ORIGINAL ARTICLE

Tomographic, cadaveric and clinical study of safe corridors for insertion of implants in the thoracolumbar spine of dogs and cats using a lateral approach

R. Lamère [*,1], S. Scotti [*], M. Saccone [†], L. Meomartino [‡], L. Auletta [§] and C. Ragetly [*]

[*]Small Animal Surgery Department, Veterinary Clinic Evolia, l'Isle-Adam, France
[†]Private Practice, Caserte, Italy
[‡]Interdepartmental Center of Veterinary Radiology, University of Napoli "Federico II", Naples, Italy
[§]Department of Veterinary Medicine and Animal Sciences (DIVAS), University of Milano, Milano, Italy

[1]Corresponding author email: romain.lamere@gmail.com

Objectives: This study aimed to: describe a lateral vertebral corridor (T6-L7) for the implantation of screws and polymethylmethacrylate to treat thoracolumbar vertebral injuries; assess the feasibility and safety of this approach using computed tomography; assess the learning curve of this technique in canine cadavers; and assess the outcomes in injured dogs and cats in a retrospective clinical study.

Materials and Methods: Tomographic study: Lateral vertebral corridors were defined using computed tomography images of normal canine spines in the transverse plane. Cadaveric study: Corridors were drilled by a novice neurosurgeon on the cadavers, and deviation from an angle of 90° was evaluated on computed tomography in chronological order to assess the learning curve. Clinical study: The medical records (from 2008 to 2022) of dogs and cats treated for thoracolumbar vertebral injury using the lateral approach were reviewed.

Results: Computed tomography revealed that the lateral corridors were safe and effective. A progressive reduction in the deviation between the measured and ideal insertion angles was observed in the cadaveric part of the study. Overall, 17/30 animals (56.7%) regained the ability to walk without assistance postoperatively and 3/11 animals (27.3%) that had lost deep pain sensation. There were 3/30 (10%) minor complications and 8/30 (26.7%) major complications, including perioperative death and euthanasia.

Clinical Significance: Lateral vertebral corridors with an orientation angle of 90° may be safely used in caudal thoracic and lumbar vertebrae (T6-L7) in a freehand technique to treat vertebral fractures and/or luxations in dogs and cats.

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INTRODUCTION

Vertebral fractures and/or luxations in dogs and cats result primarily from direct physical trauma, and the thoracolumbar region is the most commonly affected site (Bali et al., 2009; Bruce et al., 2008). Depending on the neurological deficits, degree of instability and presence of a compressive fragment within the vertebral canal, treatment can be surgical or conservative. The goals of surgical treatment include realignment of the affected vertebrae, decompression of the spinal cord and vertebral stabilisation.

A major concern in surgical treatment is the positioning of implants within the vertebrae; a sufficient amount of bone anchoring is warranted as well as avoiding damage to the spinal cord and major vascular structures. Studies have identified ideal corridors for osteosynthesis implants by analysing computed tomography (CT) scans (Schmitt et al., 2021; Vallefuoco et al., 2013; Watine et al., 2006), ex vivo trials with fluoroscopic support (Wheeler et al., 2002, 2007), or with the recent development of three-dimensionally printed animal-specific drill guides (Fujioka et al., 2019, 2020; Guevar et al., 2021; Mariani et al., 2021). The clinical applicability of these corridors without fluoroscopy or a three-dimensional printer is difficult in clinical practice because of the limited margins of error for each technique. The creation of those three-dimensionally printed drill guides is time-consuming and delays surgery, while it is desirable to operate within a short period after the trauma of an animal with a vertebral fracture/luxation.

This study included an experimental part, where CT images of canine spines were studied to assess the possibility of using a lateral vertebral corridor, and cadavers were used to check the feasibility and learning curve of this technique; then, a clinical study, where clinical cases of vertebral fracture/luxation surgically treated with this technique were reviewed.

The objectives of this study were (1) to evaluate the feasibility and the safety of a lateral vertebral corridor and define the characteristics of optimal corridors using CT; (2) to determine the learning curve of the technique on cadavers by a surgeon with no experience in neurosurgery; and (3) to assess the postoperative outcome of stabilisation using a lateral approach to treat thoracic or lumbar vertebral fractures and/or luxations in dogs and cats. We hypothesized that using a lateral corridor with an inclination angle of 90° would be safe, effective and easily reproducible in a clinical setting by both a novice and experienced neurosurgeon and that the results would be similar to those of other already described techniques.

MATERIALS AND METHODS

Study design

The study was divided into three sections: (1) a tomodensitometric study to identify the optimal safe implantation corridor of thoracic and lumbar vertebrae (from T6 to L7) in the transverse plane on CT images of the spinal column of 20 healthy dogs without spinal lesions; (2) a cadaveric study, to appraise the safety and the learning curve of the technique by drilling lateral corridors on cadavers by a surgeon without experience in neurosurgery; and (3) a retrospective clinical study, including dogs and cats admitted to a clinic with a thoracic or lumbar vertebral fracture and/or luxation treated via a lateral approach. The protocol of the cadaveric study was approved by the ethical committee of the University of Napoli “Federico II”, Napoli, Italy.

Computed tomography

Twenty CT scans of the thoracic and lumbar columns of different canine breeds were selected for review from tomodensitometric databases. CT was performed at the authors’ clinic for medical reasons unrelated to the study (mainly cancer staging). Studies involving vertebral lesions were also excluded. The CT images were reviewed to assess the safety of the lateral corridor and the amount of bone purchased using the lateral vertebral approach. One corridor per vertebra was assessed. These corridors were defined by the following: the insertion point (I), which was placed at the base of the costovertebral joint for thoracic vertebrae and at the base of the transverse process for lumbar vertebrae in the transverse plane; in the frontal plane, this point was defined at 25% of the length of the vertebral body from the cranial vertebral disc; and an insertion angle of 90° to the sagittal plane (Fig 1). With the insertion points defined, in the transverse plane, the distance between the floor of the vertebral canal and the upper margin was evaluated to determine the ideal corridor (A to B) as well as the width of the corridor (I to J); the height of the vertebral body on the sagittal plane (A to C); the maximum safe angle in the dorsal direction (β) that does not cause iatrogenic damage to the vertebral canal; the maximum safe angle in the ventral direction (γ) that does not cause iatrogenic damage and warranted the maximum amount of bone anchoring (Fig 2).

Cadaveric study

The feasibility and learning curves of the lateral vertebral corridors were evaluated in 10 canine cadavers from different breeds of medium-sized animals that were euthanized for medical reasons unrelated to the study. A surgeon with no experience in neurosurgery approached the thoracic and lumbar vertebral bodies (similar to the technique described in a clinical study). In the first case, an experienced surgeon showed the insertion point and drilling angle. Two surgical techniques were tested: for the first one, only one aperture was created per vertebra; for the second one, the feasibility to place two holes per vertebra was tested, with the second hole being created at the same ventrodorsal level as the first one, at about 25% of the distance from the caudal intervertebral disc. After the drilling process, a chronological CT examination was performed for each cadaver to assess the positioning of the holes, identify possible iatrogenic damage and assess the learning curve of appropriately placing the drilled trajectory. Details of the procedure and the evaluation of the learning curve are reported in File S1.

