Received: 18 September 2024 | Revised: 9 December 2024 | Accepted: 27 December 2024
DOI: 10.1111/vsu.14210

EXPERIMENTAL LAB RESEARCH

WILEY

Evaluation of a patient-specific 3D-printed guide for ventral slot surgery in dogs: An ex vivo study

Meagan A. Walker BSc, MSc, DVM[1] | **Adam T. Ogilvie BSc, DVM, DVSc, DACVS (Small Animal)**[1] | **Grant McSorley BEng, PEng, PhD**[2] | **William Montelpare BPHE, MSc, PhD**[3] | **Katie L. Hoddinott BSc, DVM, DVSc, DACVS (Small Animal)**[1]

[1]Atlantic Veterinary College, University of Prince Edward Island, Charlottetown, Prince Edward Island, Canada

[2]Sustainable Design Engineering, University of Prince Edward Island, Charlottetown, Prince Edward Island, Canada

[3]Applied Human Sciences, University of Prince Edward Island, Charlottetown, Prince Edward Island, Canada

Correspondence
Katie L. Hoddinott, 550 University Avenue, Charlottetown, Prince Edward Island, CIA-1P4, Canada.
Email: khoddinott@upei.ca

Funding information
Atlantic Veterinary College Companion Animal Trust Fund

Abstract

Objective: To evaluate the accuracy of ventral slot creation in canine cadavers with a three-dimensional (3D)-printed drill guide compared to the freehand technique.

Study design: Ex vivo study.

Sample population: Eight canine cadavers (23.4–39.8 kg).

Methods: Computed tomography (CT) data was used to create patient-specific 3D-printed surgical guides for ventral slot creation. Intervertebral sites were randomized to undergo either a guided ($n = 12$) or freehand ($n = 12$) ventral slot by a novice surgery resident. Postoperative CT images were used to compare ventral slot dimensions, shape, and position.

Results: Free-hand ventral slots were significantly shorter than the intended dimensions ($p < .01$). Dimensions of the guide-assisted ventral slots were not statistically different from the planned dimensions ($p = .88$, $p = .72$). Use of the guides resulted in improved accuracy for ventral slot positioning relative to midline and slot shape (difference in coefficient of variations, 32%, and 40%, respectively).

Conclusion: Ventral slot dimensions were more accurate when created with the patient-specific 3D-printed guide compared to the freehand technique.

Clinical significance: Use of a 3D-printed patient specific surgical guide improves accuracy of ventral slot creation in canine cadavers and improves surgical precision when used by a single novice surgical resident. The results of this study support evaluation of the guides in small breed cadavers and live patients.

1 | INTRODUCTION

Cervical intervertebral disc disease (IVDD) is a common cause of neurologic dysfunction and accounts for 14%–25% of intervertebral disc lesions in dogs.[1–4] Ventral slot decompression is considered the treatment of choice for most patients with severe cervical pain, neurologic deficits, and those who fail to respond to medical management.[1,2,5,6] Complications associated with ventral slot have been reported in 9.9% of cases and include vertebral instability and subluxation secondary to excessive slot

Presented at American College of Veterinary Surgeons Symposium: Residents' Forum. Louisville, Kentucky.

width, hemorrhage from the vertebral sinus or vertebral artery, and failure to improve neurologically.[2,7] A critical component of ventral slot decompression is achieving appropriate ventral slot dimensions and position. Ventral slots should be centered on midline and should not exceed 33% of the length or 50% of the width of the vertebrae, though 33% of the width is considered ideal.[2,4,7,8]

Patient-specific three-dimensional (3D)-printed guides have been successfully used to improve surgical accuracy for sacroiliac luxation, humeral intercondylar fissure fixation, and cervical stabilization.[9–11] Based on successful outcomes following the use of 3D-printed guides in veterinary surgery, the primary objective of this study was to develop a patient-specific 3D-printed guide for ventral slot creation in dogs and to evaluate the accuracy and precision of ventral slot dimensions created using the 3D-printed guides compared to the traditional freehand technique. We hypothesized that ventral slots created using the 3D-printed guides would be more accurate and have less variability than freehand ventral slots. We also hypothesized that use of the drill guides would not have a significant effect on drilling time.

