Comparison of the biomechanical performance of a customized unilateral locking compression plate with and without an intervertebral spacer applied to the first and second lumbar vertebrae after intervertebral diskectomy in canine cadaveric specimens

Julie Selz DVM

Benjamin Voumard MSc

Franck Forterre DVM

Received November 10, 2019.
Accepted March 10, 2020.

From the Division of Small Animal Surgery, Department of Clinical Veterinary Medicine, Vetsuisse Faculty (Selz, Forterre), and Institute for Surgical Technology and Biomechanics (Voumard), University of Bern, 3014 Bern, Switzerland.

Address correspondence to Dr. Forterre (franck.forterre@vetsuisse.unibe.ch).

OBJECTIVE
To determine whether a customized unilateral intervertebral anchored fusion device combined with (vs without) an intervertebral spacer would increase the stability of the L1-L2 motion segment following complete intervertebral diskectomy in canine cadaveric specimens.

SAMPLE
Vertebral columns from T13 through L3 harvested from 16 skeletally mature Beagles without thoracolumbar disease.

PROCEDURES
Complete diskectomy of the L1-2 disk was performed in each specimen. Unilateral stabilization of the L1-L2 motion segment was performed with the first of 2 implants: a unilateral intervertebral anchored fusion device that consisted of a locking compression plate with or without an intervertebral spacer. The resulting construct was biomechanically tested; then, the first implant was removed, and the second implant was applied to the contralateral side and tested. Range of motion in flexion and extension, lateral bending, and torsion was compared among intact specimens (prior to diskectomy) and constructs.

RESULTS
Compared with intact specimens, constructs stabilized with either implant were as stable in flexion and extension, significantly more stable in lateral bending, and significantly less stable in axial rotation. Constructs stabilized with the fusion device plus intervertebral spacer were significantly stiffer in lateral bending than those stabilized with the fusion device alone. No significant differences in flexion and extension and rotation were noted between implants.

CONCLUSIONS AND CLINICAL RELEVANCE
Findings did not support the use of this customized unilateral intervertebral anchored fusion device with an intervertebral spacer to improve unilateral stabilization of the L1-L2 motion segment after complete L1-2 diskectomy in dogs. (*Am J Vet Res* 2020;81:915–921)

Trauma is a common cause of spinal cord injury in dogs and is frequently associated with vertebral column fractures, luxation, and subluxation. Vertebral column fractures and luxation account for 7% of all neurologic disorders in dogs.[1] The objectives of surgical management of these conditions are to realign the vertebral canal, decompress the spinal cord, and stabilize the vertebral column.[2,3]

ABBREVIATIONS

ESF	External skeletal fixation
IVD	Intervertebral disk
LCP	Locking compression plate
LCP-IS	Locking compression plate with intervertebral spacer
PMMA	Polymethyl methacrylate
ROM	Range of motion

Various internal fixation techniques have been described for the stabilization of vertebral motion segments.[2–6] Most fixation devices are applied bilaterally to provide sufficient stability against rotation. The implantation of prosthetic vertebral body cages has been described as safe and effective in people for increasing the stability of vertebral motion segments in the thoracolumbar region[7,8] and seems promising for use in dogs with cervical spondylomyelopathy.[9] Yet, the veterinary literature[6,10] indicates that a bilateral internal fixation technique involving dorsal placement of pins or screws and PMMA remains the standard of care for stabilization of the thoracolumbar region in dogs with vertebral fractures and luxations, although successful unilateral stabilization with this technique has been reported.[6] The principal advantages of bilateral fixation with pins and PMMA are its excellent strength and stability against flexion, extension, and rotation.[11,12] However, implantation of PMMA has been associated with an increased risk of infection,[13] compromised periosteal blood supply and superficial bone viability because of tissue necrosis,[14] and difficult surgical wound closure.[15] Although uncommon, ESF has also been used successfully in dogs for vertebral column stabilization.[16–19] Compared with bilateral fixation with pins and PMMA, advantages of ESF include less soft tissue dissection and easy removal of applied fixation devices after healing.[2,18] Disadvantages of ESF are related to pin maintenance (eg, bandage changes and pin tract disinfection), pin tract inflammation, and possible traumatic dislodgment of pins or bars.[16,19] The dorsal approach necessary for pin and PMMA fixation and ESF typically involves extensive bilateral dissection of the epaxial musculature and, therefore, increased tissue trauma and risk of destabilization through disruption of the supraspinous and interspinous ligaments, compared with a unilateral approach.[19]