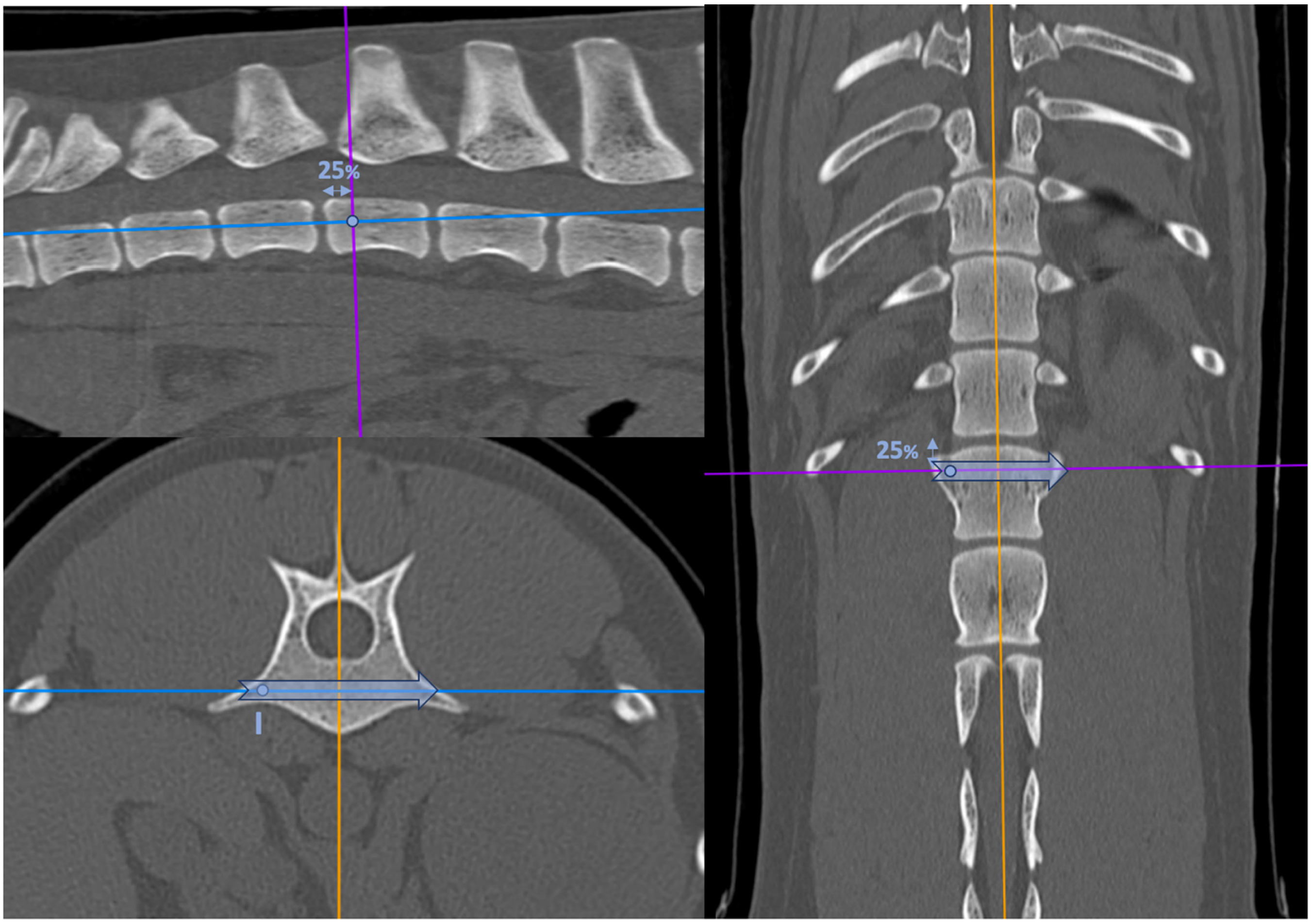

FIG 1. Illustration of the landmarks used to assess the lateral corridors in the CT scan study in the sagittal, transverse and frontal plane (L1 is represented): (I) is the insertion point, which is at 25% of the length of the vertebral body from the cranial vertebral disc and at the base of the transverse process; the arrow indicates the corridor at an insertion angle of 90° from the sagittal plane.

Clinical study

Case selection

Medical records from 2008 to 2022 were reviewed for dogs and cats with thoracic or lumbar vertebral fractures and/or luxation treated surgically with screws (DePuy Synthes, Johnson & Johnson, USA) and PMMA (Amplifix, Amplitude Surgical, France), using a lateral approach and an intended inclination corridor of 90°in the vertebral body (Figs 3 and 4). Animals euthanased, not treated surgically, treated with another surgical technique, or treated using the lateral technique for conditions other than thoracolumbar vertebral fractures and/or luxation were excluded from the study.

Data collection

Patient signalment (species, breed, weight and age), origin of trauma, neurological dysfunction, imaging method (radiographs and/or CT images), localization and nature of the injury, presence of concurrent injuries, time elapsed between trauma and surgical treatment and complications were recorded. Neurological status was classified into five grades based on the severity of dysfunction (Table S1; Vallefuoco et al. (2014)), and the degree of instability was assessed using the three-compartment model (Shores, 1992).

Surgical procedure

All surgeries were performed by a former resident in small-animal surgery or by a board-certified surgeon using the same technique. All animals were placed in right lateral recumbency (both surgeons were right-handed) with the forelimbs and hind limbs stretched and fixed to the operating table to help reduce the fractured/luxated site. Care was exercised to position the spine horizontally. A left lateral approach to the spine was used, and ostectomy of the transverse process was performed using gouge forceps to expose the implantation site (Fig 5). If the fracture site was on the thoracic spine, the approach was combined with dorsal intercostal thoracotomy and the thoracic pleura was penetrated to permit ostectomy of the proximal quarter of the adjacent rib and luxation of the costovertebral joint with gouge forceps (Fig 6). The approach was identical for the eight most caudal thoracic and lumbar vertebrae (*i.e.*, T6 to L7). In addition, for L6 and L7, a partial ostectomy