2 | MATERIALS AND METHODS

2.1 | Cadaveric specimen

Nine large breed canine cadavers weighing 23.4–39.8 kg were used. Cadavers were obtained from regional animal shelters. All cadavers were euthanized for reasons unrelated to the current study. Cadavers were stored at −20°C and thawed at room temperature for 48–72 h prior to imaging and ventral slot surgery. Cadavers with cervical pathology based on CT imaging were excluded.

2.2 | Imaging and guide design

Cadavers were positioned in dorsal recumbency with the head and neck extended. The cervical spine was imaged using computed tomography (CT) with a 64-slice multidetector scanner (Toshiba Aquilion 64, Canon Medical Systems Corporation, Otawara, Japan). Images were obtained using a bone algorithm with a slice thickness of 1 mm and stored in DICOM format.

Using randomization software (https://www.random.org/), intervertebral sites (C2–C3, C4–C5, and C6–C7) from each cadaver ($n = 24$ sites) were randomized to receive a freehanded ventral slot (FHVS) ($n = 12$) or guide-assisted ventral slot (GAVS) ($n = 12$). Alternating intervertebral spaces were chosen such that adjacent disc spaces would not have a visible ventral slot which could bias the resident during drilling. For the GAVS group, CT scans were transferred to an open-source image analysis software platform (Invesalius, version 3.1.1).

The optimal ventral slot dimensions were measured by a single surgical resident. Ventral slot dimensions were calculated as 33% of the vertebral width and 33% of the vertebral length of the adjacent vertebra. A surgical guide template was created using proprietary computer-aided design (CAD) software (Solidworks, version SP2.1). The guide was designed to fit to the ventral surfaces of the adjacent vertebrae and contained a central channel based on the calculated ventral slot dimensions. Two pin holes were designed in the cranial and caudal aspects of the guide to allow for placement of fixation pins in the event tissue glue was not sufficient for stabilization of the surgical guide on the ventral surface of the vertebra (Figure 1). An STL file of each drill guide was created. STL files of the drill guide and cervical spines were transferred to an open-source CAD software (Blender, version 3.6.1). The 3D guide was altered to conform to the exact topography of the ventral aspect of the cervical vertebrae and was centered over the dorsal aspect of the intervertebral disc (Figure 2). After completing the design of the 3D-drill guide, the STL file was transferred to the 3D printer (Creality Halot Resin Printer).

2.3 | Drill guide pilot

Prior to using the surgical guide in cadavers, proof of concept was achieved by performing guide-assisted ventral slots on two 3D-printed cervical spinal models based on one of the cadavers. The 3D drill guides, and cervical spines were printed using resin (Siraya Tech Sculpt photoreactive resin) using the Creality Halot Sky Printer. Three guide prototypes were tested, one with short outer walls, one with mid-height outer walls, and one with tall outer walls, for C4–C5. The models were taped to the operating table in dorsal recumbency, and 3D-printed guides were glued to the ventral surface of the spinal model using cyanoacrylate glue. This resulted in adequate fixation of the guides to the spinal models. A 0.035 mm Kirschner wire was cut in half and advanced through the cranial and caudal pin holes in the guide to document appropriate fit and adequate fixation in the event cyanoacrylate glue was not sufficient for guide fixation in cadavers. Ventral slots were performed using an electric high-speed drill. Drilling the short and mid-height walled guides resulted in immediate destruction of the guides. A ventral slot was successfully performed using the tall-walled guide with no appreciable damage to the guide (Figure 3).

