Effects of conventional and slanted ventral slot procedures on the biomechanical behavior of the C5-C6 vertebral motion unit in dogs

Haisheng Yang PhD
Nicolaas E. Lambrechts BVSc, MMED VET
Michael Lehner BS
Gremah M. Adam BS
Rebecca A. Packer MS, DVM
Trevor W. Moore DVM
Russell P. Main PhD

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From the Departments of Basic Medical Sciences (Yang, Packer, Main) and Veterinary Clinical Sciences (Lambrechts, Packer, Moore), College of Veterinary Medicine, the Weldon School of Biomedical Engineering, College of Engineering (Lehner, Main), and the Department of Biological Sciences, College of Science (Adam), Purdue University, West Lafayette, IN 47907. Dr. Yang's present address is Department of Pediatric Surgery, Shriners Hospital for Children, McGill University, Montreal, QC H3G 1A4, Canada. Drs. Lambrecht and Packer's present address is Department of Clinical Sciences, College of Veterinary Medicine and Biomedical Sciences, Colorado State University, Fort Collins, CO 80523.

Address correspondence to Dr. Main (rmain@purdue.edu).

OBJECTIVE
To compare the effects of conventional and slanted ventral slot procedures on the biomechanical behavior of the C5-C6 vertebral motion unit (VMU) in dogs.

SAMPLE
14 vertebral columns (C4 through C7) from canine cadavers.

PROCEDURES
Specimens were assigned to a conventional or slanted ventral slot group (n = 7/group). For each specimen, the C5-C6 VMU was tested in ventral and dorsal bending and positive and negative axial torsion before and after surgery. Range of motion (ROM), stiffness, and energy absorption were compared between the 2 groups.

RESULTS
Both procedures significantly increased the ROM and stiffness and significantly decreased the energy absorption of the C5-C6 VMU in ventral and dorsal bending. Both procedures also increased the ROM in positive and negative axial torsion. In negative torsion, total stiffness and stiffness over the maximum ROM tested decreased less for the slanted slot procedure than for the conventional slot procedure. There were no significant differences between procedures for any of the other biomechanical outcomes examined.

CONCLUSIONS AND CLINICAL RELEVANCE
Results suggested that the biomechanical response of the C5-C6 VMU to the conventional and slanted ventral slot procedures was not significantly different, especially when considering postsurgical instability induced by both procedures. This was most likely due to disruption of the nucleus pulposus and dorsal annulus fibrosus of the disk with both procedures. On the basis of these findings, neither procedure appeared biomechanically superior. Comparative clinical studies are warranted to further evaluate the 2 procedures. (*Am J Vet Res* 2016;77:846–853)

Cervical intervertebral disk herniation with associated spinal cord injury is a common condition in dogs.[1,2] The conventional ventral slot procedure is the most commonly performed surgical treatment for decompression of the spinal cord following cervical intervertebral disk herniation.[3,4] However, common concerns associated with this surgical procedure include postsurgical instability and subluxation caused, in part, by removal of the dorsal and ventral portions of the annulus fibrosus of the disk, disruption of the nucleus pulposus and longitudinal vertebral ligaments, and creation of a bone defect in adjoining vertebral bodies.[5–7] To determine the effect of various surgical procedures on the stability and stiffness of the cervical portion of the vertebral column, biomechanical tests have been performed on VMUs obtained from cadavers.[4,8,9] These biomechanical experiments have shown that the conventional ventral slot procedure substantially increases the ROM of surgically treated VMUs, compared with the ROM of intact, untreated specimens.

The slanted ventral slot procedure has been proposed as an alternative to the conventional ventral slot procedure. It was developed with the intention of reducing postsurgical instability by preserving the ventral annulus fibrosis and ventral longitudinal ligaments.[10,11] However, the effects of this procedure on VMU stiffness and ROM are unknown, and the assumption of improved postsurgical stability compared with the conventional ventral slot procedure is untested. Acquiring comparative data regarding biomechanical behavior of the cervical portion of the vertebral column following each of these surgical procedures is important in determining the most appropriate surgical approach for veterinary patients. Thus, the purpose of the study reported here was to compare the effects of

ABBREVIATIONS
ROM Range of motion
VMU Vertebral motion unit

the conventional and slanted ventral slot procedures on biomechanical behavior (ROM, stiffness, and energy absorption in ventral and dorsal bending and positive and negative axial torsion) of the C5-C6 VMU in dogs. The C5-C6 VMU was chosen because the C5-6 disk is a common site for disk-associated disease in large-breed dogs.[12]

Materials and Methods

Collection of vertebral column specimens

Fourteen skeletally mature, nonchondrodystrophic canine cadavers of various breeds were used in the study. The cadavers were obtained from local animal shelters where the dogs had been euthanized for reasons unrelated to the present study. There were 8 males and 6 females. Dogs were between 1.0 and 6.5 years old at the time of euthanasia and weighed between 17.3 and 31.3 kg.