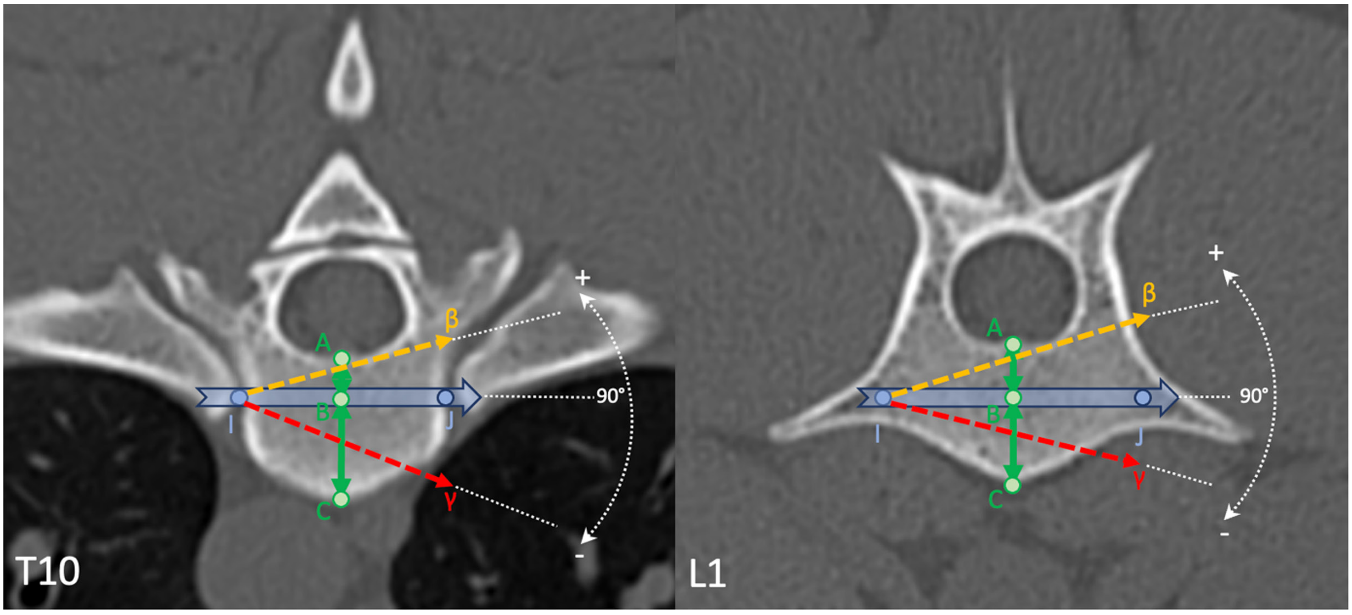

FIG 2. Measures taken for the computed tomography (CT) study in a transverse plane (illustrated on T10 and L1): (I) is the ideal insertion point; (I to J) is the width of the ideal corridor; (A to B) is the distance between the floor of the vertebral canal and the upper margin of the ideal corridor in the sagittal plane; (A to C) is the height of the vertebral body on the sagittal plane; (β) is the maximum deviation angle in the dorsal direction that does not cause iatrogenic damage; (γ) is the maximum deviation angle in the ventral direction that does not cause iatrogenic damage and allowed bone anchoring.

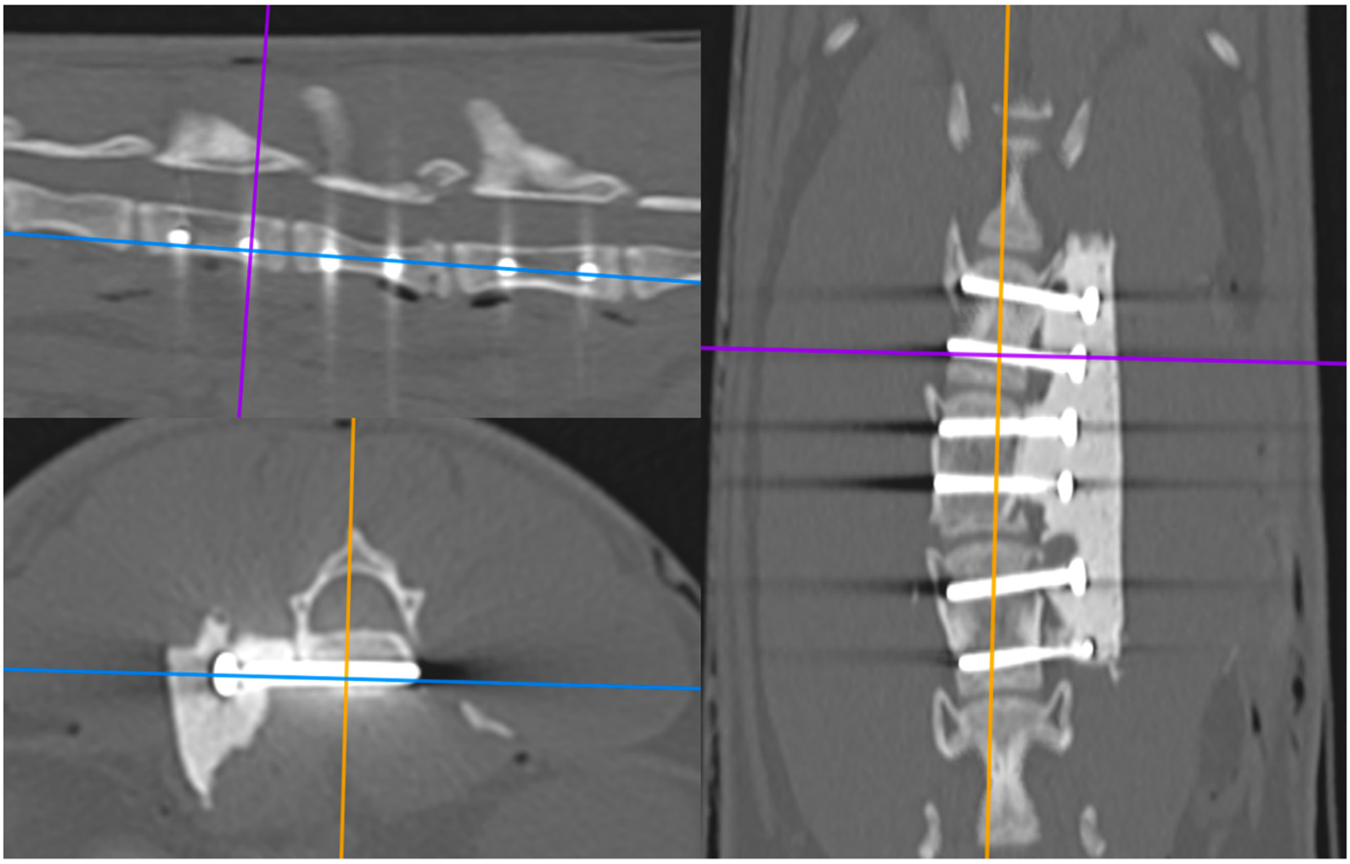

FIG 3. Sagittal, transverse and frontal views of a tomodensitometric postoperative exam of a L4 fracture and L4-L5 luxation in a cat treated with a lateral approach with screws embedded in PMMA.

