to conventional hemilaminectomy.
Study Design: Experimental; randomized, controlled design.
Animals: Canine cadavers ($n = 10$; 5 small and 5 large dogs).
Methods: Barium-impregnated agarose gel (BA-gel) was injected into the spinal canal at 3 intervertebral spaces of the thoracolumbar spine in each cadaver. Sites were randomly assigned to 1 of 3 approaches: conventional (standard) hemilaminectomy (SH), endoscopic foraminotomy (EF), or foraminotomy via an illuminated port (FP). Computed tomographic scans were performed before and after the procedures. Procedures were compared for duration, bone window size, incision length, complications and percentage of BA-gel removed via repeated measures ANOVA.
Results: The incisions created during EF and FP were similar and smaller to that of a SH. The duration of EF was prolonged compared to FP and SH. The size of the vertebral window created was greater after SH in large dogs, while no difference was found between procedures in small dogs. The amount of simulated disc material removed from the spinal canal did not differ between procedures, regardless of the size of the dog.
Conclusions: The two minimally invasive approaches were feasible in small and large dogs. Both techniques allowed similar removal of simulated disc material and may decrease soft tissue morbidity compared to SH.

Intervertebral disc disease with herniation (IVDH) is the principal cause of acute spinal injury in dogs with an overall incidence of 2.3% in 1 multicenter study.[1] The prevalence of intervertebral disc disease (IVDD) in chondrodystrophic dogs is especially high, with 19–24% of Dachshunds expected to develop clinical signs during their lifetime.[1,2] Thoracolumbar lesions account for 84–86% of all intervertebral disc lesions in dogs.[3–5] Thoracolumbar disc herniation is therefore the most common indication for neurosurgical intervention in dogs by hemilaminectomy, pediculectomy, disc fenestration, or dorsal laminectomy.[6,7] Each procedure requires an extensive surgical approach through dorsal, dorsolateral, or lateral incisions.[8] As a result, wound complications have been reported in 14% of 250 thoracolumbar hemilaminectomies and 14 laminectomies, including swelling, discharge, bleeding, seromas, and wound dehiscence.[9] Complications resulting from the dorsolateral approach to thoracolumbar disc fenestration in 127 dogs included pneumothorax (4.7%) and scoliosis (7.8%).[10]

Minimally invasive procedures for treatment of IVDH, such as microendoscopic discectomy (MED), have gained popularity in people because they have decreased incision size, morbidity, and hospitalization time while achieving comparable functional results to open procedures.[11–21] In small animals, minimally invasive surgery is becoming more popular, with the goal of effectively treating pathology with minimal disturbance of normal anatomy. However, very few attempts have been made at developing a minimally invasive approach to the treatment of IVDH in dogs. The only reports of minimally invasive access to the thoracolumbar spine in dogs consist of 2 abstracts and a cadaveric study by the same investigator.[22–24] Although reports in human and veterinary neurosurgery support the feasibility of minimal access spinal techniques in dogs, no technique has been established to allow removal of disc material extruded into the spinal canal of small dogs. This knowledge gap prevents broader application of minimally invasive treatment of IVDD in small animals, because Hansen

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Funded in part by Funded in part by Companion Animal Grant, University of Illinois Department of Veterinary Clinical Medicine.

type I thoracolumbar disc herniation in chondrodystrophic breeds is the most common indication for neurosurgical intervention in dogs.

Our purpose was to compare 2 minimally invasive decompressive techniques against conventional hemilaminectomy. Our hypothesis was that minimally invasive foraminotomy would allow adequate observation of the site of spinal compression and comparable removal of simulated disc material, while limiting soft tissue trauma compared with a conventional hemilaminectomy. Our 2nd objective was to determine the extent to which each technique would be affected by dog size. We hypothesized that the efficacy of the treatments would remain similar in an experimental model of intervertebral disc extrusion in large and small dogs.

MATERIALS AND METHODS

Dogs

Five canine cadavers weighing >13 kg were enrolled in the study to form a group of mid-to-large breed dogs. Five canine cadavers weighing <13 kg were included to test the minimally invasive techniques in small dogs.

Experimental Model of Intervertebral Disc Herniation

Agarose (0.15 g; Fisher Scientific, Hampton, NH) was mixed with powdered barium sulfate (0.4 g; Fisher Scientific) and tap water (10 mL) to create a mixture that contained 1.5% (w/v) agarose and 4% (w/v) barium (BA-gel). The liquid was heated until boiling, aspirated into a 6 mL syringe and allowed to cool to room temperature. The agarose was allowed to solidify before injection.

Dogs were positioned in sternal recumbency and the hair dorsal to the spine was clipped. Under fluoroscopic guidance, BA-gel was injected into each extradural space at T11-12, T13-L1, and L2-3 to simulate a disc extrusion. BA-gel (2.5 mL) was injected using a 6 mL syringe and a 20 g × 2.5″ spinal needle inserted via a dorsal median approach through the interarcuate space into the ventral aspect of the spinal canal at each of 3 intervertebral disc spaces. In large dogs, 4 mL gel was injected through an 18 g × 2.5″ spinal needle at each intervertebral space. Volume was determined through preliminary trials in 2 cadavers to induce simulation of compressive lesion on computed tomography (CT) images. Five clinical cases in which Hansen type I intervertebral disc herniation was confirmed by CT and surgery were evaluated to quantify the amount of disc material (mm^2) at each disc space. These findings were used as a standard to determine if the amount of BA-gel injected provided a comparable model.

CT

Each dog was examined by CT immediately after BA-gel injection and again after surgery. Dogs were positioned in a helical scanner (General Electric High Speed F/X Helical Scanner, Milwaukee, WI and General Electric Advantax Workstation, Milwaukee, WI) using the same positioning as clinical cases (ventral recumbency), and studies were acquired from T10 to L4 using our routine protocol for thoracolumbar spine imaging (2.5 mm × 1.25 mm slices, 120 kvp, 150 mA, 0.938 pitch). All CT scans were evaluated by the same board-certified radiologist (J.M.), unaware of the procedure assigned to each intervertebral space. The boundaries used to assess each site before and after surgery were defined as one-half of the vertebral body cranial and caudal to the intervertebral disc space. The area occupied by radiopaque gel in the spinal canal was determined with Kodak PACS software over each transverse image included within the boundaries. The amount of simulated disc present at each site was consequently calculated as the cumulative areas occupied by the BA-gel within the boundaries set for the intervertebral space (mm^2). The amount of BA-gel present before and after surgery was determined for each intervertebral space studied (Fig 1). The amount of simulated disc removed at each site was calculated as the difference between pre- and post-surgical values.