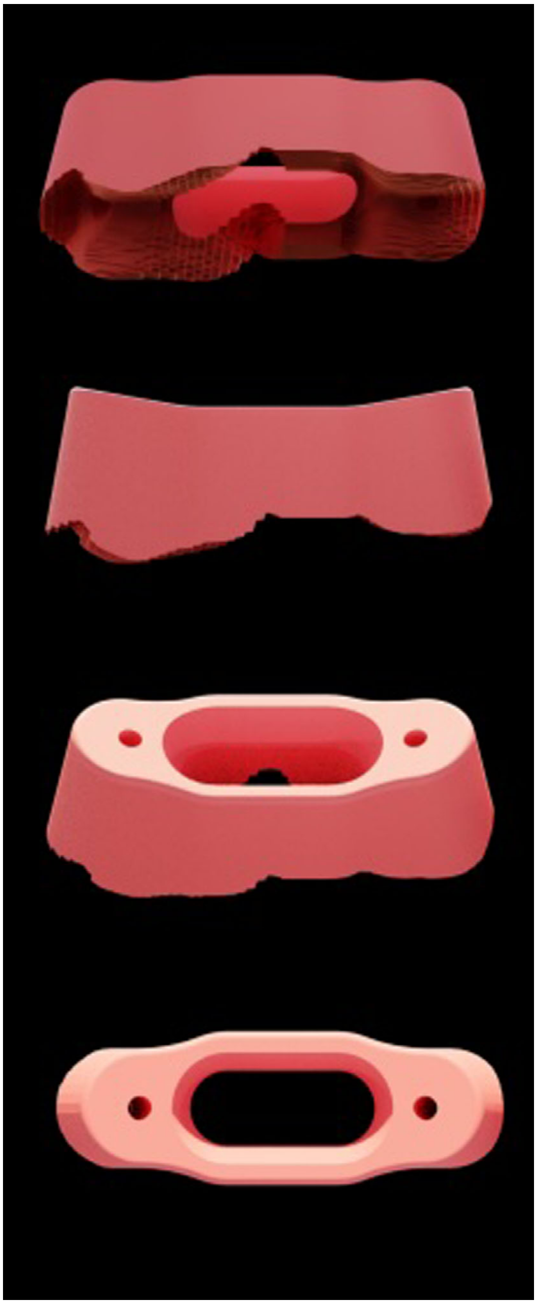

FIGURE 1 Surgical guide templates created using computer-aided design (CAD) software. Two pin holes were created in the cranial and caudal aspects to accommodate 0.035 mm Kirschner wires for guide fixation, if required.

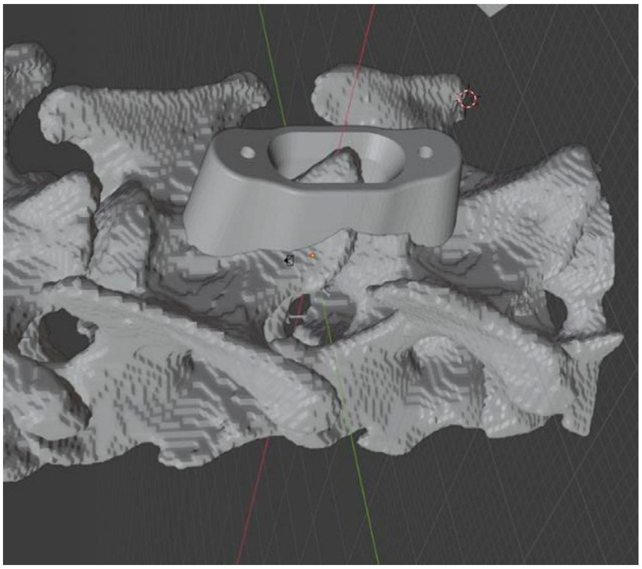

FIGURE 2 View of the drill guide over C4–C5 using computer-aided design (CAD) software. The drill guide conforms to the ventral aspect of the vertebrae and is centered over the dorsal aspect of the intervertebral disc.