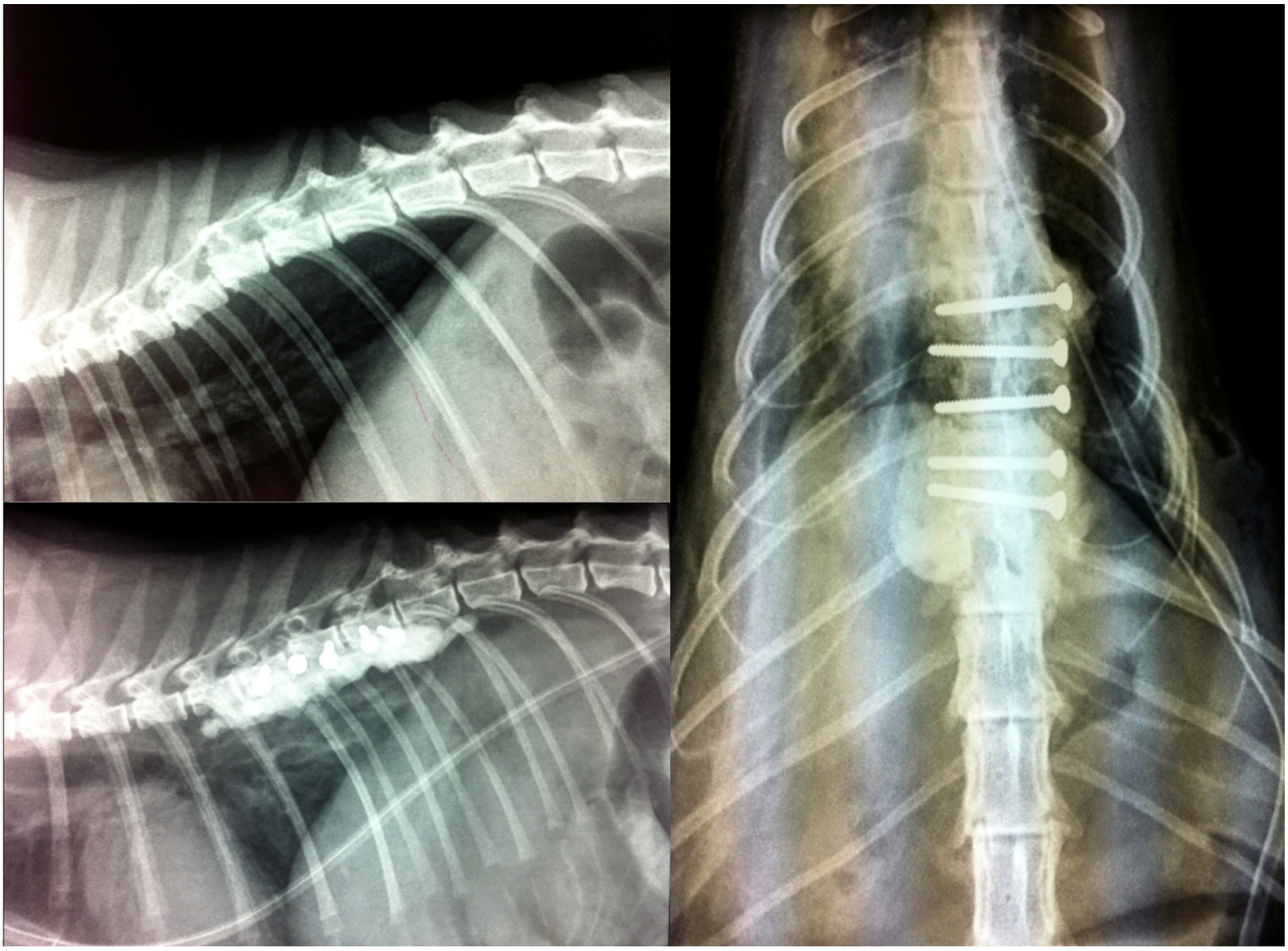

FIG 4. Preoperative and postoperative lateral and ventrodorsal radiographs views of a T8-T9 fracture/luxation in a cat treated with a lateral approach with screws embedded in polymethyl metacrylate.

of the iliac crest was performed using gouge forceps to allow access to the vertebral body (Fig 7). Needles (23 or 25 gauge, depending on the size of the patient) were introduced into the intervertebral discs as landmarks for the delineation of vertebral bodies. The insertion points (I) were at the base of the costovertebral articulation of the thoracic vertebrae and the base of the transverse process of the lumbar vertebrae. An estimated angle of 90° to the sagittal plane was used freehand (which corresponds approximately to a perpendicular to the operating table considering the lateral position of the dog), intersecting the centre of the vertebral body and exiting from the opposite cortex. Screws were inserted after tapping, with the screw head left approximately 5 to 15 mm proeminent (depending on the patient's size) for inclusion in the PMMA loaded with gentamicin (Amplifix 1G; Amplitude). Nevertheless, the implants for drilling must be individually adjusted based on the specific characteristics of each vertebra. Two or three screws were placed per vertebra if sufficient space was available in the cranial, middle, or caudal parts of the vertebral body. For comminuted fractures, screws were placed in the fractured vertebra or adjacent to it. A minimum of four screws (up to seven; two screws cranial and caudal to the injured site) were placed before the application of PMMA. The diameters of the screws were selected based on the patient's format and ranged from 1.5 to 3.5 mm. A graft of adipose tissue was placed on the nerve roots to avoid direct contact with cement. Traction was performed on the spine to realign the vertebrae by an assistant pulling on the forelimbs, with the pelvic limbs stretched and fixed to the operating table and PMMA was applied to embed the heads of the screws. Traction was maintained during the curing of the cement and irrigation with sterile saline solution to prevent thermal necrosis of the surrounding tissues. In cases of spinal cord compression by bone fragments, intervertebral disc disease, or hematoma in the vertebral canal, a hemilaminectomy was performed for decompression. Decompression during surgery was performed on a case-by-case basis by the surgeon when significant compression was observed on preoperative imaging. Finally, standard closure of the operating site was performed. A chest tube was applied if the thoracic pleura was penetrated to restore intrathoracic negative pressure and was removed postoperatively within 24 hours. Postoperative radiography or CT (depending on the year the surgery was

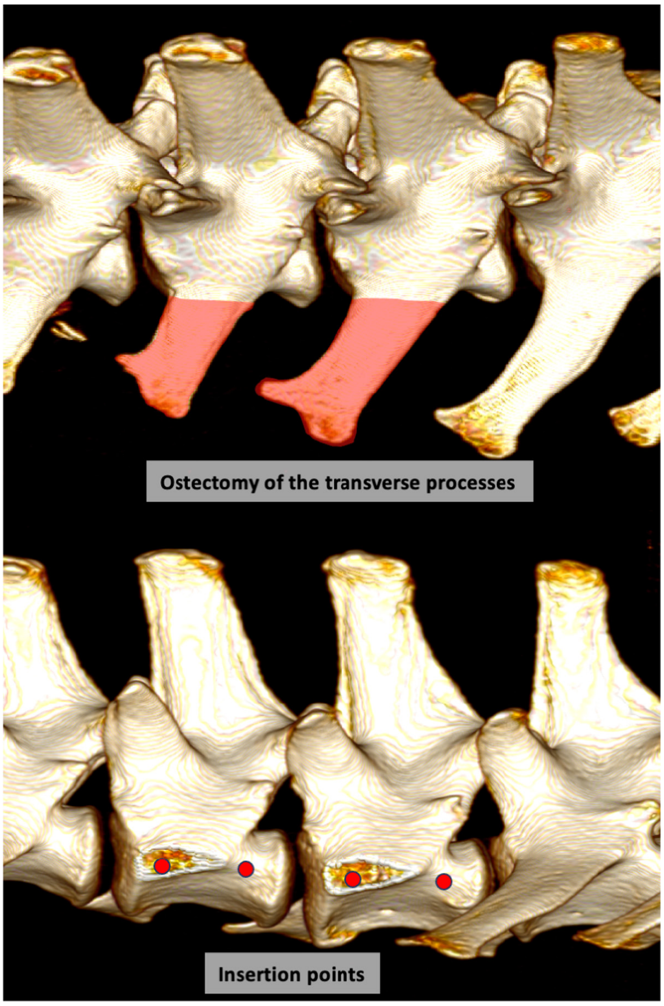

FIG 5. Illustration of the transverse processes ostectomy and insertion points for implants in lumbar spine in a three-dimensional volume rendering, here on L3 and L4 of a dog: the ostectomy is performed with gouge forceps up to the vertebral body, and the cranial insertion points are at the base of the transverse processes. Caudal insertion points are at the same level on the vertebral bodies as the cranial ones (area in red: extension of the ostectomy; points in red: insertion points).