Surgical Techniques

After preoperative CT, each dog was positioned in sternal recumbency. To localize each surgical site, a guide wire was placed using fluoroscopic guidance at each corresponding injection site. Each space was assigned to a surgical technique, and an order of performance determined using block randomization techniques to balance the groups. Side of decompression (right, left) was determined by assessment of the CT scan and the side with the greater amount of BA-gel was chosen. When the BA-gel was located ventral to the spinal cord, the side was chosen by simple randomization (flipping a coin). All surgical techniques were performed by the same surgeon (D.G.), unaware of the CT assessments. Three surgical techniques were tested in 3 intervertebral sites in each dog:

Endoscopic Foraminotomy (EF). An incision was made in the skin lateral to the dorsal spinous process, at the level of the marker Kirschner wire. A system of tubular dilators (Stryker, Kalamazoo, MI; Fig 2) was used for the approach. The initial dilator was advanced through the skin incision, subcutaneous fat, dorsolumbar fascia, and muscle until it contacted the vertebral body. The articular processes over the targeted intervertebral space were palpated using the dilator and then the end of the dilator was walked ventrally so that it rested on the pedicle (Fig 3). The depth from the skin incision to the lamina was noted by depth markings on the initial dilator. The next tubular dilator in the system was placed over the initial dilator and larger dilators were placed sequentially until a dilation of 16 mm was achieved (Fig 4). At that point, the beveled tubular retractor (16 mm diameter × 40 mm length; Stryker) was placed over the last dilator so that it came in firm contact with the lamina. Once appropriate placement was achieved, the retractor was secured in place with a positioning arm attached to the operating table (Snake Arm and Arm Post, Stryker; Fig 5).

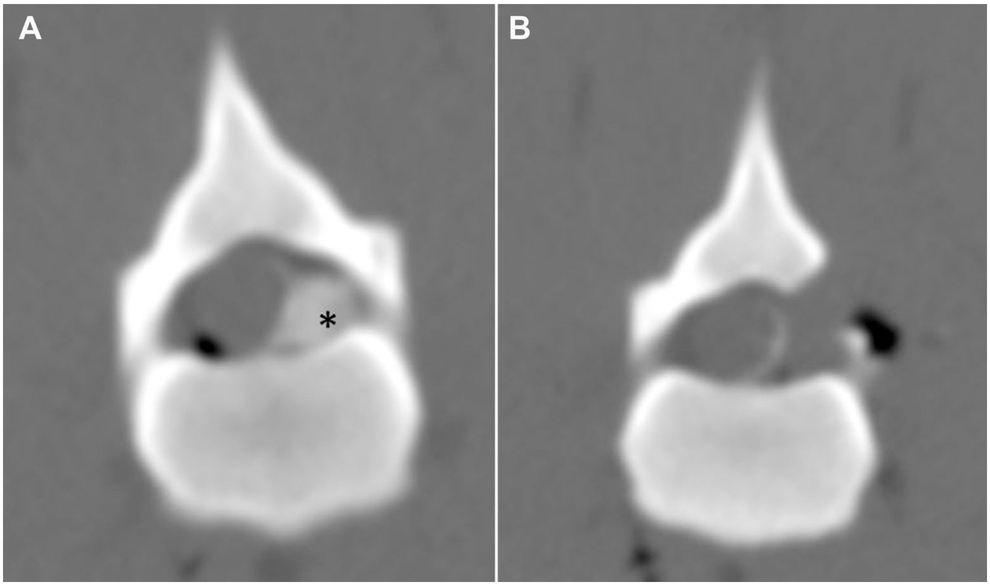

Figure 1 Transverse computed tomography. (A) The spinal cord is displaced to the right by the BA-gel (asterisk) after injection of barium/agarose gel (BA-gel) into the ventral spinal canal. (B) Same site after surgery. A small amount of BA-gel remains visible without evidence of spinal compression.

Muscle tissue obscuring the view within the lumen of the retractor was elevated with an endoscopic tissue elevator, scalpel, and forceps to expose the underlying lamina, foramen and intervertebral space. Once exposure was adequate, a 2.7 mm, 30° arthroscope and corresponding cannula (Stryker) were introduced into the lumen to improve observation of the foramen (Fig 6). The minimally invasive surgery (MIS) Endodrill (Stryker) was mounted with a 2.0 or 3.0 mm diamond endoburr, designed to remove bone while preventing trauma of the soft tissues contacting the tip of the burr (Fig 7). A foraminotomy was performed under continuous lavage through the scope cannula with the drill and Kerrison rongeurs (Fig 8). After exposure of the spinal cord, the BA-gel was identified and removed with endoscopic curettes. Finally, the retractor was removed and the fascia and skin were closed in layers.

Figure 2 Series of tubular dilators used for muscle splitting approach to thoracolumbar spinal column (Stryker).

Foraminotomy Through an Illuminated Port (FP). The approach to the vertebrae through the use of sequential dilators was performed in the same manner as in the EF procedure; however, the retractor (15 mm diameter × 40 mm length) used in this procedure was illuminated and did not have a beveled end (Spotlight, DePuy Spine, Warsaw, IN: Figs 9–11). Head loupes with 3.5× magnification were worn by the surgeon. A high-speed pneumatic burr (Hall Surgairtome II, ConMed Linvatec, Anaheim, CA) was used to initiate the foraminotomy. The foraminotomy was completed with the MIS endoburr. Removal of BA-gel, and closure were performed in the same manner as described for the EF group.

Standard Hemilaminectomy (SH, Control Group). Hemilaminectomies were performed as previously described.[5] Briefly, the skin was incised over dorsal midline extending cranial and caudal to the designated disc space. The musculature was separated from the dorsal spinous process and lamina to facilitate placement of Gelpi self-retaining retractors. The articular facets of the designated intervertebral disc space were removed and a burr was used in combination with Kerrison rongeurs to perform a hemilaminectomy. The simulated disc material was removed atraumatically with curettes followed by standard closure of the soft tissues.

Outcome Measures

Techniques were subjectively evaluated by the surgeon (D.G.) for technical ease and quality of observation. Outcome was quantified based on the length of skin incision for each surgery, the time from skin incision to closure, the size of the vertebral window, and the amount of BA-gel removed.

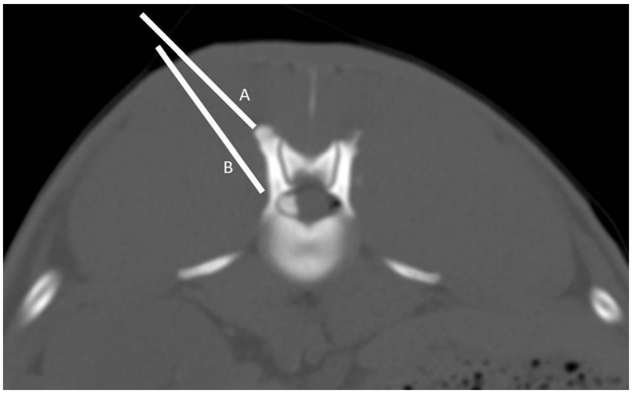

Figure 3 Transverse image from preoperative, post-injection computed tomographic study. Placement of the initial dilator was performed by first palpating the articular processes over the targeted disc space (A) and then walking the dilator ventral until it was placed on the pedicle (B). When necessary, palpation of the transverse processes or rib heads was used to aid placement.

