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A morphometric analysis of thoracolumbar vertebrae in goat by computed tomography.

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ABSTRACT

The goat spine is widely used as an animal model for preclinical research in human medicine to test new spinal implants and surgical procedures. Therefore, precise morphometric data are needed. This study aims to provide morphometric data of the goat thoracolumbar vertebrae and to define the parameters/characteristics of the optimum implantation corridors for pedicle screws in the thoracolumbar spine in goat. Eleven 36-month-old adult alpine goats were included in this study, and a sample of 198 vertebrae was measured. Subsequently, transverse and sagittal images were obtained using a multi-detector-row helical computed tomography (CT) scanner. Measurements of the vertebral bodies (ventral body width VBW, ventral body depth VBD, ventral body height ventral VBHv, ventral body high dorsal VBHd, spinal canal depth SCD, spinal canal width SCW), pedicles (pedicle length PDL, pedicle width PDW, pedicle angle PA and pedicle axis length PAL), intervertebral disc (DT) and transverse process length (TPL) were performed with dedicated software. The vertebral bodies and the spinal canal were wider than deep, mostly evident in the lumbar region. The intervertebral discs were as much as 65.7% thicker in the lumbar spine than in the thoracic spine. The pedicles were longer than wide over the thoracic and lumbar spines. The insertion angles in pedicle were approximately 30° for the T2-T4 segment, 25° for the T5-T6 segment, 23° for the T6 to T11 segment, 20° for T11 to L3, 25° for L4 and 30° for L5 and L6. In conclusion, the generated data can serve as a CT reference for the caprine thoracolumbar spine and may be helpful in using the goat spine as an animal model for human spinal research.

Introduction

Spinal abnormalities in humans have major effects on skeletal growth and the development of various organs(Newton et al., 2013). Several studies are interested in developing new surgical techniques to correct these abnormalities.

The use of human specimens is the best way to mimic the physiological situation, but many difficulties are associated with their use, such as the restricted number of fresh healthy cadavers. Several healthy cadavers are needed to eliminate the wide scattering effect associated with biological variability (Bland & Altman, 1986). Thus, an appropriate animal model should be used to mimic the human spine with chosen biomechanical characteristics and anatomical dimensions that are as similar as possible to those in humans. In addition, precise geometrical data of animal models are needed for mathematical models (Kiefer, Shirazi-Adl & Parnianpour, 1997; Yoganandan, Kumaresan, Voo & Pintar, 1996). The similarity of the anatomical characteristics of the goat spine to the human spine and the rapid growth observed in goats between the ages of 6 weeks and 8 months and between childhood and maturity in humans make caprine models an interesting replacement (Braun & Akyuz, 2005; Braun et al., 2006; Jahng, Fu & Kim, 2004; Quin et al., 2012). Moreover, several in vitro and in vivo studies have used the caprine model as an animal model for orthopaedic and neurological research. However, in those studies, neurological trauma and loss of animals due to poor implant positioning because of an under/over estimation of pedicle angulation caused time and cost losses. These facts highlight the importance of spinal monitoring and morphometrical analysis of the goat spine (McCarthy et al., 2010; Qui et al., 2015; Quin

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et al., 2012; Zhang, Zheng, Zhang & Wang, 2009).

Computed tomography (CT), a noninvasive imaging technique, has been used worldwide in humans and in animals as a gold standard to perform in vivo morphometric analysis of the spine and to determine variations in the vertebrae size and shape (Abuzayed, Tutunculer, Kucukyuruk & Tuzgen, 2010; Krag, Weaver, Beynnon & Haugh, 1988; Olsweski et al., 1990). Morphometric studies have many limiting factors, such as measurement accuracy and viewer control settings, factors that should be assessed.

Morphometry of the goat thoracolumbar spine is important for studies that contemplate its use. Design strategies, surgical techniques and interpretation of results derived from such studies require morphometry. The aim of this study is to provide quantitative reference values and a complete comprehension of the pedicle morphology and angulation in healthy adult caprine spine models using computed tomography.