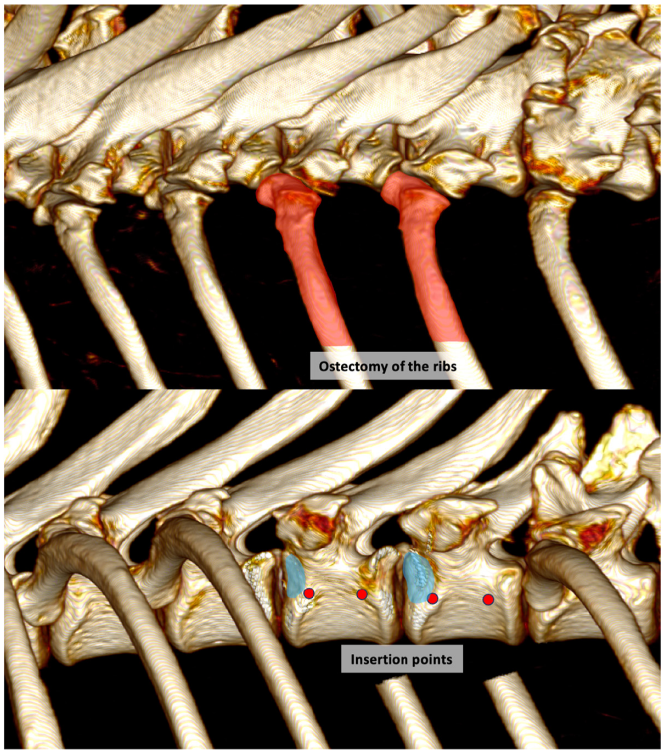

FIG 6. Illustration of the ribs ostectomy and insertion points for implants in the thoracic spine in a three-dimensional volume rendering, here on T9 and T10 of a dog: the ostectomy is performed with gouge forceps, starting distally and the costovertebral joint is luxated; the cranial insertion points are at the base of the cranial costal fovea. Caudal insertion points are at the same level on the vertebral bodies as the cranial ones (area in red: extension of the ostectomy; area in blue: cranial costal fovea; points in red: insertion points).

performed) was performed to assess the implant positioning and realignment of the spine. Vertebral canal invasion was also assessed.

Follow-up

Short-term follow-up was performed by clinical and neurological examinations and was defined by the neurological status at 2 weeks postoperatively. Long-term follow-up was performed by contacting the owners by phone or email to document the extent and timing of neurological recovery, presence or absence of urinary and faecal incontinence, presence of complications and quality of life. Clinical outcomes were defined at short- and long-term follow-up as (1) poor (no clinical improvement or worsening, non-ambulatory, chronic pain, faecal and/or urinary incontinence, death, or euthanasia), (2) guarded (mild clinical improvement, ambulatory with assistance, no pain, no or mild incontinence), (3) good (ability to ambulate without assistance, no pain, no incontinence), or (4) excellent (ambulatory with mild ataxia or complete recovery).

Statistical analysis

Clinical data were collected and analysed using Microsoft Excel for Mac, version 16.82. Data collected for the CT and cadaveric parts of the study were analysed using a statistical analysis program (Prism 10 for MacOS, v. 8.2.0, GraphPad Software Inc., La Jolla, CA, USA; JMP® Pro, v. 16.0, SAS Institute, Cary, NC, USA). For all tests, significance was set at $P<0.05$. The (A–B)/(A–C) ratio was used to compare the vertebrae of different sizes and shapes in the CT part of the study. The ratio was log-transformed and compared between the vertebrae using a standard least squares linear regression (Curran-Everett, 2013; da Costa & Johnson, 2012), and the estimate, standard error (SE), 95% confidence interval (95% CI) and P-value were evaluated and recorded when significant. The (β) and (γ) angles from the CT study, and the (α) angle were tested for normality with the Shapiro–Wilk's W test. According to data distribution, the (β), (γ) and (α) angles were compared between all vertebrae with the Kruskal–Wallis test, and post hoc the two-stage stap-up Benjamini, Krieger and Yekutieli correction method was used for multiple comparisons (Benjamini

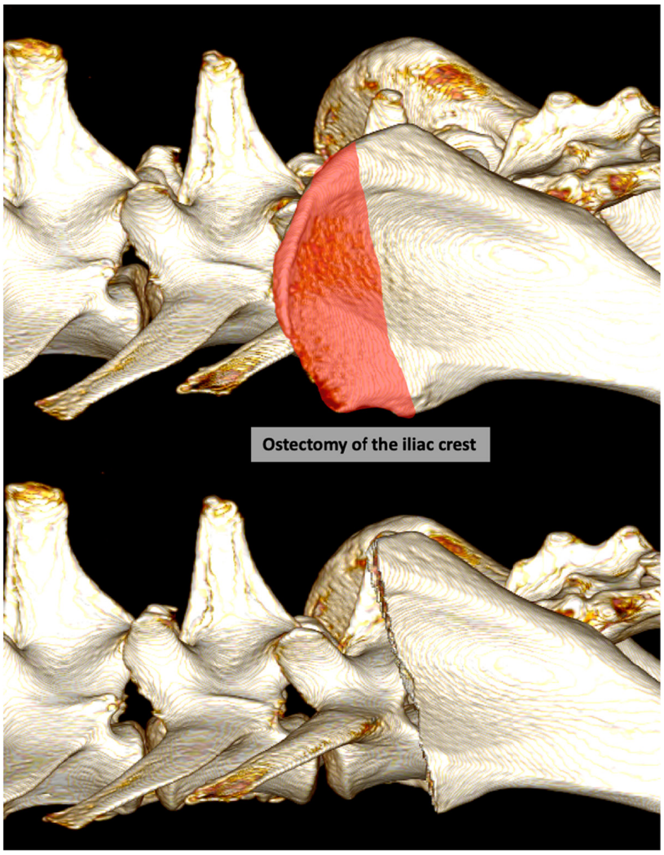

FIG 7. Illustration of the iliac crest ostectomy with gouge forceps in a three-dimensional volume rendering to allow access to L6 and L7 in a dog (area in red: extension of the ostectomy).

et al., 2006). The estimate, SE, upper and lower confidence limits (CL) and P-value were evaluated and recorded when significant. For all variables tested, a power analysis was performed using the function included in the statistical software. The deviation (Δ), that is, the difference between the measured angle (α) and the ideal angle of 90° in the cadaveric part of the study, was evaluated using a repeated measures ANOVA with the Geisser–Greenhouse correction with a mixed effect model, and a post hoc Bonferroni correction was applied for multiple comparisons between each case. The same statistical approach was applied to the overall set and then separately to the thoracic and lumbar vertebrae. The mean difference, 95% CI, and relative P-values were reported.

RESULTS

Computed tomography

One hundred and forty-two vertebrae were assessed in 20 dogs of different breeds. Non-significant results are summarised in File S2. A significant reduction in the log-transformed (A – B)/(A – C) ratio for L6 and L7 compared to all thoracic and lumbar vertebrae analysed was detected ($P < 0.05$). The corresponding P-values are reported in Tables S2 and S3. The power analysis yielded an obtained power of 99% to identify the differences between the vertebrae analysed for the log-transformed (A – B)/(A – C) ratio.