All cadavers were collected within 1 hour after euthanasia, and the cervical portion of the vertebral column from C4 through C7 was removed. During this initial dissection, care was taken not to disrupt any of the intervertebral disks, intervertebral ligaments, or joint capsules. Dorsoventral and lateral radiographs were taken of each specimen to confirm skeletal maturity and the absence of abnormalities. Spinal segments were wrapped in gauze soaked in saline (0.9% NaCl) solution, sealed in freezer bags, and stored at –20°C within 4 hours after euthanasia.

The 14 specimens were systematically assigned to 2 groups matched as closely as possible on the basis of sex, age, and body weight. Specimens assigned to the conventional ventral slot group consisted of 4 males and 3 females with a mean ± SD age of 2.8 ± 1.2 years and weight of 23.5 ± 4.7 kg. Specimens assigned to the slanted ventral slot group consisted of 4 males and 3 females with a mean ± SD age of 3.1 ± 1.9 years and weight of 23.7 ± 4.3 kg.

Specimen preparation for mechanical testing

In preparation for mechanical testing, specimens were thawed and the paravertebral musculature was removed. To ensure that intervertebral motion would only occur between C5 and C6, the C4-C5 and C6-C7 VMUs were stabilized. To stabilize the C4-C5 VMU, a single screw[a] was inserted from the ventral aspect of the body of C4 through the C5 endplate toward the spinous process of C5, and 2 additional screws were inserted through the articular process joints in a dorsoventral direction. The C6-C7 VMU was stabilized in a similar manner. The 2 ends of the specimen were then potted in fast-setting cement[b] in square aluminum tubes (7.5 cm X 7.5 cm X 15 cm), with the potting material just covering the fixation screws protruding from C5 and C6. The specimen was potted so that the C5-C6 VMU was longitudinally aligned within the tubes and the C5-6 disk was centered between the 2 pots. During specimen preparation, all specimens were kept moist by spraying them with saline solution or wrapping them with moist gauze. After specimens were potted, they were wrapped with saline-soaked towels and plastic wrap and stored frozen at –20°C until tested.

Surgical procedures

All conventional and slanted ventral slot procedures were conducted by a single surgeon (NEL). The surgical procedures were practiced and standardized on a pilot sample of 5 vertebral specimens. The primary differences between the 2 procedures pertained to the shape and location of the ventral slot and the amount of annulus fibrosus and ventral longitudinal vertebral ligaments that remained intact **(Figure 1)**. Both procedures were performed with a high-speed drill[c] and 3-mm or 4-mm burr tips, with constant irrigation with saline solution at the surgical site during drilling. The surgeon wore 3.5X magnifying optical loupes during the procedures.

Conventional ventral slot—The width of the conventional slot was 33% of the width of the body of C5 (measured with digital calipers with an accuracy of ± 0.01 mm). Length of the conventional slot was 33% of the length of C5 measured from the cranial to the caudal endplate on a lateral radiograph. The slot was centered longitudinally over the C5-6 disk space at the level of the vertebral canal (Figure 1). The ventral and dorsal components of the annulus fibrosus, longitudinal vertebral ligaments, and vertebral bone tissue in the path of the slot were excised during the course of the procedure.

Slanted ventral slot—The slanted ventral slot procedure was performed as described.[11] The width and length of the slot were calculated as described for the conventional ventral slot procedure; however, the slot was begun more cranially. A tunnel was made with the high-speed drill, starting on the ventral surface of C5, 5 mm cranial to the C5-6 disk space. The slot was slanted dorsocaudally and extended through

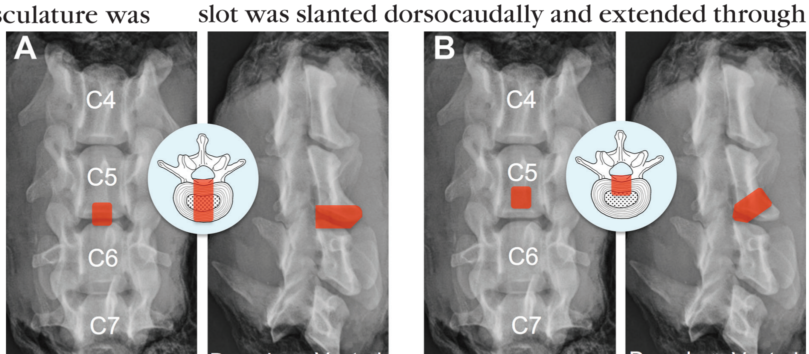

Figure 1—Ventrodorsal and lateral radiographic views of a cervical vertebral specimen (C4 through C7) from a dog illustrating the location and approximate dimensions of conventional (A) and slanted (B) ventral slot procedures (red) for decompression of the spinal cord at C5-6. Inset: cranial view at the C5-6 disk space.

the dorsal aspect of the caudal endplate of C5 (Figure 1). The slot was extended until contact was made with the drill bit at the dorsal limit of the cranial endplate of C6. A portion of the dorsal annulus and adjacent longitudinal ligament was removed during the course of the procedure, but the ventral aspect of the annulus fibrosus was preserved.