Unilateral fixation, however, may be advantageous to bilateral fixation because the epimysium of the contralateral epaxial muscles largely remains intact and the interspinous tissues of the spinous processes and the strong dorsal fascia remain undisturbed. Therefore, the injured but repaired vertebral column is better stabilized in the postoperative period when these soft tissues remain intact.[6] Additionally, the duration of surgery may be shorter, the segmental blood supply may be less disrupted,[10] and, because of less surgical trauma, the postoperative comfort of patients may be improved. Use of a unilateral fixation technique with materials other than pins, screws, and PMMA may also avoid the previously mentioned possible adverse consequences associated with bilateral fixation and PMMA. A biomechanical study[6] involving canine cadaveric specimens revealed that when bent in flexion, the lumbar portion of the vertebral column was noninferior in strength and stiffness when unilateral versus bilateral stabilization was applied.

Stabilization of the cervical vertebral column can be achieved in dogs with a standard LCP or an LCP with an intervertebral spacer or other devices.[9,20–23] The intervertebral spacer may restore disk and foraminal dimensions and stabilize the affected vertebral motion segment until bony fusion has occurred. However, to the authors' knowledge, stabilization of the thoracolumbar portion of the vertebral column of dogs with an LCP and intervertebral spacer has not been reported.

The purpose of the study reported here was to determine whether a customized unilateral intervertebral anchored fusion device that combined an LCP with an intervertebral spacer increased the stability, compared with the fusion device without an intervertebral spacer, of the L1-L2 motion segment after complete diskectomy of the L1-2 disk in canine cadaveric constructs. We hypothesized that the fusion device with the intervertebral spacer would enhance the stability of the construct in flexion and extension, lateral bending, and torsion.

Materials and Methods

Specimen preparation and handling

The study was approved by the University of Bern faculty ethical committee. The cadavers of 16 skeletally mature Beagles (9 females and 7 males) euthanized for reasons unrelated to this study were obtained. Mean age and body weight of the dogs were 5 years and 14 kg, respectively, and no dog had a history of thoracolumbar disorders. Ventrodorsal and lateral radiographic projections of the thoracolumbar vertebral column confirmed the closure of growth plates and absence of preexisting skeletal abnormalities that could have affected the results of this study. For each dog, the entire thoracolumbar portion of the vertebral column including the surrounding musculature was harvested within 12 hours after euthanasia and then stored at –20°C. The portions were later thawed at room temperature (approx 23°C) for 24 hours, and the segment T13 through L3 was dissected from the other tissues, including the associated soft tissues (ie, paravertebral musculature and the intertransverse, supraspinous, and interspinous ligaments), without disturbing the underlying facet joint capsules and IVD. Each of these specimens was then individually wrapped in a cotton towel that was soaked in saline (0.9% NaCl) solution, placed in a plastic bag, and stored at –20°C until the time of construct preparation and testing.

The specimens were thawed at room temperature for 24 hours before construct preparation and testing. They were regularly moistened with saline solution during preparation and testing and wrapped in saline solution–soaked cotton gauze between testing cycles to prevent dehydration of the IVDs and adnexal structures.

Implants

A titanium thoracolumbar intervertebral anchored fusion device[a] was custom manufactured to fit the vertebrae of the thoracolumbar region of Beagles on the basis of preliminary work involving CT evaluation of cadaveric specimens. The device combined a conventional LCP with an intervertebral spacer manufactured to match the shape of a vertebral body in this region. The LCP was composed of 4 threaded screw holes **(Figure 1)**. The fixed angle of the monocortical locking screws used with the plate made the need for precise contouring of the plate to the irregular vertebral body surface less critical than it would be with a nonlocking device. Half of the devices were manufactured for use on the left side of the vertebral column and the other half for use on the right side by changing the position of the spacer. The same LCP manufactured without the intervertebral spacer was used for LCP fixation.