Materials and methods

Animals

This study was approved by the institutional animal care and use committee at the School of VetAgro-Sup. Eleven adult alpine goats without any history or clinical signs related to spinal diseases were included in this study. All goats came from the same batch. The mean body weight of goats was 42.5 kg.

Computed tomography (CT) examination

The goats were euthanized for other experimental studies unrelated to this study. The goats were positioned in dorsal recumbency in a perpendicular position of the spine relative to the radiographic beam. CT scans were performed from the cranial aspect of T2 to the caudal aspect of L6 with a multidetector-row helical CT unit General Electric's, Brightspeed 16 elite (GE Healthcare, Buckinghamshire, England, Great Britain).

The technical settings were 120 kV, 150 mA, 1-second tube rotation and 0.625 pitch. The data were reconstructed to a transverse, sagittal and frontal image series with slice thickness ranging between 0.2 and 0.8 mm using a high-frequency image reconstruction algorithm (Osirix Imaging Software). Transverse images were reconstructed parallel to the third level of the cranial endplate of the vertebral body, whereas sagittal images were reconstructed at the midsagittal plane of the vertebra to measure the vertebral body and intervertebral disc dimensions.

Three parameters were measured from the sagittal images, and eight parameters were measured from the transverse images for each spinal level. These parameters were measured as described in the human and veterinary literature (Mageed, Berner, Hohaus, Brehm & Gerlach, 2013; Zhou, McCarthy, McCregor, Coombs & Hughes, 2000). In addition, the parameters of the implantation corridor for pedicular screws were measured from the transverse images as described by McLain McLain, Yerby & Moseley (2002).

The morphometrical parameters obtained from transverse images included vertebral body width (VBW), which is the distance between the lateral border measured at the third cranial endplate of the vertebral body, and vertebral body depth (VBD), reflecting the distance between the dorsal and ventral borders of the vertebral body. Spinal canal width (SCW) and depth (SCD) were obtained by measuring the distance between the axial pedicle cortical and the dorsal border of the vertebral body to the lamina at the midline, respectively. Transverse process length (TPL) was assessed by measuring the distance between the two tips of the transverse process (Fig. 1).

The morphometric parameters obtained from sagittal images included the distance between the cranial and caudal endplates of the vertebral body at the dorsal margin, termed the vertebral body height dorsal (VBHd); the same distance at the ventral margin was termed the vertebral body height ventral (VBHv). Disc thickness (DT) was measured at the mid-level of the intervertebral disc (Fig. 2).

Parameters concerning the implantation corridor for the pedicular screw were assessed by measuring the pedicle width (PDW), pedicle

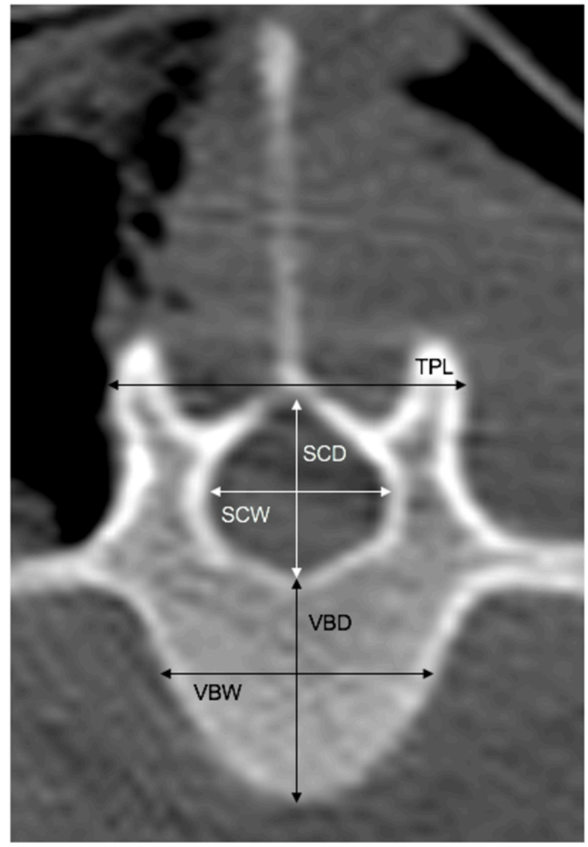

Fig. 1. Transverse CT images obtained at the cranial aspect of L4 of a goat illustrating the measurements obtained for T2 through L6. Left is right. The measurements of interest obtained for each of the thoracolumbar vertebrae are vertebral body width (VBW), vertebral body depth (VBD), spinal canal width (SCW), spinal canal depth (SCD) and transverse process length (TPL).