Biomechanical testing

Prior to biomechanical testing, specimens were thawed overnight in a refrigerator (4°C) and then for 2 to 3 hours at room temperature. Each specimen was tested in ventral and dorsal bending and in positive and negative axial torsion. For testing in ventral and dorsal bending, specimens were placed in a custom 4-point bending fixture in a materials testing machine.[d] At each end of the specimen, the distance between the upper load point and lower support point was 62.5 mm, and a compressive force of 80 N was applied through the 2 upper load points to the potted ends of the specimen **(Figure 2)**. This loading configuration resulted in a pure bending moment (M) of 2.5 Nm between the 2 load points, calculated as M = Fw/2, where F represented the applied force and w represented the distance between the upper load points and lower support points.

Specimens were initially tested in ventral bending, with the ventral surface uppermost. Specimens were then flipped and tested in dorsal bending. Angular deflection of the specimens during bending was measured and recorded with a motion capture system[e] that incorporated retroreflective markers (radius, 2 mm) glued to the rectangular tubes on either end of the specimen and to the upper load points and lower support points of the fixture. Three cameras arranged in a semicircle around the marked side of the specimen were used to record displacement of the markers, allowing angular deformation to be calculated. Prior to mechanical testing, the 3-D coordinate system for the test volume was established with a calibration kit provided by the manufacturer. The motion capture system was able to distinguish 3-D displacements of the markers as small as 0.01 mm. Load-induced changes in the angle (θ) of the C5-C6 VMU were calculated with a custom-written software program[f] as the sum of the angular changes of the left and right ends of the specimen relative to the initial position of the specimen prior to loading. The axial force was applied at a rate of 1.4 mm/s, which was equivalent to a bending load rate of approximately 2.5°/s.[9,13]

For torsion testing, specimens were hung in a torsion fixture (Figure 2) with the C4 end of the specimen fixed in the upper fixture and the C7 end held in the lower fixture. Care was taken to raise the lower fixture just enough to hold the lower end of the specimen while applying minimal (< 3 N) axial force to the C5-C6 VMU. A torque of 2.5 Nm with a load rate[13] of 2.5°/s was applied in the positive (C4-C5 rotated counterclockwise relative to C6-C7, similar to the dog rotating the top of its head to the right) and negative (C4-C5 rotated clockwise relative to C6-C7, similar to the dog rotating the top of its head to the left) directions. Torque and angular rotation were recorded with standard software associated with the materials testing machine.

Each specimen was first loaded in all 4 load directions (ventral and dorsal bending and positive and negative axial torsion) for 7 full preconditioning cycles prior to definitive mechanical testing to minimize the viscoelastic effects of the soft tissues. This preconditioning was followed by 7 cycles of loading in all 4 load directions immediately before and immediately after creation of the designated ventral slot. The order of testing in the 4 load directions was chosen randomly and was independent of surgical procedure. All testing on a given specimen was performed within a single day and within the same freeze-thaw cycle. Saline solution was used to maintain hydration of the specimens throughout the testing and surgical periods.