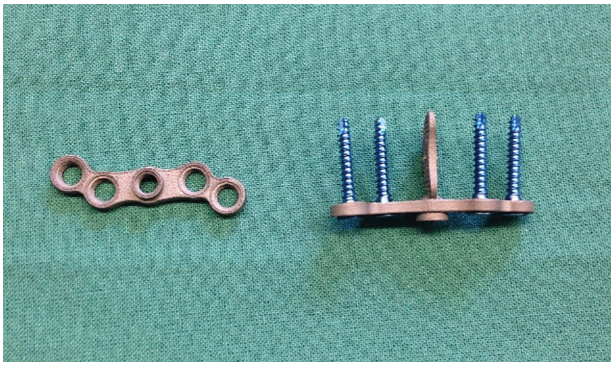

Figure 1—Photograph of a customized titanium thoracolumbar intervertebral anchored fusion device without (left; view from side) and with (right; view from top) an intervertebral spacer and four 2.7-mm monocortical locking screws.

Stabilization procedures

After stability testing of the intact specimens, complete L1-2 diskectomy was performed with a No. 11 scalpel blade. The articular processes were not manipulated. The transverse processes of L1 and L2 were removed with rongeurs to create a plane on the vertebral bodies that allowed placement of the LCP without the need to bend and contour it. Screw direction and plate placement were the same for all constructs. The L1-L2 motion segment was then stabilized with the first of 2 implants (LCP-IS or LCP).

For stabilization with the LCP-IS, the intervertebral spacer was inserted into L1-2 and the LCP was positioned ventrally to the intervertebral foramen to ensure correct placement of the screws in the vertebral body without compromising the vertebral canal. The implant was secured with 4 monocortical 2.7-mm self-tapping screws. This type of screw was chosen on the basis of a previous study,[24] and screw length was determined with pretesting CT examination of the cadaveric specimens. Because the canine cadavers used in this study were of the same size, the purchase of the screws into the vertebral bodies was comparable for all cadavers (ie, > two-thirds of the diameter of the vertebral body). Adjustment and placement of the LCP without the intervertebral spacer were performed similarly.

Biomechanical testing of constructs

To prevent motion of the T13-L1 and L2-L3 segments, 2 crossed transarticular 1.8-mm Kirschner wires and, in a ventrodorsal direction, one 2.7-mm-diameter cortical screw were applied across T13-L1 and L2-3. Then, each end of the construct (T13 and L3) was inserted into a customized metal mold designed for the simulation of pure moment loading and held in place with 4 large screws **(Figure 2)**. Polymethyl methacrylate cement[b] was cast in the custom molds to form 2 encasing blocks that only allowed movement between L1 and L2.

The embedded constructs were attached with the metal molds to a customized vertebral column loading simulator with 6 linear degrees of freedom.[25] While the construct was allowed to move in an unrestricted 3-D fashion, 3 orthogonally mounted electric motors[c] applied pure moment loading with a constant angular velocity (1°/s) until a torque of 2 N·m or –2 N·m was reached. The acting moments and forces were measured with a 6-axis load cell[d] at the cranial end (T13) of the specimen. Markers with light-emitting diodes were fixed cranially and caudally to the construct to record the 3-D pattern of motion. The spatial positions of the light-emitting diodes were tracked by an optoelectronic camera[e] positioned 2 m from the markers (nominal marker resolution, 0.1 mm) and recorded continuously at a frequency of 100 Hz. The angles between the cranial and caudal platform of the vertebral column loading simulator were calculated and synchronized with the torque data.

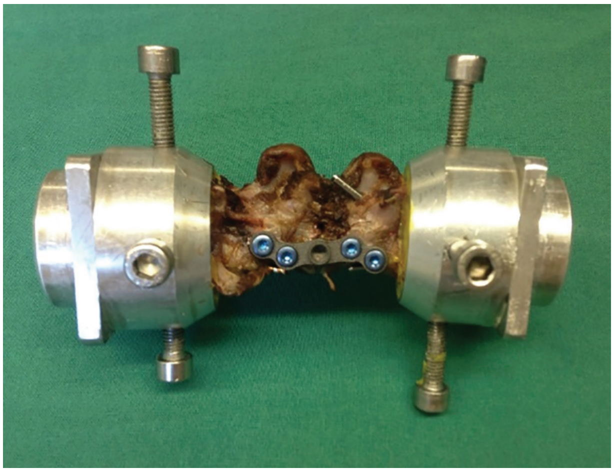

Figure 2—Photograph of customized metal molds with an L1-L2 construct prior to biomechanical testing. To create the construct, the T13-L3 motion segment including surrounding soft tissues was harvested from a Beagle cadaver, complete diskectomy was performed at L1-L2, and an LCP or LCP-IS as shown in Figure 1 was applied.