All the measured (β) angles were >90°; mean values for (β) angle of each vertebra are summarised in Table S4. The (β) angle was significantly smaller for L6 and L7 compared to vertebrae from T5 to L4. The corresponding P-values are reported in Tables S5 and S6. The power analysis yielded an obtained power of 99% to identify a difference between the vertebrae analysed for the (β) angle.

Likewise, all (γ) angles were <90°; mean values for (γ) angle of each vertebra are summarised in Table S4. The angle (γ) resulted in significantly smaller for L7 compared to vertebrae from T13 to L4. The corresponding P-values are reported in Table S7. The power analysis yielded an obtained power of 99% to identify a difference between the vertebrae analysed for the (γ) angle.

Cadaveric study

Eighty vertebrae were drilled on 10 dog cadavers of different breeds, for a total of 104 corridors. Six penetrations of the vertebral canal had been detected (5.8%): one at T8 (2.22 mm), one at T9 (2.09 mm), one at L5 (4.09 mm), two at L6 (0.20 and 2.27 mm) one at L7 (0.62 mm). Neither the lungs nor the vascular structures were on the corridor route. Details of the cadaveric study are reported in File S3 and the learning curves are reported in Fig S2–S4.

Clinical study

Study population

Thirty animals, including 22 dogs (mean ± standard deviation (SD), 13.0 ± 11.9 kg; range 1.2 to 44.0 kg; median 8.5 kg) and eight cats (mean ± SD, 4.0 ± 0.7 kg; range 3.3 to 4.9 kg; median 4.0 kg) met the inclusion criteria. Domestic Shorthair was the most common breed of cat; cockers (three cases) and Yorkshire terriers (two cases) were the most common breeds of dogs. The mean age was 4.2 years, 4.9 years for dogs and 2.4 years for cats. Road traffic accidents (nine cases, only dogs) were the main cause of injury, followed by falls from a height (six cases, three dogs and three cats) and bites from a dog (six cases, five dogs and one cat). On admission, the neurological status of 11/30 animals was grade V (nine dogs and two cats), 14/30 animals were grade IV (10 dogs and four cats) and 5/30 animals were grade III (three dogs and two cats) (Table 1). Sixteen animals had concurrent nonspinal injuries, including forelimb or hindlimb fractures, lung contusions, pneumothorax, diaphragmatic hernia and open wounds.

Diagnostic imaging

Twelve animals underwent preoperative spinal radiographic evaluation, whereas the others underwent radiographic and CT examinations. All vertebral fractures/luxations were detected between T9 and L6: 12 affected the thoracic spine, 1 affected the thoracolumbar junction and 17 affected the lumbar spine. In one case, vertebral subluxation with associated intervertebral disc herniation (T12-T13) was observed, and in one case, a fracture of three consecutive vertebrae (T11-T12 and T13-L1) was observed.

Table 1. Short and long-term grades and outcomes for the dogs and cats in the clinical study

Preoperative grade	Dogs and cats (*n*=30) Grade at short-term evaluation (*n*=24)	Dogs and cats Grade at long-term evaluation (*n*=23)	Dogs and cats Outcome	Dogs (*n*=22) Grade at short-term evaluation (*n*=16)	Dogs Grade at long-term evaluation (*n*=15)	Dogs Outcome	Cats (*n*=8) Grade at short-term evaluation (*n*=8)	Cats Grade at long-term evaluation (*n*=8)	Cats Outcome
Grade III (*n*=5)	75% II (3/4) 25% III (1/4)	75% 0 (3/4) 25% II (1/4)	60% excellent (3/5) 20% good (1/5) 20% poor (1/5)	100% II (2/2)	100% 0 (2/2)	66.7% excellent (2/3) 33.3% poor (1/3)	50% II (1/2) 50% III (1/2)	50% 0 (1/2) 50% II (1/2)	50% excellent (1/2) 50% good (1/2)
Grade IV (*n*=14)	50% II (6/12) 33.3% III (4/12) 16.7% IV (2/12)	41.7% 0 (5/12) 41.7% II (5/12) 8.3% III (1/12) 8.3% IV (1/12)	42.9% excellent (6/14) 28.6% good (4/14) 21.4% poor (3/14) 7.1% unknown (1/14)	37.5% II (3/8) 37.5% III (3/8) 25% IV (2/8)	50% 0 (4/8) 25% II (2/8) 12.5% III (1/8) 12.5% IV (1/8)	50% excellent (5/10) 10% good (1/10) 30% poor (3/10) 10% unknown (1/10)	75% II (3/4) 25% III (1/4)	25% 0 (1/4) 75% II (3/4)	25% excellent (1/4) 75% good (3/4)
Grade V (*n*=11)	25% III (2/8) 50% IV (4/8) 25% V (2/8)	42.9% II (3/7) 57.1% III (4/7)	18.2% good (2/11) 36.4% guarded (4/11) 36.4% poor (4/11) 9.1% unknown (1/11)	66.7% IV (4/6) 33.3% V (2/6)	40% II (2/5) 60% III (3/5)	11.1% good (1/9) 33.3% guarded (3/9) 44.4% poor (4/9) 11.1% unknown (1/9)	100% III (2/2)	50% II (1/2) 50% III (1/2)	50% good (1/2) 50% guarded (1/2)

Surgical procedure

Vertebral fractures/luxations were surgically treated within 1.9 days after the trauma (range 1 to 8 days); within 1.5 days for animals that were grade V preoperatively; 2.2 days for grade IV and 2.7 days for grade III. One dog underwent surgical decompression of the spinal cord after lateral stabilisation with a T12-T13 left hemilaminectomy to remove the extruded disc material. One dog died intraoperatively (grade V, fracture of the dorsal arch and vertebral body of L2) and another died 2 hours after the end of the procedure (grade IV, fracture and luxation of T9-T10), both from cardiopulmonary failure during anaesthesia. Two other dogs died 2 days after surgery after acute worsening of their general condition, most likely because of the degradation of their concomitant injury (pneumothorax in both; one grade III and one grade V, both had fracture and luxation of T12-T13). All four dogs were treated surgically during the first 24 hours after the initial trauma (one bite wound, one fall from a height and two road traffic accidents). CT revealed good positioning of the screws within the vertebral bodies in all the dogs, with no invasion of the vertebral canal, pulmonary or blood vessel injuries. Eleven animals underwent postoperative radiographic evaluation to assess implant positioning, and 18 underwent postoperative computed tomographic examinations. No invasion of the vertebral canal or other major surrounding structures was noted on imaging studies postoperatively, and all screws were bicortical. A total of 26 animals, including 18 dogs and eight cats, were discharged from the clinic; eight were grade V, 10 were grade IV, six were grade III and two were grade II.

Short and long-term outcome

The short- and long-term grades and outcomes are summarised in Table 1. Short-term follow-ups were performed through clinical examinations ($n=24$). Long-term follow-up was performed by phone ($n=13$), email ($n=1$), or clinical examination ($n=9$). The median long-term follow-up time was 962 days (range 43 to 4749 days). Two of the 26 animals discharged from the clinic were lost to follow-up (two dogs, one preoperative grade IV and one grade V).