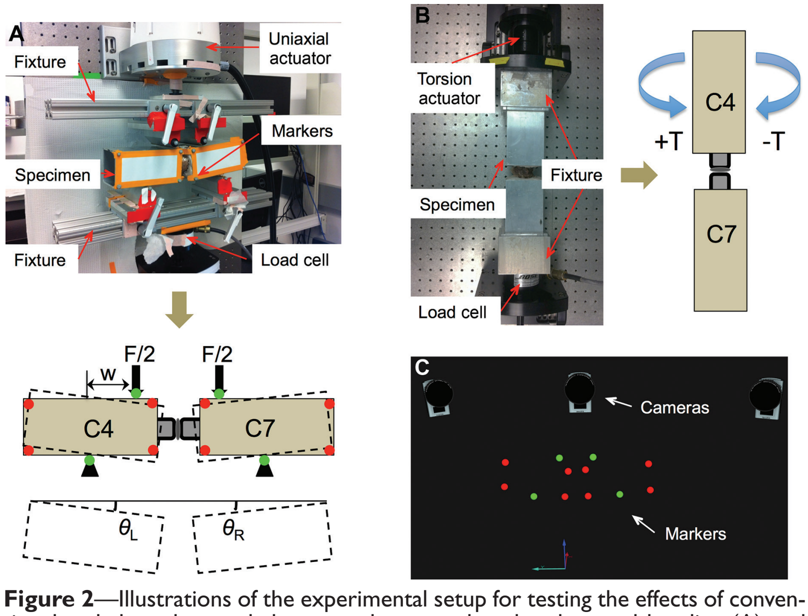

Figure 2—Illustrations of the experimental setup for testing the effects of conventional and slanted ventral slot procedures on dorsal and ventral bending (A) and positive and negative axial torsion (B) of the C5-C6 VMU in dogs. For bending tests, the specimen was placed in a custom 4-point bending fixture with a uniaxial force applied evenly to the ventral or dorsal surface of the potted ends of the specimen through 2 load points. A pure bending moment (M = Fw/2) was generated on the specimen between the 2 load points. The angular deformation ($\theta = \theta_L + \theta_R$) was calculated from the angular deformation of the VMU, which was tracked with a motion capture system that incorporated retroreflective markers (C). For torsion tests, the specimen was placed in a torsion fixture and a pure torque (T) was applied in a positive or negative direction. The angular rotation was recorded by the testing machine.

Data analysis

Biomechanical outcome parameters included ROM, stiffness, and energy absorption.[13] Initial ROM was defined as the change in angular deflection or rotation of the C5-C6 VMU without any applied load (for bending tests, this was characterized as the passive deflection under the weight of the specimen; for torsional tests, this was 0). Neutral zone ROM, a measurement of the laxity of the specimen, was defined as the angular deflection or rotation without any applied load following 7 cycles of loading (**Figure 3**; for bending tests, this included initial ROM). Total ROM was defined as the angular deflection or rotation at peak applied moment (2.5 Nm) or torque (2.5 Nm), respectively.

The last 3 cycles of the moment-versus-angle (for bending) or torque-versus-angle (for torsion) curves were highly repeatable and used for calculating stiffness and energy absorption. To calculate stiffness, a linear regression line was fit to the load-displacement curve.[9] Total stiffness was defined as the slope of the regression line averaged over the last 3 cycles, excluding the neutral zone ROM (Figure 3). Energy absorption (or dissipation) represented the viscoelastic behavior of the specimen and was defined as the area enclosed by the loading and unloading curves averaged over the last 3 cycles. To characterize the effects of surgery on stiffness at a given angular deflection or rotation, the presurgical total ROM was divided evenly into 5 ranges and pre- and postsurgical stiffness in each of these ranges were compared.

Interaction effects of the 2 surgical procedures on the biomechanical outcomes of the C5-C6 VMU in bending and torsion were tested with a linear mixed model for repeated measures[g] for which the within-subject factor was surgical status (presurgical vs postsurgical) and the between-subject factor was surgical procedure (conventional vs slanted ventral slot). Linear mixed modeling for repeated measures was also used to examine the interactive effects of bending direction (ventral vs dorsal) or torsional direction (positive vs negative) for each surgical technique; the within-subject factor was surgical status (presurgical vs postsurgical), and the between-subject factor was loading direction (ventral vs dorsal bending or positive vs negative axial torsion). When a significant ($P < 0.05$) interaction was found, post hoc pairwise comparisons were conducted with a Bonferroni correction for repeated measures. Data are reported as mean ± SD; for all analyses, values of $P < 0.05$ were considered significant.

Results

Both the conventional and slanted ventral slot procedures significantly increased the initial ROM, neutral zone ROM, and total ROM of the C5-C6 VMU during ventral and dorsal bending and positive and negative axial torsion **(Table 1)**. However, the 2 procedures had similar effects on postsurgical ROM in both bending and axial torsion. For example, in ventral bending, mean ± SD total ROM increased from 12.3 ± 2.6° to 15.4 ± 2.1° and from 12.9 ± 3.2° to 15.0 ± 2.9° following the conventional and slanted ventral slot procedures, respectively.

In ventral and dorsal bending, total stiffness of the specimen increased significantly but energy absorption decreased significantly as a result of both procedures (Table 1). By contrast, in positive torsion, both procedures caused a significant decrease in total stiffness but did not have a significant effect on energy absorption.

Table 1—Biomechanical behavior of canine C5-C6 VMUs in ventral and dorsal bending (peak applied moment, 2.5 Nm) and positive and negative axial torsion (peak applied torque, 2.5 Nm) before (presurgical) and after (postsurgical) conventional and slanted ventral slot procedures were performed at the C5-6 disk space (n = 7/group).