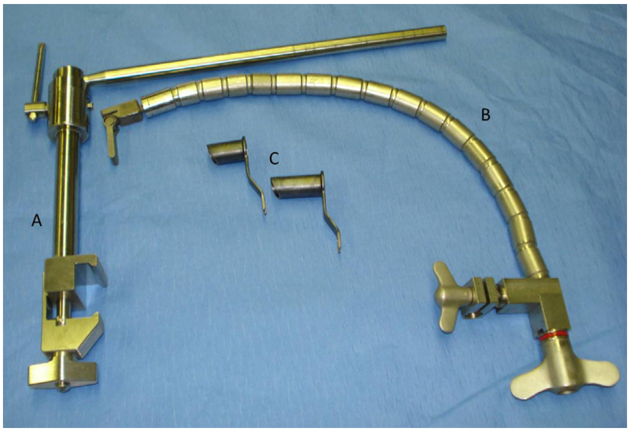

Figure 5 Instrumentation for endoscopic foraminotomy: (A) Snake Arm Post; (B) Snake Arm; (C) beveled retractors (16 mm diameter, 30 and 40 mm length).

Data Analysis

Preliminarily, summary statistics (minimum, maximum, mean ± SEM, median), marginal normality (Anderson–Darling test, Shapiro–Wilk test), multinormality (Mardia skewness and kurtosis, and Henze–Zirkler multinormality), and normal

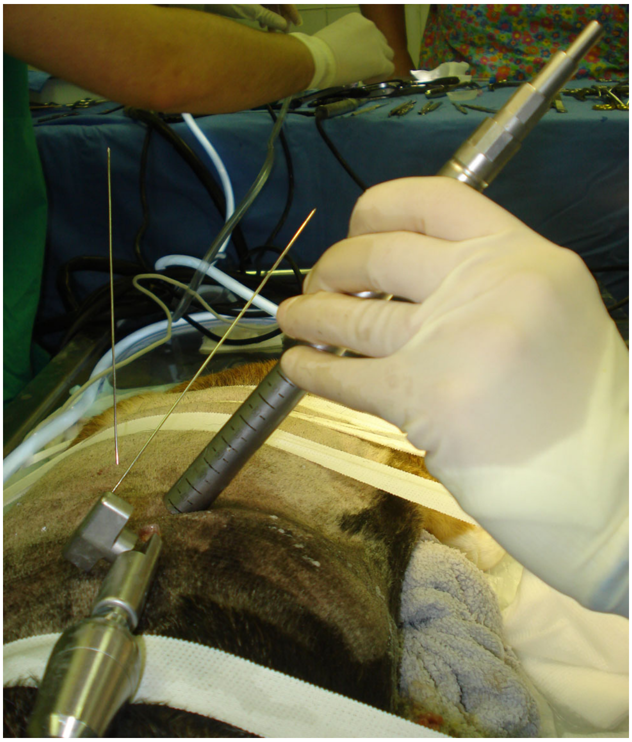

Figure 4 Placement of sequential tubular dilators for minimally invasive approaches to the thoracolumbar spine. A cannula is placed over the largest dilator.

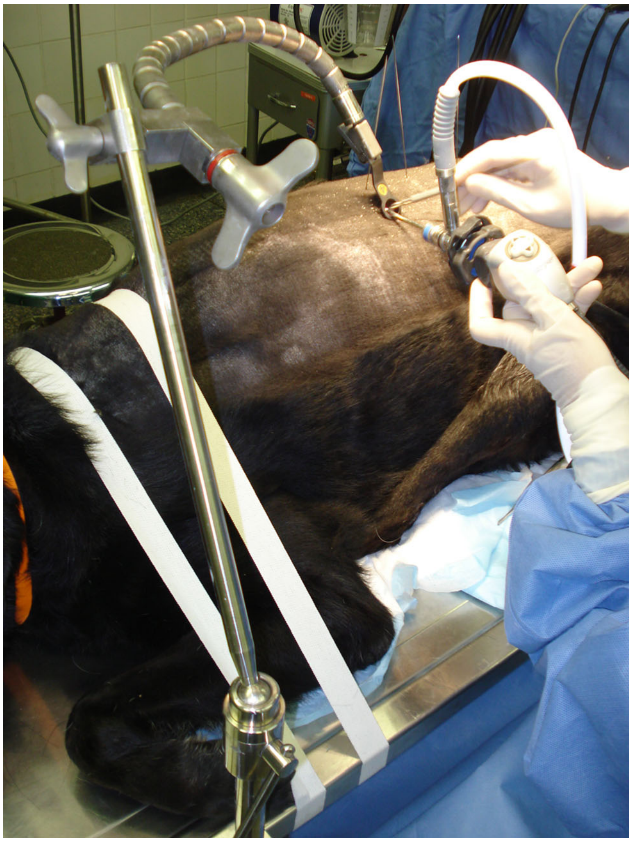

Figure 6 Endoscopic foraminotomy: A 2.7 mm 30° arthroscope is introduced in a cannula connected to a snake arm and arm post. The arm post is secured to the surgical table.

Figure 7 Stryker MIS Endodrill with curved tip and 2 mm fluted burr.

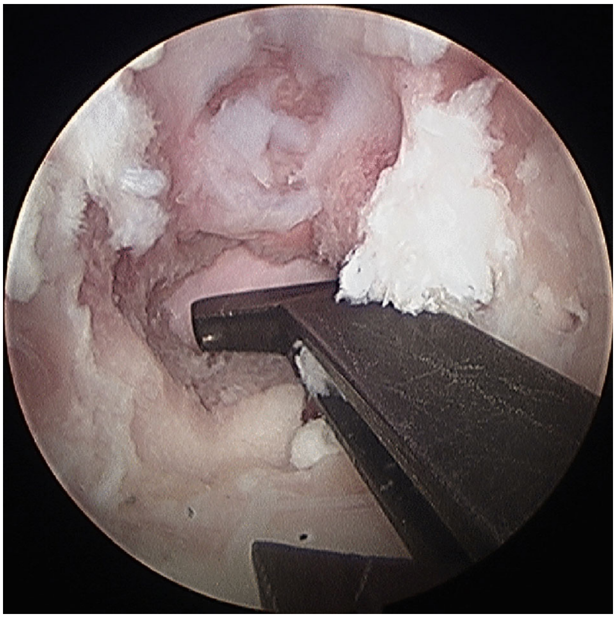

Figure 8 Endoscopic foraminotomy: endoscopic Kerrison rongeurs are used to enlarge the foraminotomy.

Figure 10 Foraminotomy through an illuminated port: the illuminated port is placed over the tubular dilator system. The dilators are next removed to allow introduction of instruments.