In short-term evaluation, nine of the 24 animals were grade II (37.5%), seven grade III (29.1%), six grade IV (25.0%) and two grade V (8.3%). One dog with grade V disease was euthanized because of a lack of improvement. Eight of the 23 animals with long-term follow-up were grade 0 (34.8%), nine grade II (39.1%), five grade III (21.7%) and one grade IV (4.3%). At long-term follow-up, three dogs were euthanized because of persistent neurological dysfunction (one grade IV and two grade III). The outcome was considered excellent in nine of the 28 animals not lost to follow-up (32.1%), good in seven (25.0%), guarded in four (14.3%) and poor in eight animals (28.6%, including the four deaths prior to discharge from the clinic and the four dogs that were euthanized). Overall, 17 of the 30 animals that underwent surgery (56.7%) regained the ability to walk without assistance postoperatively, including 3 out of the 11 animals (27.2%) that had lost deep pain perception on presentation (grade V). One patient with grade V preoperatively regained the ability to walk but with difficulty and may have developed spinal walking. In this case, faecal and urinary control were not documented.

Complications were recorded as minor (n = 3/30, 10%): wound swelling/inflammation (n = 3) or major (n = 8/30, 26.7%); perioperative death (n = 4/30, 13.3%); postoperative euthanasia due to lack of improvement in the neurological status (n = 3/30, 10%); rupture of the polymethylmethacrylate within 2 weeks; and associated deep infection (Organ-Space Infection according to the Centers for Disease Control and Prevention) (Mangram et al., 1999) and urinary incontinence that led to euthanasia several months after the first surgery despite a revision surgery (n = 1/30, 3.3%).

DISCUSSION

Based on the CT study, the lateral corridors described with an implantation angle of 90° were safe and permitted bicortical implantation while avoiding the vertebral canal and major vascular structures along the thoracic and lumbar spine in dogs. The reduction in the deviation (Δ) during the learning curve and the low rate of vertebral canal invasion in cadavers (5.8%) suggested that a neurosurgeon could quickly learn the appropriate technique, but it might take some time to perform it safely. Based on the clinical study, the lateral corridor approach combined with screws and PMMA is effective in treating vertebral fractures and/or luxations in dogs and cats. The outcomes and complication rates were similar to those of other techniques (Blass & Seim, 1984; Krauss et al., 2012; Vallefuoco et al., 2014).

Computed tomographic

Vallefuoco et al. reported that unilateral vertebral corridors with a constant implantation angle of 90° to the sagittal plane in the vertebral body of the caudal thoracic and lumbar vertebrae (T10-L7) in cats were safe (Vallefuoco et al., 2013), and the first clinical results appeared promising (Vallefuoco et al., 2014). However, the transverse process or proximal rib resection was not reported in this study. It seems much easier to properly identify the insertion points, particularly in the thoracic spine, by performing an ostectomy. All the measured (β) angles were >90°, revealing a dorsal safety margin of about 20° on average. Similarly, all (γ) angles were smaller than 90°, revealing a ventral safe margin of 7° approximately (Table S4). Hence, although narrow, these corridors offered a margin of error for dorsal and ventral deviations from the ideal angle of 90°. At L6 and L7, the log-transformed (A – B)/(A – C) ratio was significantly reduced, revealing that the corridor was closer to the floor of the vertebral canal for these two vertebrae. Moreover, (β) was also smaller for L6 and L7 as well as (γ) for L7, revealing a smaller safety margin dorsally and a larger safety margin ventrally in L6 and L7 compared to other vertebrae. Based on these results, we recommend shifting the insertion point (I) ventrally to the transverse process for L6 and L7, with the dorsal margin of the corridor contiguous to the transverse process, to increase the safety of the corridor in the dorsal direction.

Cadaveric study

The learning curve during surgery is difficult to assess, particularly in ex vivo studies. The number of complications could not be evaluated; therefore, (Δ) was used to assess the learning process (Fig S1): the significantly larger (Δ) measured in cases 4 to 6 compared to the initial small deviation in cases 2 and 3 suggested that after the experienced surgeon showed the technique for case 1, the novice surgeon deviated from the optimal angle of 90° during cases 4 to 6, before correcting his technique through cases 7 to 10. Nonetheless, the 95% CI (data shown in Figs S2–S4) show some degree of deviation from the 90° optimal angle, even at the end of the learning curve. However, this deviation was still within the safety angles measured in the CT study. For the lumbar spine, a wider range of (α) has been recorded but still within the safety angles, probably due to the anatomical peculiarities of the lumbar vertebrae. This suggests that a novice surgeon might correctly reproduce the technique just learned, but that a greater number of cases would be needed to master correctly and safely the drilling technique. It would be interesting to evaluate similar learning curves on a larger number of cases and by multiple novice neurosurgeons, and even to include cases from experienced neurosurgeons. In this study, the vertebral canal invasion during the drilling process was recorded in <6% (5.8%) of cases. Considering that the surgeon performing the procedures had no prior experience in neurosurgery, this complication might be considered to be actually rare. With the two-hole technique, the second hole was easily reproducible caudally at the same dorsoventral level as the first hole without difficulty, which would allow the placement of two screws per vertebra.

Clinical retrospective study

The unilateral stabilisation technique is biomechanically comparable to the bilateral technique in terms of bending strength and stiffness (Hall et al., 2015). Therefore, using screws embedded in PMMA with a unilateral approach to treat vertebral fractures and/or luxations is feasible and effective in a clinical setting. In spinal fractures, bone fragments, hematomas and surrounding inflammatory tissues may compress the spinal cord and necessitate decompression. The low rate of decompression procedures in this study (one dog with hemilaminectomy, 1/30, 3.33%) could be due to the preoperative diagnostic imaging modalities: 12 animals were evaluated with spinal radiographic evaluation alone and 18 with radiographic and tomographic examinations. It is possible that the need for decompression surgery has been underestimated.

At the last follow-up, 87.5% (14/16) of the animals with preoperative grade III and IV neurological status regained the ability to ambulate without assistance, and the overall complication rate was 36.7% in this study. These results were similar to those obtained using previously published surgical techniques (Blass & Seim, 1984; Krauss et al., 2012; McKee, 1990; Vallefuoco et al., 2014). Among the 11 complications, 3 were minor (wound swelling/inflammation) and 3 of the eight major complications were unrelated to the surgical technique but to euthanasia several months after the surgery due to a lack of improvement in the neurological status. It should be noted that three of the four animals that died in the perioperative period had thoracic spine fractures and, therefore, had undergone thoracotomy and proximal rib resection before positioning the implants. It is possible that the four perioperative deaths were not related to the surgical technique but to the severely traumatised status of the patient; however, whether a lateral thoracotomy may have contributed to the degradation of these animals remains unclear. Further investigations are required to determine the association between perioperative death and this surgical technique. Two grade III and one grade IV animals were euthanized during the long-term evaluation because of their inability to walk without assistance (grade IV and grade V preoperatively). The only major complication related to the surgical technique was the rupture of the PMMA and associated Organ-Space Infection (Mangram et al., 1999), which led to the euthanasia of the dog because of a persistent grade IV neurological status several months after revision surgery. The authors recommended the use of a sufficient amount of PMMA, particularly in large-breed dogs, to avoid breakage.