		Ventral bending		Dorsal bending		Positive torsion		Negative torsion	
Variable	**Status**	**Conventional**	**Slanted**	**Conventional**	**Slanted**	**Conventional**	**Slanted**	**Conventional**	**Slanted**
Initial ROM (°)									
	Presurgical	7.9 ± 3.4	9.2 ± 3.1	9.3 ± 2.2	7.9 ± 3.1	NA	NA	NA	NA
	Postsurgical	12.2 ± 2.0[a]	11.8 ± 2.7[a]	14.2 ± 2.0[a]	13.2 ± 3.7[a]	NA	NA	NA	NA
	Difference (%)	55	29	52	67	NA	NA	NA	NA
Neutral zone ROM (°)	Presurgical	9.2 ± 2.8	10.2 ± 3.2	10.8 ± 2.5	9.5 ± 2.9	1.2 ± 0.4	1.7 ± 1.0	1.4 ± 0.6	1.6 ± 0.9
	Postsurgical	13.3 ± 2.0[a]	12.8 ± 2.7[a]	15.8 ± 2.5[a]	14.7 ± 3.8[a]	2.3 ± 1.6[a]	3.4 ± 2.3[a]	3.1 ± 1.3[a]	3.0 ± 1.7[a]
	Difference (%)	45	26	46	54	92	100	113	83
Total ROM (°)									
	Presurgical	12.3 ± 2.6	12.9 ± 3.2	14.4 ± 2.5	13.5 ± 3.3	4.3 ± 0.6	5.4 ± 2.4	4.6 ± 0.7	5.3 ± 1.8
	Postsurgical	15.4 ± 2.1[a]	15.0 ± 2.9[a]	18.2 ± 2.4[a]	17.2 ± 4.2[a]	6.3 ± 2.2[a]	7.4 ± 3.6[a]	7.2 ± 1.7[a]	6.7 ± 2.7[a]
	Difference (%)	26	16	26	28	47	36	57	27
Total stiffness (Nm/°)	Presurgical	0.80 ± 0.20	0.92 ± 0.17	0.66 ± 0.11	0.61 ± 0.13	0.82 ± 0.13	0.77 ± 0.23	0.80 ± 0.10	0.76 ± 0.19
	Postsurgical	1.15 ± 0.09[a]	1.15 ± 0.19[a]	0.98 ± 0.19[a]	0.96 ± 0.17[a]	0.68 ± 0.16[a]	0.70 ± 0.18[a]	0.64 ± 0.12[b,c]	0.77 ± 0.18[b]
	Difference (%)	43	25	48	55	–17	–9	–21	1
Energy absorption (Nm•°)	Presurgical	0.87 ± 0.41	0.64 ± 0.28	1.14 ± 0.34	1.48 ± 0.30	0.72 ± 0.12	0.79 ± 0.22	0.70 ± 0.10	0.82 ± 0.19
	Postsurgical	0.48 ± 0.20[a]	0.44 ± 0.22[a]	0.73 ± 0.24[a]	0.73 ± 0.33[a]	0.78 ± 0.33	0.81 ± 0.19	0.89 ± 0.23[b]	0.70 ± 0.21[b]
	Difference (%)	–45	–32	–36	–51	9	1	26	–15

Data are reported as mean ± SD. Difference represents percentage difference between postsurgical and presurgical values (ie, 100 X [postsurgical value – presurgical value]/presurgical value).

NA = Not applicable.

[a]Significantly ($P < 0.05$) different from presurgical value. [b]Significant ($P < 0.05$) interaction between surgical status (presurgical vs postsurgical) and surgical procedure (conventional vs slanted ventral slot). [c]Significant ($P < 0.05$) effect of surgical procedure.

Table 2—Torsional stiffness (Nm/°) in quintiles of presurgical total ROM for canine C5-C6 VMUs loaded in positive and negative axial torsion (peak applied torque, 2.5 Nm) before (presurgical) and after (postsurgical) conventional and slanted ventral slot procedures were performed at the C5-6 disk space (n = 7/group).

Quintile of presurgical total ROM	Status	Positive torsion		Negative torsion	
		Conventional	Slanted	Conventional	Slanted
First					
	Presurgical	0.08 ± 0.16	0	0.08 ± 0.20	0.06 ± 0.12
	Postsurgical	0.10 ± 0.15	0	0	0
	Difference (%)	19	NA	NA	NA
Second					
	Presurgical	0.50 ± 0.15	0.30 ± 0.22	0.36 ± 0.25	0.32 ± 0.23
	Postsurgical	0.11 ± 0.17[a]	0.08 ± 0.15[a]	0	0.05 ± 0.07[a]
	Difference (%)	–77	–72	NA	–84
Third					
	Presurgical	0.64 ± 0.12	0.52 ± 0.24	0.59 ± 0.11	0.55 ± 0.21
	Postsurgical	0.24 ± 0.27[a]	0.20 ± 0.19[a]	0.14 ± 0.12[a]	0.19 ± 0.18[a]
	Difference (%)	–62	–62	–77	–66
Fourth					
	Presurgical	0.88 ± 0.16	0.83 ± 0.23	0.86 ± 0.09	0.82 ± 0.23
	Postsurgical	0.40 ± 0.38[a]	0.35 ± 0.27[a]	0.22 ± 0.14[a]	0.46 ± 0.37[a]
	Difference (%)	–54	–57	–74	–44
Fifth					
	Presurgical	1.16 ± 0.16	1.06 ± 0.24	1.13 ± 0.11	1.10 ± 0.23
	Postsurgical	0.62 ± 0.43[a]	0.63 ± 0.36[a]	0.38 ± 0.23[a–c]	0.79 ± 0.45[a–c]
	Difference (%)	–46	–40	–66	–27

See Table 1 for key.