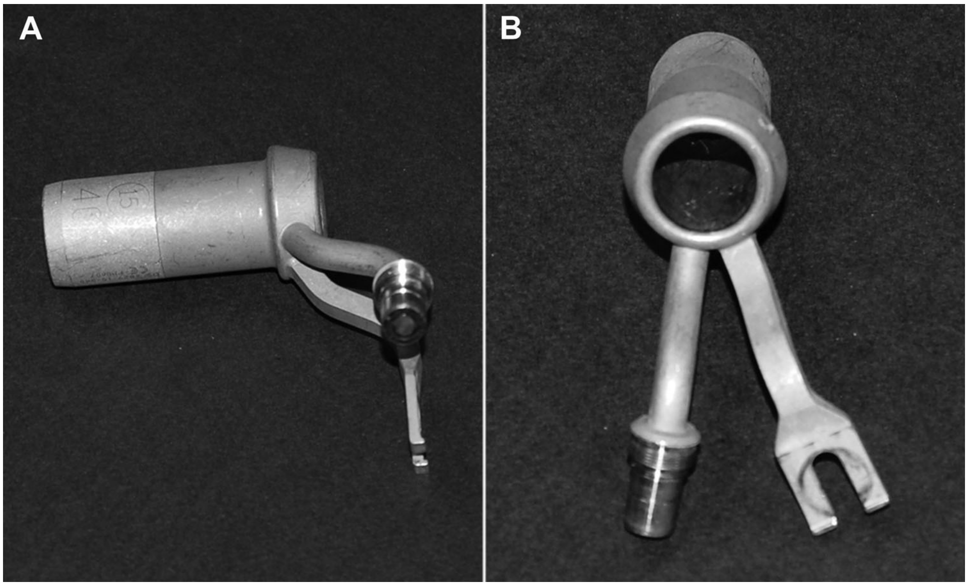

Figure 9 Spotlight illuminated retractor used in foraminotomy via illuminated port (DePuy). A = Side view; B = Frontal view

probability plots were evaluated for total area. Repeated measures ANOVA (RMANOVA) was used to test the hypotheses of no differences. Software (Systat 13, Systat Software Inc., Chicago, IL) was used for all analyses. Differences were considered significant when $P \leq .05$ and marginally different when $.05 < P \leq .1$.

RESULTS

As expected based on our inclusion criteria, mean ± SD weight for small dogs (9.94 ± 0.27 kg) was significantly less than large dogs (25.36 ± 3.07 kg; $P < .01$). In the small dog group, 4 of 5 dogs were Beagles and 1 dog was mixed-breed. In the large dog group, 3 were American Staffordshire Terriers and 2 were Labrador Retrievers.

Injection of the BA-gel yielded a consistency and appearance similar to that of extruded intervertebral disc material, while the barium facilitated CT evaluation. Injections of BA-gel under fluoroscopic guidance were not technically challenging and no attempt was made to lateralize the disc. Consequently, the distribution of the gel was ventral to the spinal cord in 3 spaces, ventral and lateralized to the left in 13 spaces, and ventral and lateralized to the right in 14 spaces. Although a portion of BA-gel spread along the spinal canal, CT evidence of compressive lesions were observed in 28 of 30 spaces. At 1 space, the BA-gel only coated the canal, and at another space, no BA-gel was found on preoperative images. The BA-gel frequently spread along the canal beyond the boundaries of the disc space as previously defined; however, the compressive aspects of the BA-gel were typically localized to the area where the injection was performed. As expected based on the volumes injected, the mean amount of BA-gel was greater in large dogs (317.8 ± 8.8 mm^2) than small dogs (193.1 ± 6.0 mm^2); however, there was no significant difference in the preoperative means between treatment groups, thereby allowing comparison between surgical procedures.

Five clinical cases of IVDH, confirmed by CT were analyzed to determine the quantity of herniated disc material within the canal using the same methods used to evaluate the BA-gel injections. Mean amount of disc material (265 ± 29.7 mm^2) was similar to the mean of all injected cases in our study (255 ± 4.3 mm^2).

The minimally invasive spinal procedures tested here differed in instruments used for retraction, bone removal, illumination and magnification of the surgical sites. The tubular retractor used for EF has a beveled end, preventing it from resting flush on the vertebral body, thereby allowing intraoperative penetration of surrounding soft tissues into the surgical field. The straight-ended illuminated port used for FP seemed to facilitate positioning and improve tissue retraction. Excellent observation of the foramen, nerve roots, spinal cord, and BA-gel was achieved with both techniques (Fig 12). No intraoperative complication or evidence of nerve root or spinal cord injury was noted. EF provided superior magnification and continuous lavage during burring of the vertebral bone and removal of BA-gel; however, removal of BA-gel was complicated by interference between the arthroscope and the instruments in the limited space offered by the retractor. In addition, the high-speed pneumatic burr cannot be used safely close to the scope and viewing was quickly obscured as debris occluded the tip of the scope. A high-speed pneumatic burr could be used through the illuminated port (FP), but required intermittent lavage to evacuate debris and maintain adequate viewing. The absence of a scope facilitated manipulation of instruments in the port. Viewing of the surgical field through the 3.5× magnification loupes used during FP was adequate,

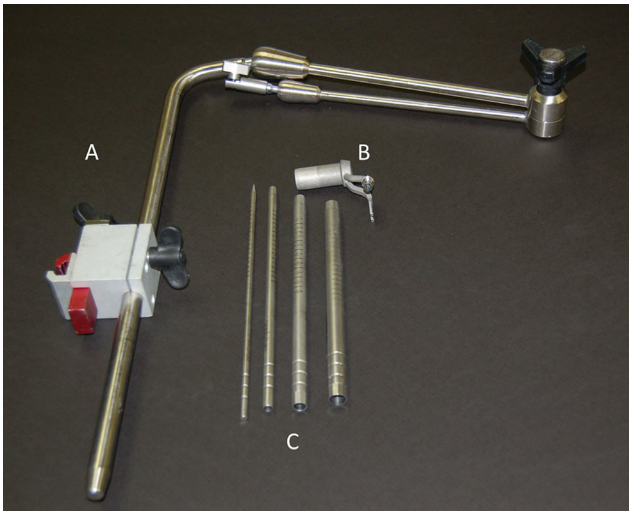

Figure 11 Instrumentation for foraminotomy via illuminated port: (A) Arm post and table clamp; (B) Spotlight illuminated port; (C) Dilators.

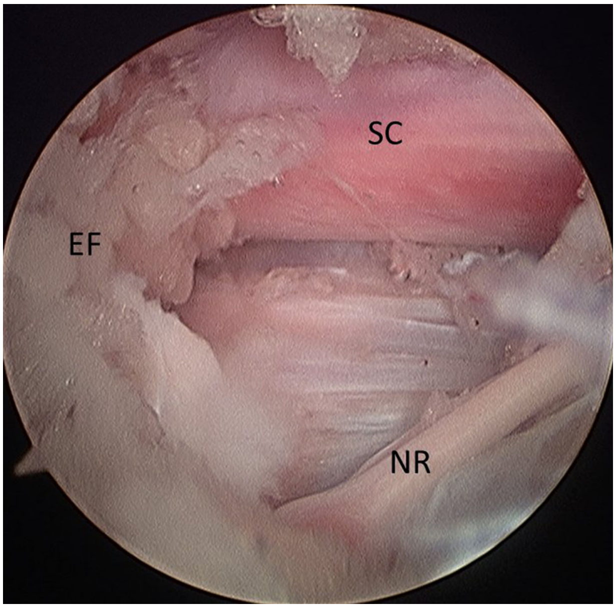

Figure 12 Endoscopic foraminotomy: foraminotomy with spinal cord (SC), nerve root (NR), and epidural fat (EF) visible.