Animals with thoracolumbar vertebral fracture/luxation and absent nociception at presentation are considered to have poor outcomes, and euthanasia is often performed because of the extremely low recovery rate reported in the literature. The fact that three out of eight animals (37.5%) that were grade V (excluding two animals that died perioperatively and one lost to follow-up; recovery for these is unknown) regained the ability to walk without assistance questions this practice. All three animals underwent surgery shortly after trauma (two in the first 24 hours and one within 30 hours). In contrast, among the five other grade V animals that did not regain the ability to walk without assistance, only one was operated on within 24 hours, three underwent surgery 48 hours after the initial trauma and the delay was unknown for one animal. Stabilisation of the vertebral fracture/luxation as soon as possible after trauma is recommended by the authors. This study suggests that the prognosis for an animal with a thoracolumbar vertebral injury with absent nociception at presentation may be good in some cases, especially those operated within a short period after the trauma. However, this statement must be confirmed in a larger group of dogs and cats in a future study because only a small number of grade V cases were included, and all the grade V animals treated in this study had <50% degree of vertebral displacement on imaging. Performing a surgery immediately on a severely traumatised patient is challenging because the initial sequence of damage control approach is limited. A cascade of events may lead to systemic inflammatory response syndrome (SIRS), multiple organ dysfunction syndrome (MODS), disseminated intravascular coagulation (DIC), acute respiratory distress syndrome (ARDS), or infection, all of which would increase perioperative mortality. The timing of surgery should be selected on a case-by-case basis. In recent studies of dogs involved in trauma, the reported mortality rate (non-survivors to discharge from the hospital) was between 9.5% and 16.8% (Hall et al., 2014; Klainbart et al., 2018; Lux et al., 2018; Streeter et al., 2009), which is similar to our perioperative mortality rate of 13.3% (four deaths in the perioperative period out of 30 animals surgically treated). However, the 13.3% mortality rate should be interpreted with caution because only animals that were surgically treated were included in the study; animals euthanized at the admission or those who died before the surgery were not included, which may underestimate the mortality rate. Moreover, four dogs were euthanized postoperatively because of failure to improve, which increased the total mortality rate to 26.7%.

This study has several limitations owing to its retrospective nature for the clinical part, variability in follow-up (phone interview or clinical examination) and imaging modality. The first thoracic vertebrae, T1 to T5, were not assessed in the CT scan or cadaveric studies, which prevented us from establishing whether the lateral corridors were safe and effective. The CT study did not evaluate images of cat spines, and the cadaver part focused only on dogs; however, based on the results of Vallefuoco et al. these lateral corridors were also feasible and safe in cats from T10 to L7 vertebrae (Vallefuoco et al., 2013). Only one surgeon drilled the corridors. Therefore, it would have been interesting to investigate whether the learning curve was the same for several novice neurosurgeons. Drillings were performed on cadavers with intact thoracic and lumbar spines; it would have been more difficult to perform the approach, visualise the landmarks and perform drillings on fractured vertebrae with adjacent hematoma or damaged muscles. For the clinical part, before 2013, CT scans were not available in the clinic and only radiographs were performed. This could lead to an underestimation of the vertebral canal invasion due to a lower sensitivity of radiographs to detect invasion compared to CT scans (Hettlich et al., 2010). However, the perpendicular nature of the lateral vertebral corridor made it easily accessible on radiography (Fig 4). Not all grade V patients who presented to the clinic underwent surgery: those with high degree of vertebral displacement (>50%) were not operated (except for fracture of the caudal lumbar vertebrae involving the cauda equina) due to suspected severe damage to the spinal cord with such a displacement and very low percentage of functional recovery estimated, which induced a bias in case selection. Finally, spinal walking may have been underestimated due to the retrospective nature of the study and the fact that some long-term follow-up was documented by phone or email.

In conclusion, a thoracic and lumbar lateral vertebral corridor allowed implant placement in a bicortical fashion with an easily reproducible and constant orientation angle of 90°, with complication rates and outcomes similar to those of other previously published techniques. Moreover, the rate of vertebral canal invasion was low, and the learning curve to drill the corridors correctly for screw placement was short, which may facilitate the use of this surgical technique to treat vertebral fractures/luxations during emergencies.

Author contributions

R. Lamère: Data curation (equal); formal analysis (equal); investigation (lead); methodology (equal); writing – original draft (lead); writing – review and editing (equal). **S. Scotti:** Conceptualization (lead); data curation (equal); methodology (lead); supervision (equal); validation (equal); visualization

(equal); writing – review and editing (supporting). **M. Saccone:** Data curation (equal); formal analysis (equal); investigation (equal); methodology (equal); resources (equal); software (equal). **L. Meomartino:** Formal analysis (supporting); visualization (supporting). **L. Auletta:** Formal analysis (lead); methodology (equal); software (lead); writing – review and editing (equal). **C. Ragetly:** Methodology (equal); supervision (lead); validation (equal); writing – review and editing (lead).

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Conflict of interest

None of the authors of this article has a financial or personal relationship with other people or organisations that could inappropriately influence or bias the content of the paper.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Fig S1. Illustration of the measures on the CT scan of the canine cadavers after the drilling process (illustrated on T10 and L1): the corridor obtained is in purple, the ideal corridor in blue; (a to b) is the distance between the floor of the vertebral canal and the upper margin of the hole obtained in the sagittal plane; (α) is the obtained angle of the drilled corridor, 90° being the ideal insertion angle; the deviation (Δ) is the difference between the measured angle (α) and the ideal angle of 90°.

Fig S2. Graphic representation of the median Δ plotted over time (*i.e.*, Case#). The bars represent the 95% confidence intervals.

Fig S3. Graphic representation of the median Δ plotted over time (*i.e.*, Case#) for the thoracic spine. The bars represent the 95% confidence intervals.

Fig S4. Graphic representation of the median Δ plotted over time (*i.e.*, Case#) for the lumbar spine. The bars represent the 95% confidence intervals.

File S1.

File S2.

File S3.

Table S1. Neurological status classification based on the severity of dysfunction (Vallefuoco et al., 2014)

Table S2. Significant differences in the comparison of the Log-transformed (A – B)/(A – C) ratio between L6 and the thoracic and lumbar vertebrae analyzed

Table S3. Significant differences in the comparison of the log-transformed (A – B)/(A – C) ratio between L7 and the thoracic and lumbar vertebrae analyzed
Table S4. (β) and (γ) angles measured in the transverse plane in the CT study. Data are reported as mean ± standard deviation [minimum – maximum]
Table S5. Significant differences in the comparison of the angle (β) between the thoracic and lumbar vertebrae analyzed and L6
Table S6. Significant differences in the comparison of the angle (β) between the thoracic and lumbar vertebrae analyzed and L7
Table S7. Significant differences in the comparison of the angle (γ) between the thoracic and lumbar vertebrae analyzed and L7
Table S8. Significant differences in the comparison of the angle (α) between the thoracic and lumbar vertebrae analyzed and L5, L6 and L7
Table S9. Significant differences in the comparison of the Δ between Case 4 and Case 2 and 3, and Case 6 and Case 2
Table S10. Significant differences in the comparison of the Δ between Cases for the thoracic spine
Table S11. Significant differences in the comparison of the Δ between Case 2 and 3 and Case 10 for the lumbar spine