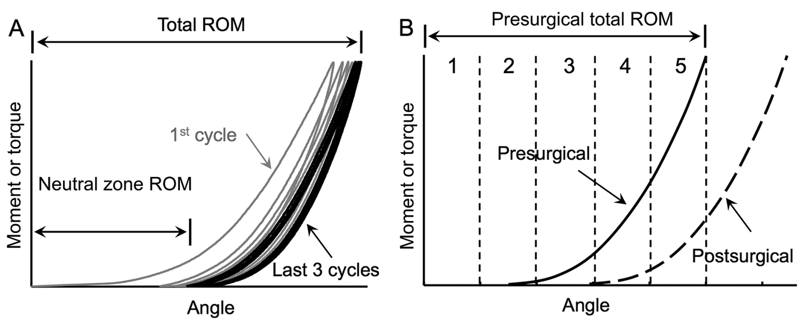

Figure 3—Load-displacement curves generated during torsion testing of a representative C5-C6 VMU from a dog. A—Typical presurgical curves generated when the C5-C6 VMU was loaded (peak applied torque, 2.5 Nm) in torsion for 7 cycles. Notice the portions of the curves corresponding to the neutral zone and total ROM. Because the last 3 cycles were highly repeatable, they were used to calculate total stiffness and energy absorption. B—Pre- and postsurgical load-displacement curves showing the definition of 5 angular displacement ranges based on the presurgical total ROM. Notice that the neutral zone ROM was increased after surgery.

Interactive effects between surgical status (presurgical vs postsurgical) and surgical procedure (conventional vs slanted ventral slot) on total stiffness and energy absorption of the specimen were found only for negative torsion. In negative torsion, the change in total stiffness caused by the conventional ventral slot procedure was significantly greater than that caused by the slanted ventral slot procedure. There were no significant differences between procedures for any of the other biomechanical outcomes that were examined.

As expected, torsional stiffness of the C5-C6 VMU was decreased following both the conventional and slanted ventral slot procedures **(Table 2)**, mainly as a result of increased neutral zone ROM **(Figure 3)**. Stiffness in negative torsion in the fifth of the 5 ranges for presurgical total ROM decreased significantly more following the conventional ventral slot procedure (–66%) than after the slanted ventral slot procedure (–27%). Owing to the postsurgical increase in neutral zone ROM, there was no overlap between the presurgical and postsurgical ROMs for ventral and dorsal bending (ie, the postsurgical neutral zone ROM was larger than presurgical total ROM). In other words, the postsurgical stiffness over any range of the presurgical total ROM was 0.

For the conventional ventral slot procedure, there was no significant difference in surgically induced changes in ROM, stiffness, or energy absorption between ventral and dorsal bending **(Figure 4)**. For the slanted ventral slot procedure, surgically induced changes in initial and neutral zone ROM and energy absorption were significantly less in ventral bending than in dorsal bending. We did not identify any significant interactive effects of loading direction (ventral vs dorsal bending or positive vs negative torsion) and surgical status (presurgical vs postsurgical) for any of the other biomechanical outcomes that were examined.