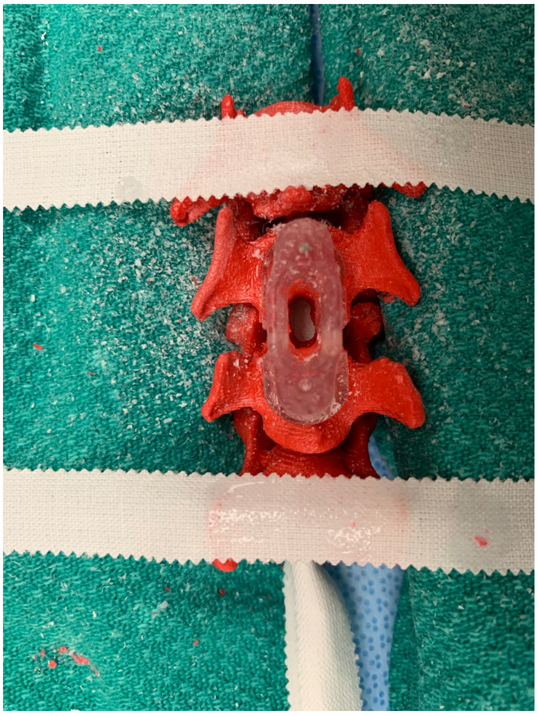

FIGURE 3 Completed drill-guide assisted ventral slot using a three-dimensional (3D) printed cervical spine.

2.4 | Cadaver surgery

All ventral slot procedures were performed by a single surgical resident under the direct supervision of a board-certified surgeon. The board-certified surgeon did not provide feedback on the appropriateness of slot location or dimension to prevent bias. Two ventral slot procedures were performed per session and included one free-handed ventral slot and one guide-assisted ventral slot. Free-handed ventral slots were performed first to prevent biasing of the surgery resident. To prevent bias due to natural acquisition of skill, a minimum of 7 days was required between ventral slot sessions. Cadavers were refrozen at −20°C between sessions.

The cadavers were positioned in dorsal recumbency on the operating table with the thoracic limbs pulled caudally and held in place with tape. A standard approach to the ventral cervical spine was performed in all cadavers. Previously made ventral slots, if present, were covered with gauze to prevent biasing of the surgery resident. For the FHVS group, a standard ventral slot was performed by visually estimating an appropriate slot dimension based on the length and width of the adjacent vertebra using a high-speed electric drill. For the GAVS group, the 3D-printed drill guide was fixed to the ventral aspect of the vertebrae using cyanoacrylate glue applied through the pin holes. This resulted in adequate fixation and Kirschner wires were not used. Ventral slots were performed using a high-speed electric drill within the confines of the 3D-printed guides until the vertebral canal was accessed (Figure 4). Surgical time was recorded from the start of burring until the spinal canal was entered at all aspects of the slot. Burr sizes and sleeves were changed intraoperatively at the discretion of the surgery resident. Time was not stopped during burr or sleeve changes.

2.5 | Post ventral slot CT and data analysis

Postoperative CT was performed in all cadavers to assess ventral slot morphology. Cadavers were positioned in dorsal recumbency with the head and neck extended in an attempt to mimic preoperative positioning. Images were transferred to the open-source image analysis software platform. One surgery resident made all measurements in triplicate and the mean value was calculated. All measurements were linear and made in millimeters.

2.5.1 | Slot dimensions

For each ventral slot, measurements were taken in the coronal plane at the ventral aspect of the slot and dorsal aspect of the slot. Length was measured from the most cranial to most caudal aspect of the slot. Width was measured at the level of the caudal and cranial vertebral endplates (Figure 5). Comparison of realized slot dimensions to target slot dimensions was performed using a two-sample *t*-test for freehand and guide-assisted ventral slots.

2.5.2 | Slot shape

For each ventral slot, measurements were taken in the coronal plane at the ventral and dorsal aspects of the slot. Approximate slot area was measured by multiplying slot length by slot width. Slot shape (rectangular vs. conical) was approximated by calculating the ratio of the area at the ventral aspect to the area of the dorsal aspect of the slot. A slot ratio of 1 represented a slot with the same area at the ventral and dorsal aspects and thus a rectangular shape. Slots with ratios >1 represented larger ventral areas and thus a conical shape. Slots withs ratios <1 represented smaller ventral areas and thus an inverted conical shape. Slot ratios were compared using a two-sample *t*-test.