Table 1 Mean ± SEM Incision Size, Vertebral Body Window Size, and Procedure Time for Foraminotomy Via Illuminated Port (FP), Endoscopic Foraminotomy (EF), and Standard Hemilaminectomy (SH)

	Incision Size (cm)			Window Size (mm^2)			Procedure Time (min)		
	<13 kg	>13 kg	All	<13 kg	>13 kg	All	<13 kg	>13 kg	All
FP	2.4 ± 0.04	2.5 ± 0.04	2.6 ± 0.04	25.2 ± 4.6	38.2 ± 10.4	31.7 ± 5.8	40.2 ± 3.4	39.0 ± 1.2	39.6 ± 1.7
EF	2.3 ± 0.06	2.4 ± 0.1	2.4 ± 0.08	22.8 ± 3.5	32.0 ± 5.0	27.4 ± 3.3	79.6 ± 11.3	71.4 ± 6.6	75.5 ± 6.3
SH	5.3 ± 0.31	8.3 ± 0.48	8.0 ± 0.63	31.2 ± 6.4	91.4 ± 28.0	61.3 ± 16.9	32.8 ± 5.6	32.6 ± 1.2	32.7 ± 2.7

Results are shown for the "Small Dog" group (<13 kg), the "Large Dog" group (>13 kg), and "All Dogs."

although instruments tended to obstruct the field of vision. From an educational standpoint, FP has limited value as the field of vision is restricted to the primary surgeon. In contrast, EF allows projection of the arthroscopic view on a monitor, as well as image and video capture.

Regardless of dog size, the surgical incisions were similar in the FP and EF groups and were both smaller ($P < .01$) than with standard hemilaminectomy (Table 1, Figs 13 and 14). Dimensions of the vertebral window created for minimally invasive procedures (EF and FP) were similar, and both were smaller than the window created during standard hemilaminectomy, when data from all 10 dogs were considered ($P = .04$; Table 1). Similar results were obtained when data were restricted to large dogs; however, no difference in window size was detected between procedures, when data were restricted to small dogs (Fig 15). Dog size therefore marginally influenced the dimensions of the vertebral window ($P = .079$). Window position was determined to be consistently located ventral to the articular facets and centered over the intervertebral disc space. Duration of EF was prolonged compared with FP and SH ($P < .02$, Table 1); these results were not influenced by dog size (Fig 16).

There was no difference in the amount of BA-gel removed by each procedure, regardless of dog size ($P = .52$, Fig 17). In other words, the amount of BA-gel removed by each procedure was similar in small dogs, in large dogs, and in all dogs. As expected, the amount of BA-gel postoperatively was significantly less than the amount of preoperative BA-gel for all treatments ($P < .001$). Residual BA-gel was present in all sites except 2 instances (1 SH, 1 EF) but did not seem to compress the spinal cord. Based on our subjective evaluation of the postoperative CT scans, the spinal cord tended to maintain its compressed shape even after decompression (Fig 1). We believe that this finding may be because of the use of cadavers in our study and the dehydrated nature of the spinal cord.

DISCUSSION

The minimally invasive techniques we tested were derived from previous descriptions in people. Minimally invasive

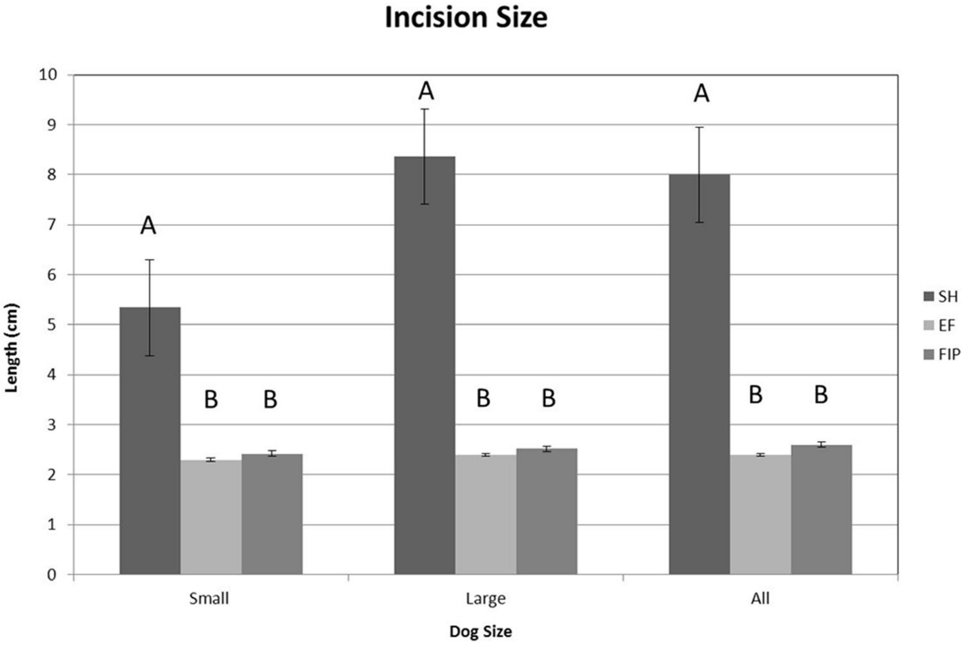

Figure 13 Length of the skin incision for foraminotomy via illuminated port (FP), endoscopic foraminotomy (EF), and standard hemilaminectomy (SH). Results are shown for the "Small Dog" group (<13 kg), the "Large Dog" group (>13 kg), and "All Dogs." Values presented as mean ± SEM.

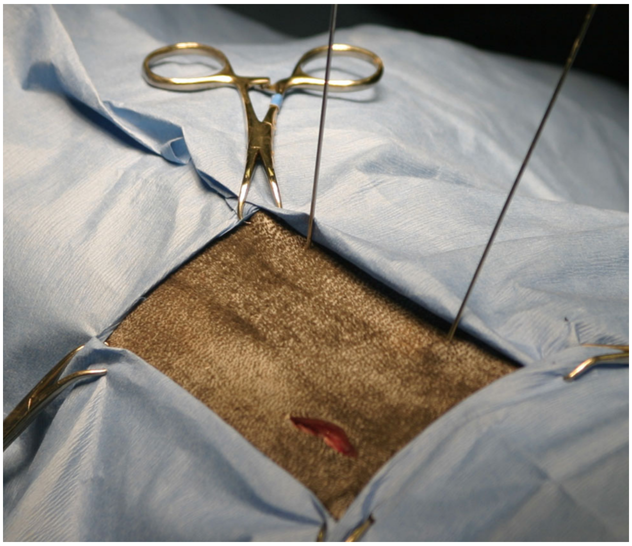

Figure 14 Placement of skin incision after removal of EF instrumentation and before closure. Note the position of the incision approximately 3 cm lateral to midline.