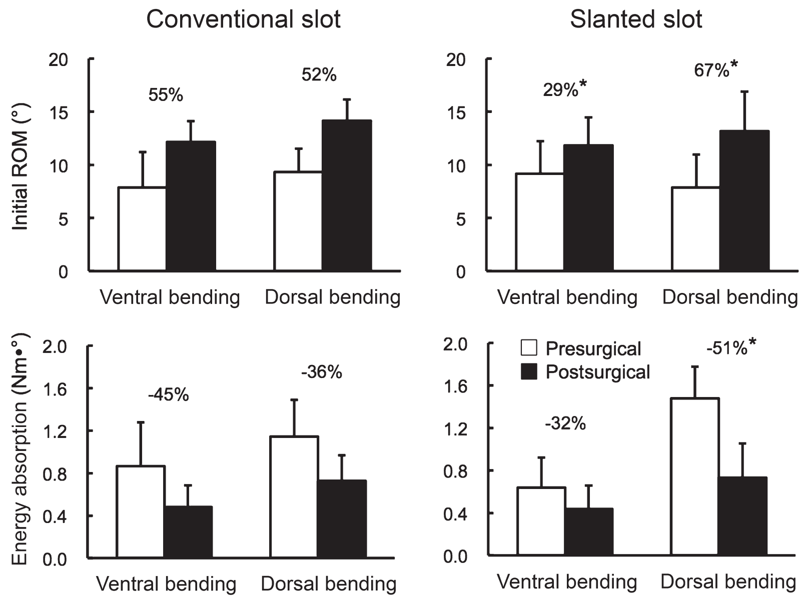

Figure 4—Mean initial ROM and energy absorption of the C5-C6 VMU (n = 7/group) in ventral and dorsal bending (peak applied moment, 2.5 Nm) before and after conventional and slanted ventral slot procedures were performed. *A significant ($P < 0.05$) interactive effect of loading direction (ventral vs dorsal) and surgical status (presurgical vs postsurgical) was identified. Error bars represent SD. Percentages represent percentage difference between postsurgical and presurgical values (ie, 100 X [postsurgical value – presurgical value]/presurgical value). Results for neutral zone ROM were similar to those for initial ROM and are not shown.

Discussion

Results of the present study suggested that, in general, the conventional and slanted ventral slot procedures had similar effects on ROM and stiffness of the C5-C6 VMU in ventral and dorsal bending and positive and negative axial torsion. Only in negative torsion were total stiffness and stiffness over the maximum ROM tested significantly less after the slanted slot procedure than after the conventional slot. However, this biomechanical effect in negative torsion might not be important from a clinical point of view, especially with respect to the overall postsurgical instability of the cervical portion of the vertebral column. Taken together, our results suggested that the conventional and slanted ventral slot procedures had similar biomechanical effects on the C5-C6 VMU.

In ventral and dorsal bending, both the conventional and slanted ventral slot procedures altered ROM, stiffness, and energy absorption for the C5-C6 VMU, but no significant differences were found between the 2 procedures with respect to their impact on these bending outcomes when compared with each other. The similarity in these results could have been due to disruption of the nucleus of the disk with both procedures. In a healthy disk, the nucleus behaves like an incompressible fluid to primarily carry and distribute loads across the vertebral endplates, with the annulus acting like a tensile shell to restrain the nucleus.[14] Disruption of the hydrostatic nucleus would largely compromise the biomechanics of the VMU, especially in ventral and dorsal bending,[15] causing the annulus to function simply as a fibrous pad to resist compressive loading on the concave aspect of the vertebral column.[16] Because both procedures evaluated in the present study disrupted the nucleus, removing the ventral component of the annulus with the conventional slot procedure or maintaining it with the slanted slot procedure did not appear to lead to a large difference in the bending behavior of the VMU. This observation was consistent with results from a previous study[4] showing that formation of ventral slots with widths of 33% or 50% of the vertebral width did not result in any significant differences in ROM for either ventral-dorsal or lateral bending.

Our analysis of the effects of the 2 procedures on the biomechanics of ventral versus dorsal bending showed that the slanted slot procedure had less of an effect on initial and neutral zone ROM and energy absorption in ventral bending than in dorsal bending. In contrast, the effects of the conventional slot procedure on these parameters were similar in ventral and dorsal bending. This result could be explained by the removal of both the ventral and dorsal components of the disk annulus with the conventional slot procedure, but removal of only the dorsal component of the disk annulus with the slanted slot procedure. Despite this difference in effects between the 2 procedures, there was no difference in any of the biomechanical outcome parameters when comparing the 2 procedures for a given loading direction (ventral or dorsal bending), suggesting that maintaining the ventral portion of the annulus plays only a minor role in preserving the biomechanical behavior of the C5-C6 VMU in ventral or dorsal bending.

In the present study, effects on total stiffness and stiffness at the maximum ROM in negative torsion were less for the slanted slot than the conventional slot procedure. These results suggested that, compared with the conventional slot procedure, maintaining the ventral portion of the annulus and ligaments with the slanted slot could have led to a significant improvement in torsional stiffness of the C5-C6 VMU. It has been experimentally and computationally shown that torsion is primarily resisted by the disk annulus and articular facets,[17] with the annulus contributing more to torsional resistance than the facets.[18,19] Compared with the conventional slot procedure, the slanted slot procedure preserves a larger portion of the annulus, which could increase the resistance of the VMU to torsion. From a clinical perspective, it might be better for recovery if the amount of disk removed is minimized. However, it should be noted that we did not find any significant difference between the 2 procedures in positive torsion, suggesting an asymmetry between positive and negative torsion. However, our statistical analyses did not show any differences between positive and negative torsion for the outcomes measured for both procedures. Thus, the directional asymmetry may have been caused by the procedures themselves or may have been a result of the small sample size (n = 7/group) combined with the high coefficient of variation for the positive torsion tests or may have been a result of anatomic differences unaccounted for in the present study.

Our results showed that stiffness over the same angular deflection or rotation decreased following either procedure. Mainly because of an increase in neutral zone ROM, the total stiffness (defined as the slope of the regression line of the load-displacement curve, excluding the neutral zone ROM) in ventral and dorsal bending increased following both procedures. Both the conventional and slanted slot procedures disrupt the intervertebral disk, leading to a decrease in disk height. This causes the 2 adjoining vertebrae to be closer together and the total stiffness of the motion unit to become greater because it is less flexible in the displacement range from the end of the neutral zone ROM to the end of the total ROM.