Each L1-L2 construct was first tested intact, after complete L1-2 diskectomy and unilateral stabilization with one of the implants, and lastly after removal of the first implant and stabilization with the other implant on the contralateral side. Testing was not performed after complete diskectomy without stabilization with an implant because of the severe instability induced after diskectomy, which may have led to complete luxation of L1 and L2. Specimens were randomly assigned to 4 groups by use of a computer-generated random number table; 1 group represented each possible combination of order of side (right vs left) and stabilization method (LCP-IS vs LCP), with 4 constructs/group: LCP-IS left and then LCP right, LCP-IS right and then LCP left, LCP left and then LCP-IS right, and LCP right and then LCP-IS left. Testing of each construct was completed in < 2 hours.

Each construct was tested successively in flexion and extension, lateral bending in both directions (towards and away from the implant), and right and left torsion for 4 complete loading-unloading cycles.

Table 1—Range of motion (%), relative to the ROM for intact specimens,* under various biomechanical testing conditions for L1-L2 constructs prepared from cadavers of 16 skeletally mature Beagles following complete L1-2 diskectomy and application of a customized titanium thoracolumbar intervertebral anchored fusion device with (LCP-IS) or without (LCP) an intervertebral spacer.

	LCP-IS		LCP	
Condition	**Mean (SD)**	**Range**	**Mean (SD)**	**Range**
Flexion and extension	100.83 (17.06)	71.99–133.78	103.72 (18.89)	76.67–138.69
Lateral bending	71.82 (8.44)†	61.86–89.06	79.48 (10.09)†	58.66–95.82
Torsion	203.73 (36.61)	139.07–267.37	208.29 (36.29)	163.78–268.94

Torsion data represent results for only 12 constructs.
*Considered to have 100% ROM. †Indicates significant ($P < 0.05$) difference between implants.

The first cycle was conducted to set the construct at a starting position to minimize the viscoelastic creep effect. Testing order was the same for all specimens. The caudal platform of the vertebral column loading simulator was free to translate in x-, y-, and z-axes by means of air bearings. The mean of the last 3 loading-unloading cycles was calculated with a customized code.[f] The difference between the angles at torques of 2 N·m and –2 N·m was defined as the ROM. The relative ROM of the treated segment (LCP-IS or LCP) was defined as the percentage of the ROM relative to the ROM of the untreated segment (intact specimen), which was considered to have 100% ROM. The neutral zone was defined as the region in the load-displacement curve in which intervertebral motion with little or no resistance was evident.[26]

Statistical analysis

Statistical analyses were performed with a software program.[g] The Shapiro-Wilk test was performed to determine whether the data were normally distributed. The ROM and neutral zone data were compared between the 2 implants (LCP-IS and LCP) with the Mann-Whitney test. The effect of testing order on these data was not evaluated because we assumed testing order did not influence ROM and torque owing to probable symmetry of the constructs and their stability throughout the maximum 2-hour testing period. Values of $P < 0.05$ were considered significant.