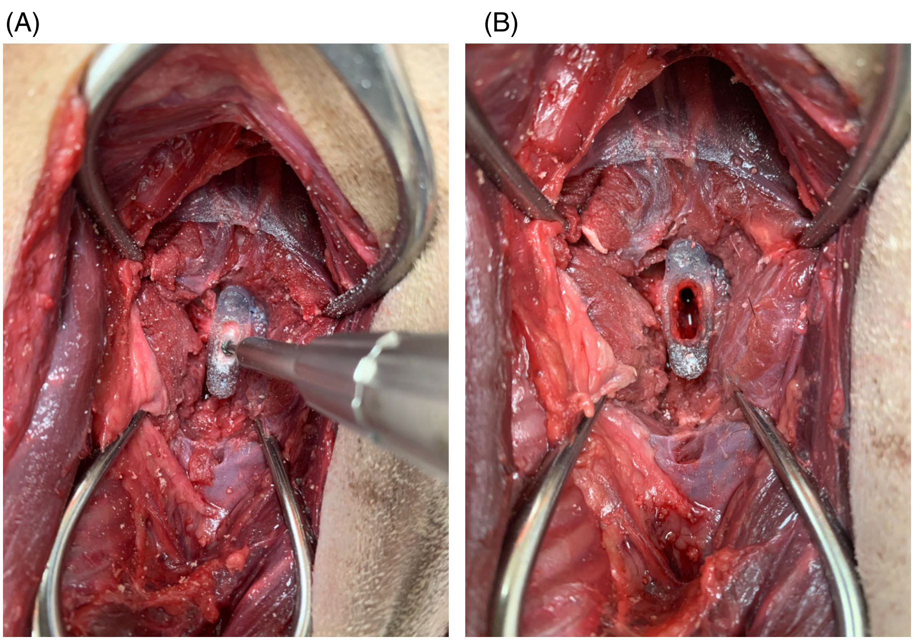

FIGURE 4 (A) Intraoperative drilling of a C4–C5 ventral slot using the three-dimensional (3D) printed patient specific drill guide. (B) Completed C4–C5 guide-assisted ventral slot.

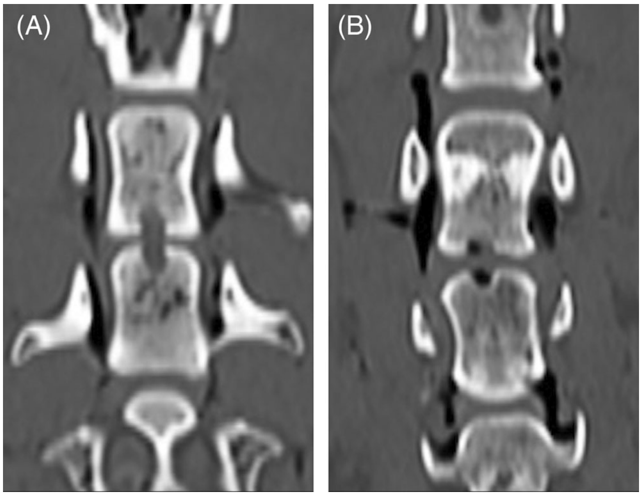

FIGURE 5 Coronal views of (A) a C4–C5 guide-assisted ventral slot and (B) freehand ventral slot. Length of the ventral slot was measured from most cranial to most caudal aspect of the slot. Width was measured at the level of the vertebral endplates.

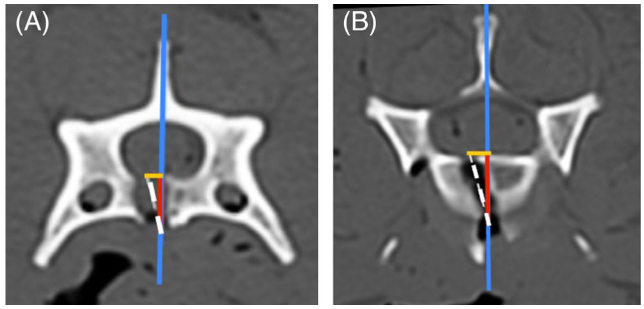

FIGURE 6 Axial views used to measure slot divergence from (A) midline of C4 for a guide-assisted ventral slot and (B) freehand ventral slot. The blue line bisects the center of the dorsal spinous process and vertebral body. The yellow line (measurement a) measured the distance between the center of the ventral slot and midline at the dorsal aspect of the slot. The red line (measurement b) measures the depth of the ventral slot. The slot divergence angle was measured using the formula tan A = measurement a/measurement b. The slot divergence angles for the above ventral slots were (A) 7.1° to the right and (B) 8.4° to the right.