neurosurgery is frequently performed in people and has many advantages over open neurosurgical procedures. Insertion of a modified arthroscope into the intervertebral disk space was initially described in 1983.[25] Arthroscopic microdiscectomy consequently reached a success rate approximating 87%.[26] Tubular access to lumbar discs was proposed in 1991, leading the way for development of tubular retractor systems and low profile instrumentation.[27] The initial description of a MED was reported by Foley and Smith in 1997. Orthopedic surgeons quickly followed that trend because of their familiarity with arthroscopy.[15] The procedure is designed to replace extensive muscle dissection by sequential dilation of paraspinal muscles directly in line with the diseased disc space, under fluoroscopic guidance. These dilators are replaced by a tubular retractor, which, in the 2nd generation MED system, may be instrumented with endoscopy or standard microscopy.[28] These techniques have gained popularity because of public awareness and demand for minimally invasive treatments, but also because of their advantages over traditional open approaches. Schick et al concluded in their study of 30 people with lumbar disc disease that MED resulted in a smaller incision, less tissue trauma, and irritation of the nerve root with comparable viewing of nerve structures compared to the open approach.[18] These conclusions were based on the lower electromyographic (EMG) activity recorded during lumbar discectomy in people treated using an endoscopic medial approach compared those treated with open microscopic discectomy. These results concur with other publications reporting decreased blood loss and decreased need for postoperative analgesia in people treated by MED. Collectively, these benefits explain the shortened hospital stay and faster functional recovery with the minimally invasive discectomy.[26,29–32] The outcomes of minimally invasive spinal surgery do not seem affected by the body mass index of patients, suggesting that this approach is relevant to the management of overweight or obese people.[16]

In spite of the increasing popularity of minimally invasive surgery in veterinary medicine, few reports describe this

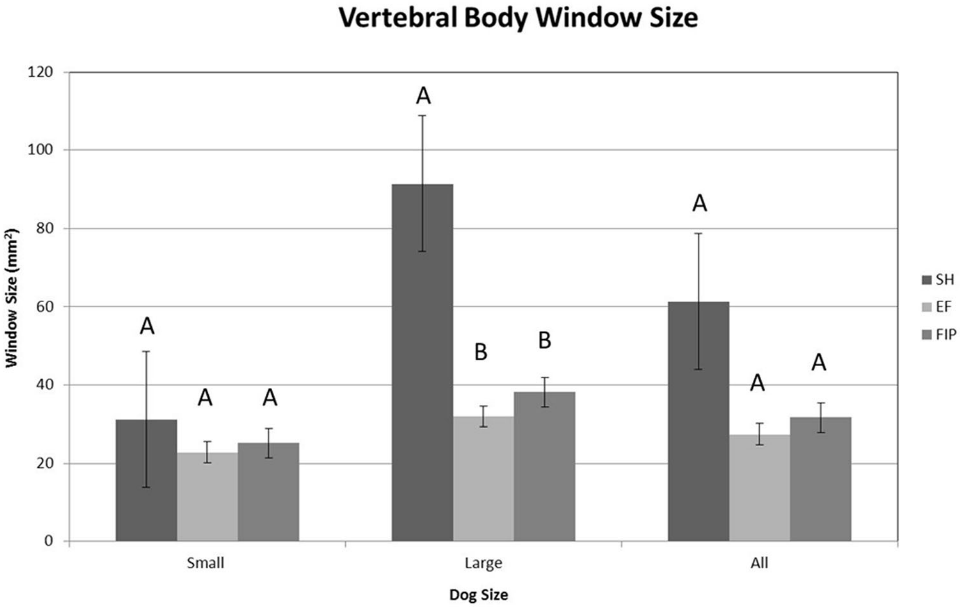

Figure 15 Area of vertebral body removed during foraminotomy via illuminated port (FP), endoscopic foraminotomy (EF), and standard hemilaminectomy (SH). Results are shown for the "Small Dog" group (<13 kg), the "Large Dog" group (>13 kg), and "All Dogs." Values presented as mean ± SEM.

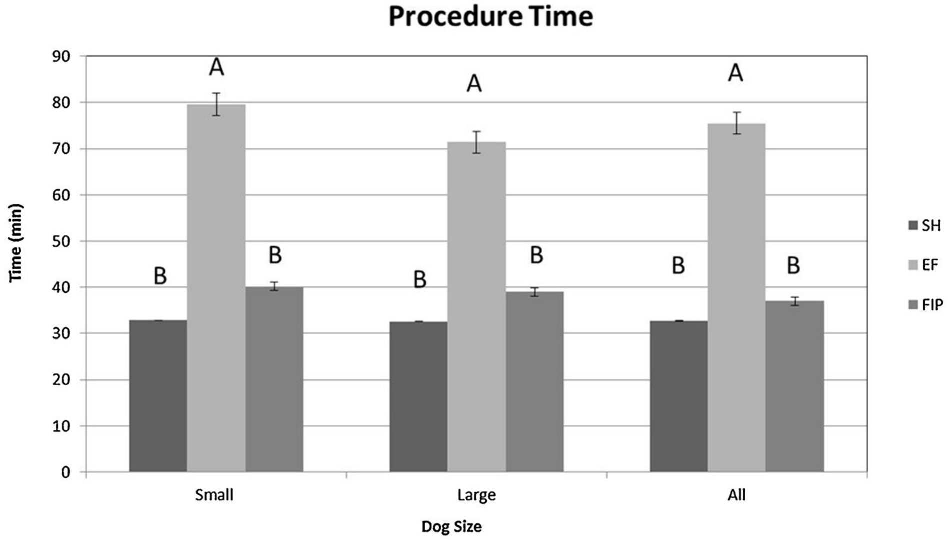

Figure 16 Procedure time for foraminotomy via illuminated port (FP), endoscopic foraminotomy (EF), and standard hemilaminectomy (SH). Results are shown for the "Small Dog" group (<13 kg), the "Large Dog" group (>13 kg), and "All Dogs." Values presented as mean ± SEM.

approach for spinal procedures in dogs. The first report of an endoscopic assisted approach to the spine in dogs described a foraminotomy over the lumbosacral space of 6 normal dogs.[33] This study supported the use of an arthroscope to improve viewing but did not use a minimally invasive technique for access and was not relevant to the thoracolumbar spine. Minimally invasive neurosurgical procedures have been described for the cervical spine and the lumbosacral region.[24] Two abstracts and a recent publication by Carozzo et al describe video-assisted, minimally invasive approach to the thoracolumbar spine in dogs.[22–24] These reports support the viability of a minimally invasive approach to the spine, but use