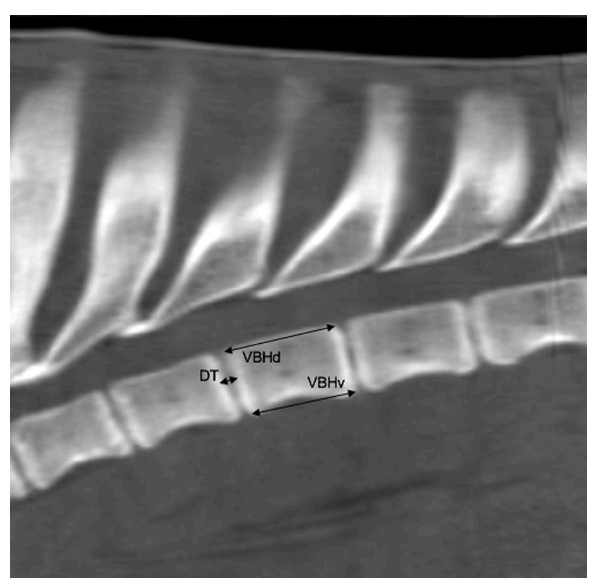

Fig. 2. Sagittal CT images with measurements at T10 in a goat illustrating the vertebral body height at the dorsal border (VBHd), at the ventral border (VBHv) and disc thickness (DT). Cranial is to the left.

length (PDL), pedicle angle (PA) and pedicle axis length (PAL) on transverse images (Figs. 3 and 4). PDW was defined as the narrowest part of the pedicle. In the thoracic vertebrae, PDL reflects the distance between the dorsal pedicle cortex and the line perpendicular to the vertebral midline (tangent to the ventral border of the spinal canal). In the lumbar vertebrae, PDL reflects the distance between the dorsal pedicular cortex and the junction of the ventral border of the transverse process. PAL was measured from the dorsal cortex of the articular facet to the midpoint of the ventral vertebral body cortex. Finally, PA was the angle between the PAL and the vertebral sagittal midline.

Statistical analysis

Descriptive data are presented as means and standard deviations (SDs). Assessment of intraobserver reliability was calculated by randomly selecting three goats in which measurements were performed four times by the same operator. A coefficient of variation (CV) was used to assess reliability. The Mann-Whitney/Two-tailed test was used to determine differences between the vertebral levels for each parameter. Statistical analysis was performed with dedicated available software (Microsoft Excel 2010, XLSTAT ®). The level of significance was set at $p < 0.05$, and CV<5% was considered acceptable.

Results

A total of 198 vertebrae (132 thoracic vertebrae and 66 lumbar vertebrae) from 11 mature goats' thoracolumbar vertebral columns were measured. CT images revealed that all the goats had 6 lumbar vertebrae and 13 thoracic vertebrae (the first thoracic vertebra was not measured in this study). Assessment of intraobserver reliability revealed a high level of reliability (Table 1), with values ranging between 0.06% and 3.13%. Tables 2, 3, and 4 present the means and standard deviations