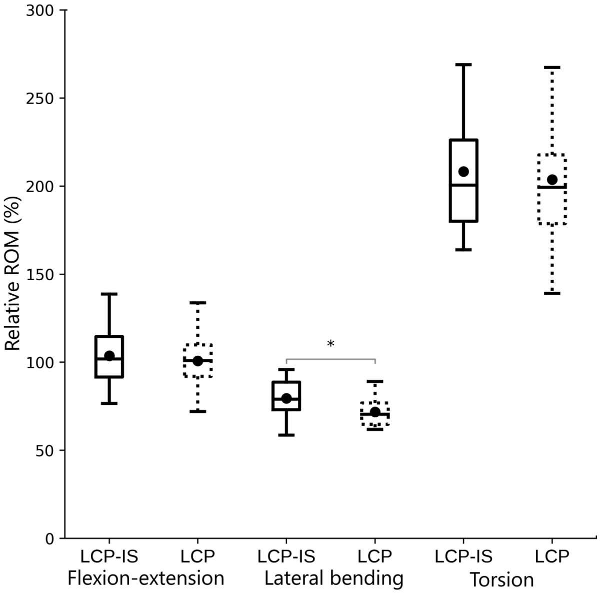

Figure 3—Box-and-whisker plots showing the ROM (%) in flexion and extension, lateral bending, and torsion of the L1-L2 constructs of Figure 2, relative to the ROM of the intact specimens (considered to have 100% ROM), after L1-2 diskectomy and application of an LCP-IS or LCP. For each plot, the horizontal line within each box represents the median, the box represents the interquartile (25th to 75th percentiles) range, and the whiskers represent the range. The circles within each box represent the mean. Torsion data represent results for only 12 constructs. *Relative ROM was significantly ($P = 0.033$) less in lateral bending with the LCP-IS than with the LCP.

Results

All 16 specimens were suitable for testing of flexion and extension and lateral bending with both implants. The torsion data of 4 specimens, however, were excluded from analysis because the stabilization had been too rigid, such that the loading simulator could not perform the 3 loading-unloading cycles in the correct order; therefore, they could not produce readable load-displacement curves. The L1-L2 motion segment of each construct was inspected after testing, and only 1 construct had slight screw pullout. The load-displacement curve of each construct had a characteristic sigmoid shape.

Mean ROM in flexion and extension was not significantly different between intact specimens and L1-L2 constructs stabilized with an LCP or LCP-IS. In lateral bending, constructs stabilized with an LCP-IS (mean, 24.23°; SD, 6.34°; range, 14.77° to 34.37°) or LCP (26.57°; 6.23°; 16.70° to 38.82°) had significantly ($P < 0.001$) smaller ROMs than did intact specimens (33.47°; 6.67°; 22.80° to 47.28°). In torsion, constructs stabilized with an LCP-IS (mean, 9.68°; SD, 2.20°; range, 6.23° to 13.28°) or LCP (10.16°; 2.14°; 7.34° to 14.48°) had significantly ($P < 0.001$) higher ROMs than did intact specimens (5.04°; 1.21°; 0° to 6.82°).

Mean relative ROM in lateral bending was significantly ($P = 0.033$) lower for constructs stabilized with the LCP-IS than for constructs stabilized with the LCP **(Table 1; Figure 3)**. Mean relative ROM for both implants was not significantly different in flexion and extension and torsion (**Supplementary Table S1**, available at: avmajournals.avma.org/doi/suppl/10.2460/ajvr.81.12.915).

No significant difference was noted between the percentages, relative to the intact specimens, of the neutral zone in the load-displacement curves for constructs stabilized with either implant. Regardless of the implant used, the side of unilateral stabilization performed first (right then left vs left then right) yielded no significant difference in mean relative ROM in flexion and extension, lateral bending, and torsion.

Discussion

The aim of the study reported here was to determine whether a customized unilateral thoracolumbar anchored fusion device with an intervertebral spacer (LCP-IS), compared with a customized fusion device alone (LCP), would increase the stability of the L1-L2 motion segment after complete L1-2 diskectomy in dogs. Use of the same fusion device without the intervertebral spacer for unilateral LCP fixation allowed for direct comparison of the biomechanical test results and isolation of the effects the added spacer had on the results. The L1-L2 motion segment was evaluated because fractures and luxations generally occur at junctions between mobile and immobile sections of the vertebral column and the thoracolumbar region is most frequently affected in dogs.[1,27]

The results of this study indicated that unilateral stabilization with both implants reduced ROM in lateral bending, compared with the intact specimens. These results were consistent with those of a recent study[10] in which the biomechanical properties of a conventional LCP were compared with those of positive-profile pins and PMMA for stabilization of the L1-L2 motion segment. However, the addition of an intervertebral spacer to the LCP in the present study provided better stability in lateral bending, compared with that reported[10] in the other study.

Likewise, in the present study, unilateral stabilization provided as much stability in flexion and extension as that of intact specimens. These results were also consistent with the results of the previous study,[10] in which ROMs in flexion and extension were not different between LCP and intact specimens. With vertebral column fractures and luxations in dogs, the vertebral column loses its ability to withstand forces in flexion when its ventral components are unstable.[10] Because flexion and extension are the predominant motions of the thoracolumbar region in dogs, these motions are likely the most important to counteract when stabilizing a fracture and luxation.[10–28] Although adding an intervertebral spacer improved stability in lateral bending, its addition did not improve the stability of constructs in flexion and extension.