2.5.3 | Slot divergence from midline

Measurements of slot divergence were measured in the axial plane at the cranial aspect and caudal aspect of the ventral slot. A linear measurement tool was used to create a straight line through the midline of the vertebral body, bisecting the dorsal spinous process. Slot divergence angle (angle A) was measured using the formula tan A = measurement a/measurement b, where measurement a represented divergence of the center of the slot from vertebral midline and measurement b represented depth of the ventral slot (Figure 6). Divergence angles were compared using a two-sample *t*-test.

2.5.4 | Slot position

Slot position was measured in the coronal plane at the ventral aspect of the ventral slot at the caudal and cranial endplates. The width of bone to the left and right of the slot were measured and the ratio was calculated. A ratio of 1 represented a slot that was positioned on midline. A ratio <1 represented a slot that was positioned to the left of midline. A ratio >1 represented a slot that was positioned to the right of midline. Slot position was compared using a two-sample *t*-test.

2.6 | Statistical analysis

Statistics were performed using SAS software (SAS Institute, North Carolina, USA). Normal distribution of data was confirmed using a Shapiro–Wilk test. Surgical time was compared between groups using a two-sample *t*-test. Surgical precision related to slot position, divergence from midline, and shape was compared using coefficient of variation.

3 | RESULTS

3.1 | Cadaveric specimen

One cadaver was excluded due to cervical pathology noted on preoperative CT. Eight canine cadavers were included. Mean bodyweight was 30.4 kg (range 23–40 kg). The age at time of euthanasia was not available; however, all dogs were skeletally mature.

3.2 | Surgical time

There was no significant difference between surgical time for GAVS (20.15 ± 13.7 min) and FHVS (11.9 ± 4.8 min; $p = .071$).

3.3 | Slot dimensions

Relative and absolute ventral slot dimensions are summarized in Table 1. FHVS were significantly shorter in length at both the ventral and dorsal aspects compared to the intended dimensions ($p < .01$). There was no significant difference in FHVS width at either the ventral or dorsal aspect of the slot compared to the intended dimensions (p = .592, .897, respectively). Dimensions of the GAVS were not statistically different at either the ventral or dorsal aspects from the intended dimensions for both length (p = .722, .172, respectively), and width (p = .875, .651, respectively). Post hoc power analysis using parameters of slot length revealed a power of 1.0 (100%).

3.4 | Slot shape, divergence, and position

A total of 13 of 24 ventral slots had a shape ratio >1 indicating an inverted conical shape (1.17 ± 0.58). Mean shape ratio of the GAVS was 1.12 ± 0.28 which was not significantly different from FHVS (1.23 ± 0.79; p = .636). No significant difference in divergence from midline between GAVS (7.73 ± 3.94) and FHVS (6.59 ± 3.53) was identified (p = .463). There was no bias in direction of deviation between right (12/24) or left (12/24). A significant difference in slot position relative to midline was not reported for either group (p = .235). Use of the guide reduced the coefficient of variation for slot position from 63% to 29% (32% reduction) and slot shape from 65% to 24% (40% reduction). Use of the guide reduced the coefficient of variation for slot divergence from midline from 54% to 50% (4% reduction).

4 | DISCUSSION

3D-printed patient specific surgical guides improved the accuracy of ventral slot creation in canine cadavers, allowing acceptance of our hypothesis. Further, the guides resulted in improved surgical precision of a novice surgery resident.

Achieving accurate ventral slot dimensions is essential to successful spinal cord decompression following cervical intervertebral disc extrusion. Inaccurate slot creation can lead to several complications which may necessitate additional surgical procedures, longer durations of hospitalization, and may result in worse surgical outcomes.[2,4,7] Use of a surgical guide to improve ventral slot accuracy may therefore reduce surgical complications. It is interesting to note that freehand ventral slots in this study were significantly shorter than the intended dimensions. This may be a result of inherent fear in novice surgery residents to create inappropriately large ventral slots. Use of the 3D-printed guides may therefore promote the creation of more appropriate ventral slots to allow for adequate spinal cord decompression. Further investigation of inherent biases in multiple surgical residents and in board-certified surgeons is warranted.