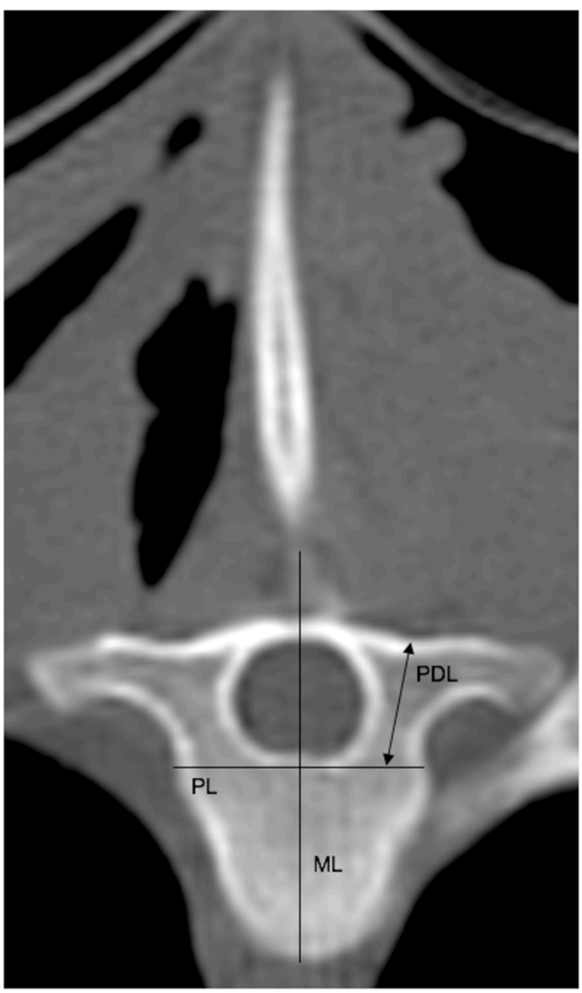

Fig. 3. Sagittal CT images with measurements at T10 in a goat illustrating the vertebral body height at the dorsal border (VBHd), at the ventral border (VBHv) and disc thickness (DT). Cranial is to the left.

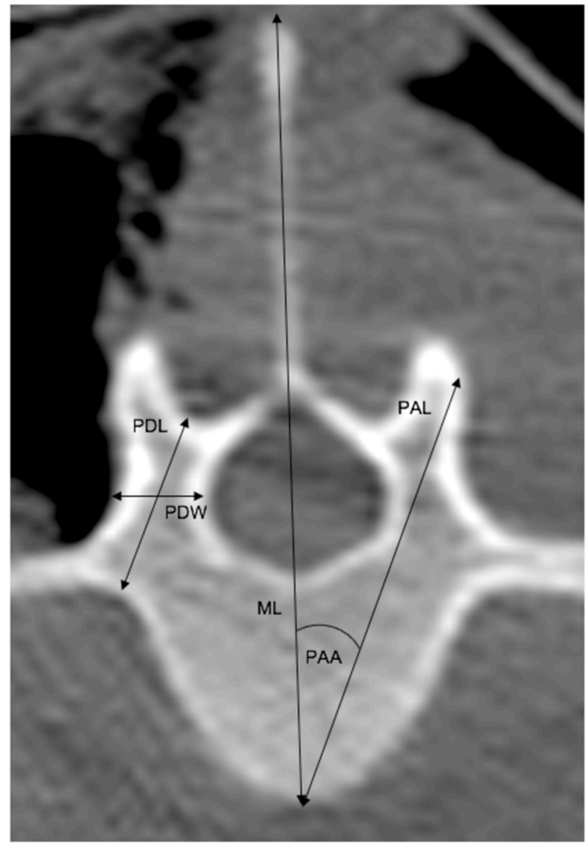

Fig. 4. Transverse CT images obtained at the cranial aspect of L4 of a goat. Left is right. The measurements of interest obtained were pedicle length (PDL), referring to pedicle type II (lumbar vertebrae); pedicle width (PDW); pedicle axis length (PAL); pedicle axis angle (PAA); and sagittal midline (ML) for each vertebra.

Table 1
Means and standard deviations of the coefficient of variation (CV) values of the thoracolumbar spine measurements of the three goats. DT = Disc Thickness, VBW = Vertebral body width, VBD = Vertebral Body Depth, VBHd = Vertebral Body Height dorsal, VBHv = Vertebral Body Height ventral, SCW = Spinal Canal Width, SCD = Spinal Canal Length, TPL = Transverse Process Length, PDL = Pedicle Length, PDW = Pedicle Width, PA = Pedicle Angle, PAL = Pedicle Axis Length.