Axial torsion is also an important force acting on the thoracolumbar portion of the vertebral column. The facet joints of the caudal thoracic and lumbar vertebrae play an important role in transferring axial torsion to the pelvis.[29] This allows the lumbar motion segment to be loaded under torsion, whereas torsional moments in the thoracic motion segment must be compensated by muscular forces.[29] Furthermore, the IVD provides the single most important contribution to the rotational stability of the vertebral column in dogs.[11] Few studies[11,17] have evaluated the effect of unilateral and bilateral stabilization on the rotational stability of the thoracolumbar region. One study[11] revealed that constructs with dorsally placed pins and PMMA provide the greatest rotational stability and strength, compared with Lubra plates applied to the spinous processes, vertebral body plates, and a combination of vertebral body and dorsal spinal plates. Yet their rotational stability and strength were inferior to those of intact specimens.[11] A recent study[17] of the L3-L4 motion segment, however, revealed that ROM during rotation was not significantly different between intact specimens and those stabilized with bilaterally applied pins and PMMA or ESF. The 2 implants evaluated in the present study did not allow the stabilized constructs to regain as much stability in rotation as the intact specimens. This may be explained by the unilateral, monoplanar nature of the stabilization techniques. To our knowledge, no study has been reported that shows stability in rotation of a unilateral fixation technique similar to that of intact vertebral columns.

The only major advantage of both implants evaluated in the present study was the lateral surgical approach to affix them. The intervertebral spacer of the LCP was designed to fill the space created by a complete diskectomy, as may be required because of a torn IVD and vertebral column luxation, but it was not designed to cause marked distraction of the motion segment. In other words, its intended use was for situations in which the spacer can be easily introduced into the intervertebral space. Yet spacers of variable widths inserted into the intervertebral spaces may allow for greater distraction of the affected motion segment and act as a buttress and, therefore, impart better stability in all directions. In addition, placing the locking screws in a bicortical fashion may improve the rotational stability of the implant[10]; comparisons between unicortical and bicortical constructs of the lumbar portion of the vertebral column, however, have not yet been reported.

One of the limitations of the present study was only specimens from skeletally mature Beagles were used, with the aim to obtain a sufficient number of specimens with similar anatomic features. The use of skeletally mature dogs may have allowed for better anchorage of the screws in the bone, compared with the use of skeletally immature dogs, and thus influenced the stability of the implants.

Furthermore, the results of this ex vivo study cannot completely reflect the in vivo state. The vertebral columns were freed from the stabilizing epaxial musculature, thereby not accounting for the in vivo influences of this musculature, the fascial planes, and the abdominal muscles. The axial compression created by the musculature, in combination with the intervertebral spacer of the LCP, may yield greater stability than that shown in the present study. Also, storage of the specimens at –20°C and subsequent freeze-thaw cycles may have affected the results reported here. However, no specimens underwent freeze-thaw cycles between tests, and studies[30,31] show no influence of multiple freeze-thaw cycles on the biomechanical properties of vertebral column specimens from porcine and human cadavers.

Because in vivo loading of the vertebral column in dogs is complex and not fully understood, physiologic forces applied to the constructs of the present study may not have been accurate representations of those applied to the vertebral column of live dogs.[26] Moreover, the complexity of the vertebral column and the dynamic nature of healing fractures make modeling of clinical loading conditions difficult. The amount of vertebral column stability necessary for bony union and the maximal angulation of the vertebral canal that does not cause spinal cord compromise have not yet been quantified.[17,32] For this reason, when the performances of implants are compared, they must be compared with performances of others that have been similarly tested, biomechanically or clinically.

Also, the LCP-IS was initially designed for vertebral column luxation secondary to a tear in an IVD, such that after complete diskectomy, the intervertebral spacer could easily be inserted into the intervertebral space. However, the LCP-IS may not be workable for the repair of vertebral body fractures in which a spacer may not easily be inserted into the space, and the LCP-IS has not yet been evaluated for unilateral stabilization of vertebral body fractures. Additionally, the LCP-IS was customized through CT evaluation of the thoracolumbar region in Beagles; therefore, its application to the thoracolumbar region of other breeds of dogs is unknown.