In this study, there was no significant difference in slot position, divergence from midline, or slot shape between freehand and guided techniques; however, use of the guides resulted in increased surgical precision for a

TABLE 1 Relative (%) and absolute (mm) ventral slot dimensions.

Dimensions		Relative dimensions (%)		Absolute dimensions (mm)	p-value
Ventral length	FHVS	Intended	33	19.0 ± 4.7	p = .002
		Postoperative	23 ± 2.6	13.0 ± 3.5	
	GAVS	Planned	33	20.3 ± 5.0	p = .72
		Postoperative	32 ± 1.5	19.7 ± 3.2	
Dorsal length	FHVS	Intended	33	19.0 ± 4.7	p = .0003
		Postoperative	20 ± 1.8	11.7 ± 3.3	
	GAVS	Planned	33	20.3 ± 5.0	p = .17
		Postoperative	30 ± 6	17.7 ± 4.2	
Ventral width	FHVS	Intended	33	5.4 ± 0.8	p = .88
		Postoperative	35 ± 4.4	5.5 ± 1.9	
	GAVS	Planned	33	5.3 ± 0.8	p = .59
		Postoperative	32 ± 7.0	5.0 ± 1.8	
Dorsal width	FHVS	Intended	33	5.4 ± 0.8	p = .65
		Postoperative	36 ± 5.3	5.7 ± 2.7	
	GAVS	Planned	33	5.3 ± 0.8	p = .82
		Postoperative	33 ± 6.5	5.2 ± 1.1	

Abbreviations: FHVS, freehand ventral slot; GAVS, guide-assisted ventral slot.

novice surgery resident. It is possible that use of these surgical guides may also improve confidence and competence in surgical residents when performing these procedures during their training.

The surgical guides in this study were fixed to the ventral surface of the vertebrae using cyanoacrylate tissue glue, thus eliminating the need for additional instrumentation or implants such as k-wires or screws. Adequate soft tissue dissection was required for appropriate guide fit and fixation. Subjectively, the authors found application of the guides to be easy, added minimal time to the procedure, and did not have a significant effect on drilling time. While the lateral walls of the guide were tall enough to limit some divergence, the surgeon remains vulnerable to deviattion from midline while using the guide and thus must always be cognisant of the trajectory of their burr when using the guides.

Potential disadvantages to clinical use of the 3D-printed surgical guides include limited availability of CAD software and 3D-printing facilities and the potential delay from presentation to surgery to facilitate guide design, printing, and sterilization. Fortunately, most patients with cervical intervertebral disc extrusion present with cervical hyperesthesia alone, which may afford time for guide preparation.[2,12,13]

Limitations of this study include the use of cadavers instead of live dogs. Further, the cadavers in this study were all >20 kg and may less accurately represent the population of small-breed dogs who also suffer from cervical intervertebral disc extrusion. Positioning of the cadavers between CT and surgery was subject to variability and thus may have affected slot geometry. Additionally, field of view was not constant for all CT studies thus voxel size and resolution were variable. Future studies are needed to evaluate the development and feasibility of use of the 3D-printed surgical guides in small breed dogs and live patients. Additionally, the benefit of the guide was only evaluated by a novice surgery resident. Studies evaluating the benefit of these guides in the hands of additional surgery residents during training and experienced surgeons are warranted.

In conclusion, use of a patient specific 3D-printed surgical guide improves accuracy of ventral slot creation in canine cadavers and improved surgical precision in a novice surgery resident.