Dimension	Mean CV%
VBHd	0.3686 ± 0.273
VBHv	0.5734 ± 0.393
DT	1.7505 ± 0.852
VBW	0.8735 ± 0.312
VBD	0.9694 ± 0.558
SCW	0.7073 ± 0.755
SCD	1.4508 ± 1.076
TPL	0.3319 ± 0.25
PDL	0.5324 ± 0.211
PDW	1.1618 ± 0.999
PAL	2.46 ± 0.7204
PA	0.326 ± 0.173

Table 2
Means and standard deviations of the CT measurement dimensions related to intervertebral disc and vertebral bodies of 11 healthy goat thoracolumbar spines. DT = Disc Thickness, VBW = Vertebral Body Width, VBD = Vertebral Body Depth, VBHd = Vertebral Body Height dorsal, VBHv = Vertebral Body Height ventral.

	Transverse view		Sagittal view		
Vertebrae	VBW (mm)	VBD (mm)	DT (mm)	VBHd (mm)	VBHv (mm)
T2	18.37 ± 2.7	12.10 ± 0.4	2.83 ± 0.4	20.71 ± 0.7	20.55 ± 0.7
T3	16.76 ± 1.5	12.30 ± 0.8	2.19 ± 0.2	21.33 ± 0.8	22.45 ± 3.2
T4	15.17 ± 2.0	12.16 ± 0.6	1.93 ± 0.2	21.12 ± 1.2	21.77 ± 0.9
T5	13.78 ± 1.2	12.09 ± 0.8	2.00 ± 0.4	21.14 ± 0.9	21.38 ± 0.8
T6	13.71 ± 1.0	11.84 ± 0.9	1.77 ± 0.2	20.90 ± 0.9	20.78 ± 0.9
T7	13.41 ± 0.9	12.39 ± 0.6	1.71 ± 0.2	20.87 ± 0.8	20.99 ± 1.0
T8	13.12 ± 0.8	12.24 ± 0.5	1.79 ± 0.2	21.85 ± 1.4	21.65 ± 1.0
T9	13.14 ± 1.0	12.19 ± 0.7	1.76 ± 0.3	23.00 ± 1.1	22.40 ± 1.2
T10	13.41 ± 1.4	11.66 ± 0.6	1.74 ± 0.4	24.06 ± 1.3	23.22 ± 1.3
T11	13.96 ± 1.2	12.00 ± 1.0	1.77 ± 0.2	25.48 ± 1.5	24.49 ± 1.2
T12	14.36 ± 1.2	12.03 ± 0.8	1.90 ± 0.2	27.79 ± 1.2	25.15 ± 1.8
T13	14.58 ± 1.9	12.70 ± 0.7	1.99 ± 0.4	29.83 ± 1.7	28.63 ± 1.3
L1	15.43 ± 1.5	12.96 ± 0.5	2.67 ± 0.6	33.01 ± 1.3	31.15 ± 1.3
L2	15.25 ± 1.1	13.21 ± 0.9	2.89 ± 0.7	34.26 ± 1.4	32.25 ± 1.4
L3	14.75 ± 1.4	12.63 ± 0.9	2.84 ± 0.7	34.69 ± 1.2	32.26 ± 1.2
L4	15.08 ± 1.2	12.17 ± 0.8	2.73 ± 0.5	34.94 ± 1.3	33.25 ± 1.3
L5	17.16 ± 1.5	11.66 ± 0.7	2.91 ± 0.6	34.52 ± 1.8	32.01 ± 2.1
L6	18.71 ± 2.4	11.40 ± 0.8	3.32 ± 0.8	29.63 ± 2.1	26.67±1.8

Table 3
Means and standard deviations of the CT measurement dimensions related to the spinal canal and transverse processes of 11 healthy goat thoracolumbar spines. SCW = Spinal Canal Width, SCD = Spinal Canal Depth, TPL = Transverse Process Length.