In conclusion, the results of this ex vivo study suggested that stabilization of the L1-L2 motion segment after complete L1-2 diskectomy was achieved with a unilateral thoracolumbar intervertebral anchored fusion device with an intervertebral spacer without distraction of the segment, and this combination yielded better stabilization in lateral bending, compared with the device alone. Although both implants did not yield differences in stability in flexion and extension, compared with the intact specimens, rotational stability was weaker. Therefore, the findings reported here did not support the use of this customized unilateral thoracolumbar intervertebral anchored fusion device with an intervertebral spacer without distraction to stabilize the L1-L2 motion segment after L1-2 diskectomy in dogs. Future studies could include examination of the effect of variably sized intervertebral spacers on distraction of the L1-L2 motion segment and comparison of unilateral and bilateral stabilization techniques on motion segments adjacent to L1 and L2.

Acknowledgments

This work was funded by the Gesellschaft Kynologischer Forschung, Bonn, Germany.

The authors declare that there were no conflicts of interest.

Footnotes

a. Rita Leibinger Medical GmbH & Co KG, Neuhausen/Tuttlingen, Germany.
b. Technovit 3040, Heraeus Kulzer, Germany.
c. EC40 120W, Maxon Motor Ag, Sachseln, Switzerland.
d. MC3A, AMTI, Watertown, Mass.
e. Optotrak Certus, Northern Digital Inc, Waterloo, ON, Canada.
f. NumPy, Python Software Foundation, Beaverton, Ore.
g. Python, version 2.7, Python Software Foundation, Beaverton, Ore.

References

1. Bali MS, Lang J, Jaggy A, et al. Comparative study of vertebral fractures and luxations in dogs and cats. *Vet Comp Orthop Traumatol* 2009;22:47–53.
2. Weh JM, Kraus KH. Vertebral fractures, luxations, and subluxations. In: Tobias KM, Johnston SA, eds. *Veterinary surgery: small animal*. 2nd ed. St Louis: Elsevier, 2018;529–548.
3. Bruecker KA. Principles of vertebral fracture management. *Semin Vet Med Surg Small Anim* 1996;11:259–272.
4. Garcia JN, Milthorpe BK, Russel D, et al. Biomechanical study of canine spinal fracture fixation using pins or bone screws with polymethylmethacrylate. *Vet Surg* 1994;23:322–329.
5. Krauss MW, Theyse LFH, Tryfonidou MA, et al. Treatment of spinal fractures using Lubra plates: a retrospective clinical and radiological evaluation of 15 cases. *Vet Comp Orthop Traumatol* 2012;25:326–331.
6. Hall DA, Snelling SR, Ackland DC, et al. Bending strength and stiffness of canine cadaver spines after fixation of a lumbar spinal fracture-luxation using a novel unilateral stabilization technique compared to traditional dorsal stabilization. *Vet Surg* 2015;44:94–102.
7. Graillon T, Rakotozanany P, Blondel B, et al. Circumferential management of unstable thoracolumbar fractures using an anterior expandable cage, as an alternative to an iliac crest graft, combined with a posterior screw fixation: results of a series of 85 patients. *Neurosurg Focus* 2014;37:E10.
8. Richardson B, Paulzak A, Rusyniak WG, et al. Anterior lumbar corpectomy with expandable titanium cage reconstruction: a case series of 42 patients. *World Neurosurg* 2017;108:317–324.
9. De Decker S, Caemaert J, Tshamala MC, et al. Surgical treatment of disk-associated wobbler syndrome by a distractable vertebral titanium cage in seven dogs. *Vet Surg* 2011;40:544–554.
10. Sturges BK, Kapatkin AS, Garcia TC, et al. Biomechanical comparison of locking compression plate versus positive profile pins and polymethylmethacrylate for stabilization of the canine lumbar vertebrae. *Vet Surg* 2016;45:309–318.
11. Waldron DR, Shires PK, McCain W, et al. The rotational stabilizing effect of spinal fixation techniques in an unstable vertebral model. *Prog Vet Neurol* 1991;2:105–110.
12. Sharp NJ, Wheeler SJ. Trauma. In: *Small animal spinal disorders*. 2nd ed. St Louis: Elsevier Mosby, 2004;281–318.
13. Van de Belt H, Neut D, Schenk W, et al. Infection of orthopedic implants and the use of antibiotic-loaded bone cements: a review. *Acta Orthop Scand* 2001;72:557–571.
14. Roush JK, Wilson JW. Effects of plate luting on cortical vascularity and development of cortical porosity in canine femurs. *Vet Surg* 1990;19:208–214.
15. Jeffery ND. Vertebral fracture and luxation in small animals. *Vet Clin North Am Small Anim Pract* 2010;40:809–828.
16. Wheeler JL, Lewis DD, Cross AR, et al. Closed fluoroscopic-assisted spinal arch external skeletal fixation for the stabilization of vertebral column injuries in five dogs. *Vet Surg* 2007;36:442–448.