AUTHOR CONTRIBUTIONS

Walker MA, BSc, MSc, DVM: Contributed to the design of the study, performed CT measurements, performed ventral slots, and interpreted data. Ogilvie AT, BSc, DVM, DVSc, DACVS (Small Animal): Contributed to the design of the study. McSorley G, BEng, PEng, PhD: Contributed to the design of the study, developed, and printed the 3D-printed guides. Montelpare W, BPHE, MSc, PhD: Analyzed data for statistical significance. Hoddinott KL, BSc, DVM, DVSc, DACVS (Small Animal): Contributed to the design of the study and supervised ventral slot procedures. All authors provided a critical review of the manuscript and endorse the final version. All authors are aware of their respective contributions and have confidence in the integrity of all contributions.

FUNDING INFORMATION

Atlantic Veterinary College Companion Animal Trust Fund.

CONFLICT OF INTEREST STATEMENT

The authors confirm there is no conflict of interest.

ORCID

Meagan A. Walker https://orcid.org/0000-0003-3177-9937
Katie L. Hoddinott https://orcid.org/0000-0001-5399-1977

REFERENCES

1. Argent V, Perillo R, Jeffery N, Freeman P. Recurrence of signs consistent with cervical intervertebral disc extrusion in dogs. *J Small Anim Pract*. 2022;63(6):454-459.
2. Brisson BA. Intervertebral disc disease in dogs. *Vet Clin N Am*. 2010;40(5):829-858.
3. Farrell M, Solano MA, Fitzpatrick N, Jovanovik J. Use of an ex vivo canine ventral slot model to test the efficacy of a piezoelectric cutting tool for decompressive spinal surgery. *Vet Surg*. 2013;42(7):832-839.
4. Fauber AE, Wade JA, Lipka AE, McCabe GP, Aper RL. Effect of width of disk fenestration and a ventral slot on biomechanics of the canine C5-C6 vertebral motion unit. *Am J Vet Res*. 2006;67(11):1844-1848.
5. Leperlier D, Manassero M, Blot S, Thibaud JL, Viateau V. Minimally invasive video-assisted cervical ventral slot in dogs - a cadaveric study and report of 10 clinical cases. *Vet Comp Orthop Traumatol*. 2010;24(1):50-56.
6. Hermann A, Voumard B, Waschk MA, Hettlich BF, Forterre F. In vitro biomechanical comparison of four different ventral surgical procedures on the canine fourth-fifth cervical vertebral motion unit. *Vet Comp Orthop Traumatol*. 2018;31(6):413-421.
7. Rossmeisl JH, White C, Pancotto TE, Bays A, Henao-Guerrero PN. Acute adverse events associated with ventral slot decompression in 546 dogs with cervical intervertebral disc disease. *Vet Surg*. 2013;42(7):795-806.
8. Coates JR. Intervertebral disk disease. *Vet Clin N Am*. 2000;30(1):77-110.
9. McCarthy DA, Granger LA, Aulakh KS, Gines JA. Accuracy of a drilling with a custom 3D printed guide or free-hand technique in canine experimental sacroiliac luxations. *Vet Surg*. 2022;51(1):182-190.
10. Easter TG, Bilmont A, Pink J, Oxley B. Accuracy of three-dimensional printed patient-specific drill guides for treatment

of canine humeral intracondylar fissure. *Vet Sci*. 2020;49(2): 363-372.
11. Hamilton-Bennett SE, Oxley B, Behr S. Accuracy of a patient-specific 3D printed drill guide for placement of cervical transpedicular screws. *Vet Surg*. 2018;47(2): 236-242.
12. Ryan TM, Platt SR, Llabres-Diaz FJ, McConnell JF, Adams VJ. Detection of spinal cord compression in dogs with cervical intervertebral disc disease by magnetic resonance imaging. *Vet Rec*. 2008;163(1):11-15.
13. Cherrone KL, Dewey CW, Coastes JR, Bergman RL. A retrospective comparison of cervical intervertebral disk disease in nonchondrodystrophic large dogs versus small dogs. *J Am Anim Hosp Assoc*. 2004;40(4):316-320.

How to cite this article: Walker MA, Ogilvie AT, McSorley G, Montelpare W, Hoddinott KL. Evaluation of a patient-specific 3D-printed guide for ventral slot surgery in dogs: An ex vivo study. *Veterinary Surgery*. 2025;54(3):594-601. doi:10.1111/vsu.14210