	SCW (mm)	SCD (mm)	TPL (mm)
T2	12.60 ± 1.4	9.57 ± 0.2	42.69 ± 3.0
T3	12.13 ± 1.0	9.38 ± 0.3	42.56 ± 2.5
T4	11.02 ± 12	9.16 ± 0.6	40.77 ± 2.4
T5	10.25 ± 0.5	8.53 ± 0.6	41.22 ± 1.8
T6	9.53 ± 0.4	8.34 ± 0.5	38.97 ± 1.7
T7	9.27 ± 0.4	8.20 ± 0.4	38.38 ± 2.4
T8	9.07 ± 0.4	7.94 ± 0.4	39.53 ± 2.2
T9	9.13 ± 0.3	8.12 ± 0.3	40.24 ± 2.3
T10	9.19 ± 0.5	7.84 ± 1.0	40.21 ± 2.0
T11	9.26 ± 0.4	8.12 ± 0.4	39.67 ± 2.8
T12	10.07 ± 0.5	8.70 ± 0.7	42.03 ± 3.2
T13	9.88 ± 0.4	8.38 ± 0.6	45.64 ± 2.3
L1	10.24 ± 0.4	8.81 ± 0.7	92.63 ± 8.1
L2	10.63 ± 0.3	9.01 ± 0.6	101.86 ± 5.7
L3	11.25 ± 0.4	9.38 ± 0.8	105.48 ± 6.9
L4	12.12 ± 0.8	10.06 ± 0.8	108 ± 8.6
L5	14.35 ± 1.2	11.14 ± 0.8	108.65 ± 8.7
L6	16.68 ± 0.7	10.53 ± 0.9	89.53 ± 7.8

Table 4
Means and standard deviations of the CT measurement dimensions and angles related to the pedicles of 11 healthy goat thoracolumbar spines. *PDL = Pedicle Length, PDW = Pedicle Width, PA = Pedicle Angle, PAL = Pedicle Axis Length.*

	PDL (mm)	PDW (mm)	PA (°)	PAL (mm)
T2	9.54 ± 0.6	6.04 ± 0.4	30.334 ± 0.62	24.3 ± 1.5
T3	9.44 ± 0.3	5.87 ± 0.3	30.457 ± 0.55	25.3 ± 1.5
T4	9.60 ± 0.3	5.38 ± 0.2	26.359 ± 0.77	26.2 ± 1.4
T5	10.30 ± 1.0	5.18 ± 0.4	24.465 ± 0.45	26.8 ± 1.3
T6	9.82 ± 0.7	4.88±0.4	23.214 ± 0.46	27.2 ± 1.3
T7	9.72 ± 0.8	4.97 ± 0.4	22.663 ± 0.63	27.2 ± 1.2
T8	9.24 ± 0.7	4.91 ± 0.3	23.059 ± 0.73	26.3 ± 1.1
T9	8.84 ± 0.4	5.07 ± 0.4	22.944 ± 0.58	25.2 ± 1.0
T10	8.52 ± 1.0	5.23 ± 0.4	23.388 ± 0.50	24.8 ± 0,9
T11	8.43 ± 1.0	5.61 ± 0.5	23.957 ± 0.80	24.3 ± 1.3
T12	10.56 ± 0.5	4.77 ± 0.6	20.960 ± 0.51	25.1 ± 1.7
T13	11.11 ± 0.5	4.49 ± 0.3	20.050 ± 0.49	27.7 ± 1.3
L1	12.06 ± 1.4	5.20 ± 0.5	21.771 ± 0.83	29.1 ± 1.1
L2	12.24 ± 1.5	6.24 ± 0.8	22.596 ± 0.91	30.6 ± 1.1
L3	12.28 ± 1.0	6.28 ± 0.4	23.035 ± 0.91	31.6 ± 1.4
L4	12.14 ± 0.9	6.39 ± 0.5	24.061 ± 1.12	31.6 ± 2.3
L5	12.08 ± 1.6	6.66 ± 0.8	29.519 ± 0.49	31.6 ± 2.1
L6	11.37 ± 1.2	8.10 ± 1.0	33.440 ± 1.23	32.5 ± 2.2

of the CT measurements in the thoracolumbar spines of the 11 goats.