17. Walker TM, Pierce WA, Welch RD. External fixation of the lumbar spine in a canine model. *Vet Surg* 2002;31:181–188.
18. Lanz OI, Jones JC, Bergman R. Use of an external fixator to correct spinal fracture/luxation and instability in three dogs. *Vet Neurol Neurosurg* 2000;2:1–14.
19. Wheeler JL, Cross AR, Rapoff AJ. A comparison of the accuracy and safety of vertebral body pin placement using a fluoroscopically guided versus an open surgical approach: an in vitro study. *Vet Surg* 2002;31:468–474.
20. Schöllhorn B, Bürki A, Stahl C, et al. Comparison of the biomechanical properties of a ventral cervical intervertebral anchored fusion device with locking plate fixation applied to cadaveric canine cervical spines. *Vet Surg* 2013;42:825–831.
21. Rohner D, Kowaleski MP, Schwarz G, et al. Short-term clinical and radiographical outcome after application of anchored intervertebral spacers in dogs with disc-associated cervical spondylomyelopathy. *Vet Comp Orthop Traumatol* 2019;32:158–164.
22. Steffen F, Voss K, Morgan JP. Distraction-fusion for caudal cervical spondylomyelopathy using an intervertebral cage and locking plates in 14 dogs. *Vet Surg* 2011;40:743–752.
23. Bergman RL, Levine JM, Coates JR, et al. Cervical spinal locking plate in combination with cortical ring allograft for a one level fusion in dogs with cervical spondylotic myelopathy. *Vet Surg* 2008;37:530–536.
24. Hettlich BF, Allen MJ, Pascetta D, et al. Biomechanical comparison between bicortical pin and monocortical screw/polymethylmethacrylate constructs in the cadaveric canine cervical vertebral column. *Vet Surg* 2013;42:693–700.
25. Gédet P, Thistlethwaite PA, Ferguson SJ. Minimizing errors during in vitro testing of multisegmental spine specimens: considerations for component selection and kinematic measurement. *J Biomech* 2007;40:1881–1885.
26. Wilke HJ, Wenger K, Claes L. Testing criteria for spinal implants: recommendations for the standardization of in vitro stability testing of spinal implants. *Eur Spine J* 1998;7:148–154.
27. Bruce CW, Brisson BA, Gyselinck K. Spinal fracture and luxation in dogs and cats: a retrospective evaluation of 95 cases. *Vet Comp Orthop Traumatol* 2008;21:280–284.
28. Smith GK, Walter MC. Spinal decompressive procedures and dorsal compartment injuries: comparative biomechanical study in canine cadavers. *Am J Vet Res* 1988;49:266–273.
29. Smit TH. The use of a quadruped as an in vivo model for the study of the spine – biomechanical considerations. *Eur Spine J* 2002;11:137–144.
30. Hongo M, Gay RE, Hsu J, et al. Effect of multiple freeze-thaw cycles on intervertebral dynamic motion characteristics in the porcine lumbar spine. *J Biomech* 2008;41:916–920.
31. Dhillon N, Bass EC, Lotz JC. Effect of frozen storage on the creep behavior of human intervertebral discs. *Spine (Phila Pa 1976)* 2001;26:883–888.
32. Knell SC, Bürki A, Hurter K, et al. Biomechanical comparison after in vitro laminar vertebral stabilization and vertebral body plating of the first and second lumbar vertebrae in specimens obtained from canine cadavers. *Am J Vet Res* 2011;72:1681–1686.