In the present study, each specimen was tested in ventral and dorsal bending and in positive and negative axial torsion before and after surgery. Because multiple tests were conducted on each specimen, it was important that we guarantee that all tests remained within the elastic range of the specimens and that no failure occurred in any of the anatomic structures. We applied a moment of 2.5 Nm and a torque of 2.5 Nm to the C5-C6 VMU for ventral and dorsal bending and for positive and negative torsion, respectively. These load magnitudes for the canine cervical vertebral column were recommended in a previous study[13] and were similar to the loads (3 Nm) used in another ex vivo study[4] on the canine C5-C6 VMU. Before the tests reported here were conducted, preliminary tests on trial specimens with a load of 5 Nm confirmed that the specimens were in their elastic range at loads < 2.5 Nm.

Similar to a prior cadaver study,[4] our mechanical testing was only conducted on the C5-C6 VMU and surgeries were performed on the C5-6 intervertebral disk. Other ex vivo mechanical studies[8,9] have examined multiple cervical VMUs (C3 through C6) and showed that the largest change in ROM resulting from the ventral slot procedure occurs at the treated VMU. Testing a single VMU in our study allowed us to isolate the effect of surgery on the treated site, preventing any compound effect induced by inclusion of multiple motion units.[20] However, it remains interesting to investigate how surgical modifications (conventional and slanted ventral slot) on an intervertebral disk affect the biomechanics of adjacent VMUs or the entire cervical vertebral column.

While our biomechanical testing suggested that the slanted slot procedure may have some advantages in preserving some aspects of the torsional mechanical behavior of the C5-C6 VMU, compared with the conventional slot procedure, our model, similar to other relevant ex vivo biomechanical models of the cervical vertebral column,[4,8,9] may not accurately reflect the dynamic behaviors occurring in living patients in which soft tissues are preserved and multiplanar motion occurs. Thus, these findings might not translate directly into the clinical situation. Furthermore, when selecting a surgical technique, other factors need to be considered in addition to biomechanics. These include visualization of the surgical site during the procedure, which is less for the slanted slot than for the conventional slot procedure; surgical time; postoperative pain and morbidity; ability to perform surgery on multiple consecutive disks without complications such as fractures and subluxations; recovery time; and complication rates.[10] It is also presently unknown whether the slanted slot procedures provide the same degree of disk decompression as the conventional slot procedures. All of these aspects would require a well-designed prospective clinical study to address. In addition, vertebral columns from dogs without evidence of orthopedic lesions were used in the present study, whereas the cervical vertebral column in dogs with disk disease may already have altered biomechanical behavior. Further studies focusing on specimens from dogs with disk disease may be warranted.

The present study had a few limitations that could be addressed in future work. First, we performed only ventral and dorsal bending tests, excluding lateral bending. Because surgical modifications associated with both the conventional and slanted slot procedures are located in the ventrodorsal plane, we thought that ventral and dorsal bending tests would be the most clinically relevant. A previous study[4] examining the effect of disk fenestration and ventral slot formation on biomechanics of the canine C5-C6 VMU showed that disk fenestration affects ROM in flexion and extension but not in lateral bending. Because we did not find much difference between the 2 procedures in ventral or dorsal bending, we would expect no differences between the 2 procedures in their effects on lateral bending. However, this speculation should be verified in future studies. Second, a constrained 4-point bending configuration was used in the present study to measure the bending behavior of the C5-C6 VMU, and a similar configuration has been widely used in other similar biomechanical studies.[9,21–24] This loading configuration is limiting in that it forces the VMU to move in a particular plane of motion, thus limiting multiplanar physiologic motions of the spine. Because these physiologic motions may be important for the highly flexible cervical vertebral column, using a nonconstrained testing system would be more appropriate.[8,25]

In summary, the present study sought to compare the effects of conventional and slanted ventral slot procedures on the biomechanical behavior of the C5-C6 VMU in dogs. Our results showed that, overall, the biomechanical response did not differ between the 2 procedures. This was most likely because both procedures caused disruption of the nucleus pulposus and dorsal aspect of the annulus fibrosus. Further clinical studies are needed to determine whether one technique confers an advantage over the other.

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Footnotes

a. Stainless steel screw (No. 9 X 5 cm), ACE Hardware, Chicago, Ill.
b. Bondo body filler, 3M, Saint Paul, Minn.
c. Electric Pen Drive, Synthes, West Chester, Pa.
d. TestBench, Bose, Eden Prairie, Minn.
e. Qualisys, Qualisys AB, Gothenburg, Sweden.
f. MathWorks, Natick, Mass.
g. SPSS Statistics, IBM, Armonk, NY.

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