Vertebral body measurements (transverse and sagittal view)

Values and variation of the ventral body width (VBW) are summarized in Table 2 and Fig. 5. The value of VBW was greater for T2, T3 and for L5 and L6. VBW was significantly higher in the lumbar segment compared to the thoracic segment ($p = 0.02$). The value of the ventral body depth (VBD) was fairly constant around 12 mm in the thoracic and lumbar segment (Table 2 and Fig. 5).

In the thoracic region, VBHd was constant, at approximately 22 mm, and then increased steadily from T9 until T13 to reach 29 mm. In the lumbar region, VBHd was fairly constant at approximately 34 mm, except at L6, where it was smaller at 29.6 mm. Similar to VBHd, VBHv was smaller at the level of L6 (26.7 mm). VBHv was constant at approximately 21 mm from T2 to T9 and then increased from T10 to T13. VBHd was always larger than VBHv in both the lumbar and thoracic regions (Table 2 and Fig. 6).

DT ranged between 1.71 and 2.83 mm in the thoracic region, while in the lumbar region, it showed greater values ranging between 2.67 and 3.32 mm (Table 2). The largest point of DT was between the fifth and the sixth lumbar vertebrae. In the lumbar segment, DT was 1 mm thicker than in the thoracic spine.

Spinal canal and transverse process measurements (transverse view)

Table 3 and Fig. 7 show that T2, T3, T4 and L4, L5, L6 vertebrae share the maximal spinal canal width (SCW) and depth (SCD). Concerning transverse process length, it was constant at approximately 41 mm in the thoracic region. In the lumbar region, the value measured twice the length (around 90 mm). The maximum TPL was observed in L4 and L5 (Table 3).

Pedicle parameters (transverse view)

The pedicle parameters are listed in Table 4; interesting variations are reported in Fig. 8. Pedicle width (PDW) was significantly greater in the lumbar vertebrae, ranging from 5.20 to 8.10 mm, than PDW in the thoracic vertebrae, which ranged from 4.49 to 6.04 mm ($p = 0.002$). PDW reached its maximum at the sixth lumbar vertebra (8.10) and its minimum at T13 (4.49).

Pedicle length (PDL) showed a significant difference ($p = 0.0001$) between the thoracic and lumbar vertebrae, reaching its maximum at L3 and its minimum at T11. In the thoracic segment, the PDL values ranged

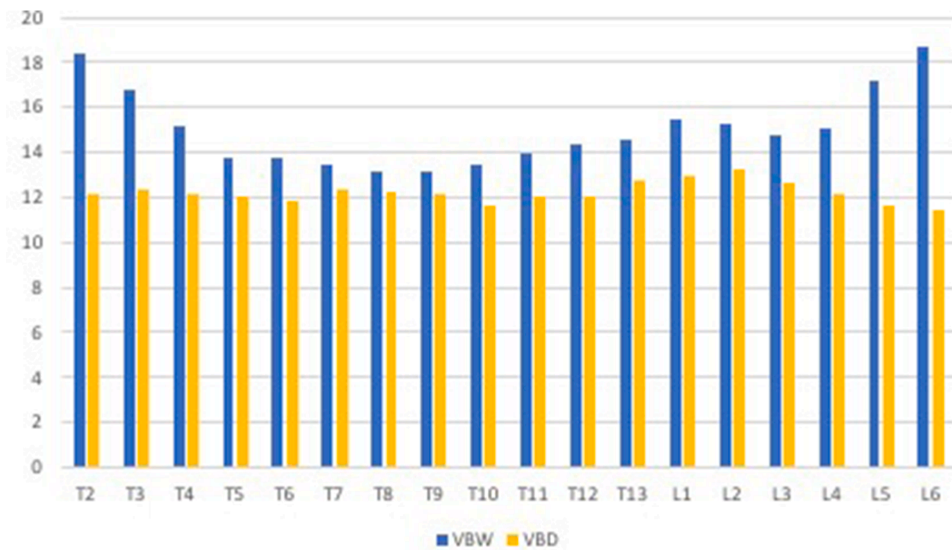

Fig. 5. Variation of the ventral body width (VBW) and ventral body depth (VBD) (mean values).