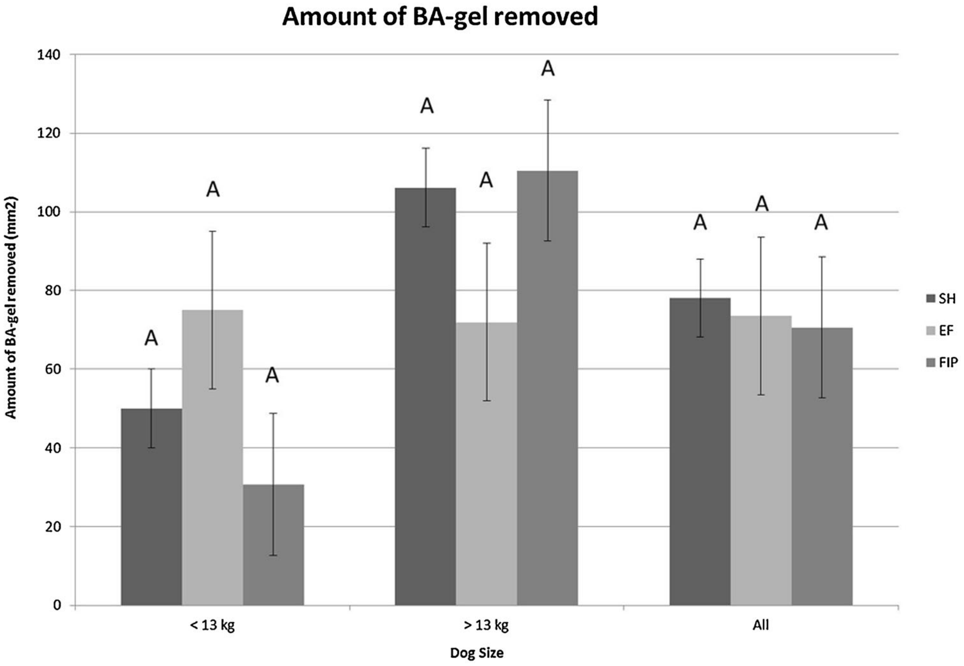

Figure 17 Amount of barium/agarose gel removed for foraminotomy via illuminated port (FP), endoscopic foraminotomy (EF), and standard hemilaminectomy (SH). Results are shown for the "Small Dog" group (<13 kg), the "Large Dog" group (>13 kg), and "All Dogs." Values presented as mean ± SEM.

Figure 18 Bayoneted instrumentation for minimally invasive spine surgery (DePuy; Stryker).

different instrumentation and decompressive strategy (corpectomy) than reported here.

The main goal of spinal surgery in dogs with IVDD is to alleviate compression by removal of herniated disc.[5] The amount of BA-gel seen on postoperative imaging studies was reduced compared with preoperative measurements, regardless of surgical procedure. Based on our results, minimally invasive foraminotomy using endoscopy or through an illuminated port allowed similar removal of simulated disc material as a standard hemilaminectomy. Some BA-gel remained visible on postoperative CT in all cases except 2 sites in small dogs (1 EF, 1 SH). On subjective evaluation of the postoperative sites, the remaining BA-gel did not appear to be sufficient to cause compression of the spinal cord. Based on the fact that some BA-gel remained in most sites (including the hemilaminectomy site), caution is warranted when extrapolating our data to clinical cases. In addition, the cadaveric nature of our study does not allow us to evaluate the potential impact of hemorrhage on the effectiveness of the procedures tested here. Hemorrhage is especially important after inadvertent laceration of the internal vertebral venous plexus. In our study, intraoperative observation was not impaired and no evidence of venous sinus laceration was noted; however, mild hemorrhage may also occur as a result of muscle dissection or may be present with extruded disc within the spinal canal. The resulting loss of view may be more important during minimally invasive than open spinal surgery because of the smaller operating field. Bipolar cautery and suction are adequate to limit hemorrhage during minimally invasive procedures in people.[13–15] Hemorrhage originating from the epaxial musculature may be less problematic in minimally invasive spinal surgery because of the use of the cylindrical retractor. Once the retractor has been placed and immobilized, the muscle is shielded from the surgical site. In our cadaveric study, the magnification and visual field afforded by endoscopy was excellent, and anatomic structures could be easily identified. While this superior view would not eliminate intraoperative complications such as hemorrhage in a pathologic condition, we feel the incidence of hemorrhage could perhaps be minimized.

We evaluated the efficacy of the procedures by creating a cadaveric model of IVDH using the injection of a gel that was similar in appearance and texture to extruded intervertebral disc material. Hydrogels, such as a barium and agarose gel, have frequently been considered in tissue engineering of the nucleus pulposus because of similarities in composition.[34] Agarose was chosen for this model because of its low cost, and because it can be mixed with radio-opaque material to facilitate fluoroscopic and CT viewing.[35,36] The BA-gel could be easily placed by injection so that the normal anatomy would not be disturbed and the barium component allowed it to be evaluated by CT. The gel was heated before injection but solidified quickly as it cooled, which allowed the formation of masses within the spinal canal. The compressive lesion produced each time was variable, similar to disc herniations in the clinical setting, based on reviews of computed tomographic findings of dogs with Hansen type I disc disease. Certain factors that commonly accompany disc rupture, such as hemorrhage and dural adhesions were not represented by the model. While no model can truly equal an actual disc herniation, the use of BA-gel injections provided a fair imitation of Hansen type I disk disease, thereby supporting the application of the techniques to dogs with isolated spinal cord compression. Minimally invasive approaches may be less appealing in dogs with extrusions at multiple sites, requiring multiple approaches or "wanding" of the retractor to adjacent sites.[15] This technique consists of adjusting the angle of the retractor in different directions to enlarge the field of view. Although our model was not designed to simulate Hansen type II disc herniation, these approaches may be worth considering, based on the ability to visualize the ventral floor of the spinal canal, especially under endoscopy, and the potential for decreased morbidity in large dogs. There was a significant difference in the amount of BA-gel seen in large dogs compared to small dogs before the procedures. This was expected as more BA-gel was injected at each disc space in the large dogs so that a compressive lesion could be produced in the larger spinal canal. Within the small dog group and within the large dog group, the amount of BA-gel on preoperative scans was similar between treatment groups. These findings lead us to conclude the model yielded consistent results and that it could be used for further research or teaching models.

The variety of dog breeds included in the study was based on availability of canine cadavers euthanized for reasons unrelated to the study and our criteria for inclusion based on body weight. Cadavers of Dachshunds could not be located for our study. However, we were able to obtain cadavers from Beagles, another small breed predisposed to IVDD. Landmarks seemed easier to identify in small dogs but the level of technical difficulty was overall similar between breeds of dogs. Although the conformation of each breed varies, especially with chondrodysplastic breeds, we do not believe the conformational differences in the spinal column would be significant enough in Dachshunds to preclude use of the techniques described.

The creation of a vertebral window allows visualization and access for spinal decompression in dogs with IVDD. The size of the vertebral window was compared between procedures tested in our study because compressive lesions are rarely localized to the canal directly above the disc space. Instead, they often extend cranial and caudal to the site of herniation. In our study, the size of the window created during each approach was similar in dogs weighing <13 kg. However, the window created during hemilaminectomy tended to be larger ($P=.079$) than during either minimally invasive approach in large dogs. We used the same tubular retractor in all dogs, with a diameter of 15 or 16 mm. In most small breed dogs, this diameter covers enough space to access the spinal canal on each side of the intervertebral disc space. In large breed dogs, this diameter was sufficient to allow foraminotomy, but further exposure was not adequate. The window was consequently enlarged, as needed to remove simulated disc material, using a technique referred as "wanding" in the human literature. This approach tailors the extent of the bone window to the individual needs of the patient. In contrast, the hemilaminectomy was performed using standard landmarks. This procedure was chosen as our control treatment because this technique is well described and the outcomes are documented thoroughly in the veterinary literature.[3] In addition, standard hemilaminectomy remains the approach most commonly used by surgeons and represents the standard of care in our institution. Procedures such as the pediculectomy and mini-hemilaminectomy have been described to allow spinal cord decompression while minimizing muscle dissection and preserving vertebral stability.[3] Selecting either of these procedures as our control group may have eliminated the difference in the sizes of vertebral windows created in large dogs. Indeed, mini-hemilaminectomy and pediculectomy preserve the zygapophyseal joint and would therefore be expected to preserve vertebral stability to the same extent as the minimally invasive techniques tested here. However, mini-hemilaminectomy and pediculectomy both require dissection and retraction of the epaxial muscles. Future studies would be warranted to compare open mini-hemilaminectomy techniques with minimally invasive approaches, and determine the clinical significance of differences.

Our study provides some evidence to suggest that both minimally invasive approaches were equally effective in minimizing soft tissue morbidity. The skin incision was similar between sites approached via endoscopy or through an illuminated port, and was smaller than in the hemilaminectomy group, regardless of dog size (small dogs, large dogs, and all dogs). Muscle penetration paralleled the skin incision and muscle trauma was therefore not individually assessed in our study. In human neurosurgery, several methods have been proposed to objectively assess the difference in soft tissue morbidity between MED and open techniques. One study evaluated serum creatinine phosphokinase (CPK) levels and visual analog scale (VAS) scores of postoperative pain 1 and 5 days after open surgery or MED and found both pain and CPK to be significantly higher at both time points in patients who had open procedures.[19] Other studies reported a relationship between open procedures and long-term back pain because of increased muscle damage when compared with MED.[37] Several publications have documented direct correlations between the length of muscle retraction during a procedure and chronic back pain and magnetic resonance imaging has been used to document that muscle injury is significantly greater 3 months after surgery in people with prolonged muscle retraction.[19,38,39] Intraoperative EMG studies have found irritation of nerve roots to be greater with open techniques.[18] Although the cadaveric nature of our study prevents the use of these techniques, these results justify the development of neurosurgical techniques that minimize the degree of muscle damage and retraction required during decompressive procedures as a strategy to limit postoperative pain and improve long-term function.

The preservation of muscle tissues during minimally invasive approaches could also contribute to preserving the stability of the spine compared to a traditional hemilaminectomy. Indeed, the approach for a standard hemilaminectomy required the paraspinal muscles (*longissimus* and *transversospinalis* muscle groups) to be detached from the vertebrae. A decrease in the stiffness of an intervertebral joint has consequently been documented after experimental hemilaminectomy in canine cadavers.[40] Although the clinical relevance of these findings remain unclear, the use of a muscle-splitting approach in minimally invasive procedures precludes the need for musculotendinous detachment of these muscle groups, and may therefore preserve the muscle support surrounding the spine. The preservation of the zygapophyseal joint during foraminotomy would further contribute to the stability of the spinal column, in patients undergoing minimally invasive foraminotomy rather than open hemilaminectomy.

The minimally invasive approaches we used were designed to evaluate 2 strategies to achieve viewing of the surgical sites. These strategies influenced the instrumentation required to create a bone window under magnification and illumination. Subjectively, the magnification and illumination provided by a scope improved observation of the spinal cord and adjacent structures, compared to other approaches. The superior view provided by videoscopy is well established and has greatly improved assessment of joint diseases in small animals.[41]

Duration of EF was twice as long in all groups of dogs compared with the other 2 procedures. Interference between the scope and the instrumentation contributed to this difference and was most problematic during the approach. Differences in the drills used for each procedure also likely played a role. Only the less aggressive endodrill was used for EF procedures, as the size of the pneumatic drill precluded its use in conjunction with the scope. During FP procedures, the pneumatic burr was used for most of the approach and the endodrill was used once the inner cortex was reached. For the SH procedure, the pneumatic drill was used for the entire approach, as is done clinically. The procedure times for EF decreased throughout the study indicating progression along a learning curve, whereas FP and procedure times remained stable throughout. Beside technical factors, cost may be another consideration influencing the selection of a surgical approach.

Most of the equipment used would be available in a hospital performing videoscopic surgery and standard surgical treatment of IVDD. Instruments specific to the foraminotomy via illuminated port included dilators, illuminated port, arm post, and magnifying loupes. Those required for EF included dilators, non-illuminated retractor, snake arm post and endoburr. These instruments were loaned for the study but their cost for human surgery would be ~$9–10,000 for the foraminotomy via illuminated port and $11–12,000 for the endoscopic approach. Instruments designed for endoscopic surgery such as Kerrison rongeurs, nerve root retractors, and curettes are advantageous given the size and depth of the surgical site (Fig 18). Because of the large size of the bayoneted instruments that were manufactured for use in people, we used our own spinal instrumentation for most cadavers except the larger dogs. Adaptation of the equipment for a veterinary surgery may improve the cost effectiveness of these techniques in the future.

Fenestration of herniated discs at the time of cord decompression may reduce the risk for re-herniation.[3,42] Whereas we did not perform fenestration of the intervertebral disc, the dorsal aspect of the intervertebral disc space was readily apparent and approachable. We feel that disc fenestration via the minimally invasive techniques would be feasible by "wanding" or angling of the retractor. Based on personal experience on cadavers, we believe that videoscopic guidance improves observation of the surgical site, thereby facilitating fenestration. Magnification assists in proper localization of relevant structures and disk material, potentially decreasing the risk of iatrogenic complications while improving disk removal.

EF and foraminotomy via illuminated port both were feasible in small and large dogs. Both techniques allowed similar removal of simulated disc material compared with SH. Both minimally invasive approaches could be performed through a smaller skin incision, compared with a standard hemilaminectomy, regardless of dog size. Compared to the use of an illuminated port, EF subjectively improved observation of the spinal canal and allowed display of the procedure on a monitor for educational purposes. However, this technique was associated with a prolonged surgical time, because of the use of an endoscopic burr and interference between the scope and instruments complicating the removal of simulated disk. Further studies should focus on adapting the instrumentation to small animals, and exploring the possibility of combining an initial approach through an illuminated port, with a final endoscopic approach. Ultimately, further trials will be warranted to evaluate visual access in a live dog, morbidity and clinical outcome in dogs with IVDH.

ACKNOWLEDGMENT

We thank the DePuy Spine and Stryker companies for providing the instrumentation used in the study. We would also like to thank Sue Hewitt for her technical assistance.

DISCLOSURE

The authors report no financial or other conflicts related to this report.

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