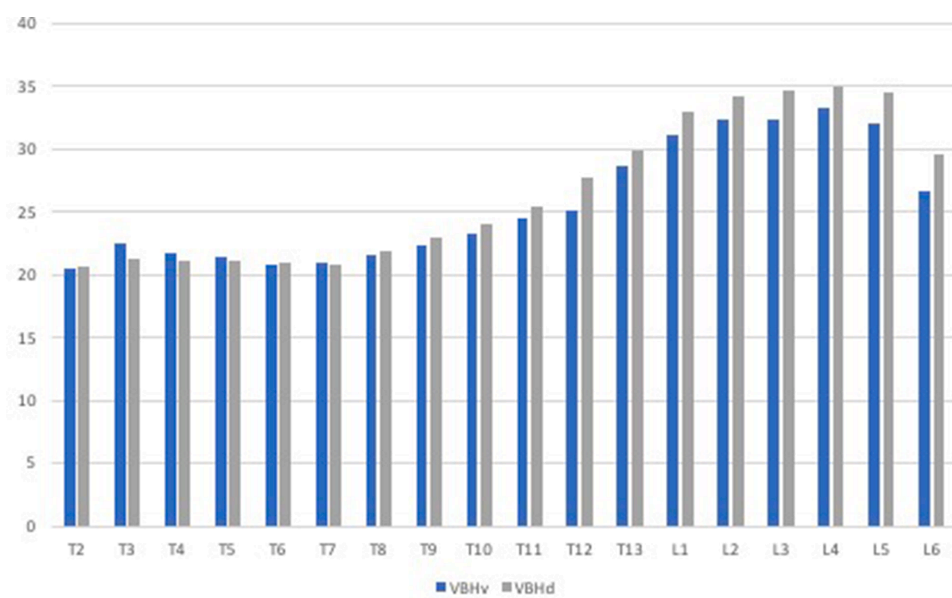

Fig. 6. Variation of the ventral body height dorsal (VBHd) and ventral body heigh ventral (VBHv) (mean values).

from 8.43 to 11.11 mm, and in lumbar segment, the PDL values ranged from 11.37 to 12.28 mm. Pedicle axis length (PAL) showed a significant difference ($p = 0.0008$) between the thoracic and lumbar vertebrae, reaching its maximum at the L6 level and its minimum at T2. PAL ranged between 29.1 and 32.5 for the lumbar vertebrae and between 24.3 and 27.7 for the thoracic vertebrae. Pedicle angle (PA) showed higher value between T2 and T3 (around 30°) and between the L5-L6 segment (around 30° to reach its maximum point of 33.4° at L6). T12 and T13 showed the lowest pedicular angulation (around 20°). PA value was around 25° for T4-T5, 23° between T6 and T11, 22° between L1 and L3 and at 24° for L4.

In Table 5, mean values and standard deviation for each parameter are summarized for the thoracic and lumbar segment.

Discussion

Several in vitro studies have used the goat as an animal model for orthopaedic spinal research. The goat is particularly interesting because of the similarity of its spine to the human spine and the rapid growth observed in goats between the ages of 6 weeks and 8 months, which mimics human growth. Moreover, goats are readily available, inexpensive, easy to handle and well accepted as an ethical animal model. Therefore, precise morphometric data of the goat spine are mandatory to improve the quality of implant fixation and implantation and, thus, to avoid loss of the animal (Braun & Akyuz, 2005; Cachon, 2018; (Braun et al., 2003)). In a previous study, eleven goats were used to develop a Shilla-like growth stem (McCarthy et al., 2010). During the experiment, one goat became paraplegic after the insertion of a pedicular screw. In another study about development of a scoliosis model by Zhang *et al.*, 28% (4/14) of goats were excluded from the results due to a failure in pedicular screw implantation (McCarthy et al., 2010; Zhang et al., 2009). In this last study, pedicular screws were inserted between T6-T7, with an angulation of 30° in the sagittal plane and an angulation of 40° at the lumbar level. In the current study, the implantation corridor for the pedicle screws at the level of T6-T7 was 23° and did not exceed 30° in the lumbar region. These facts explain the needed CT reference values

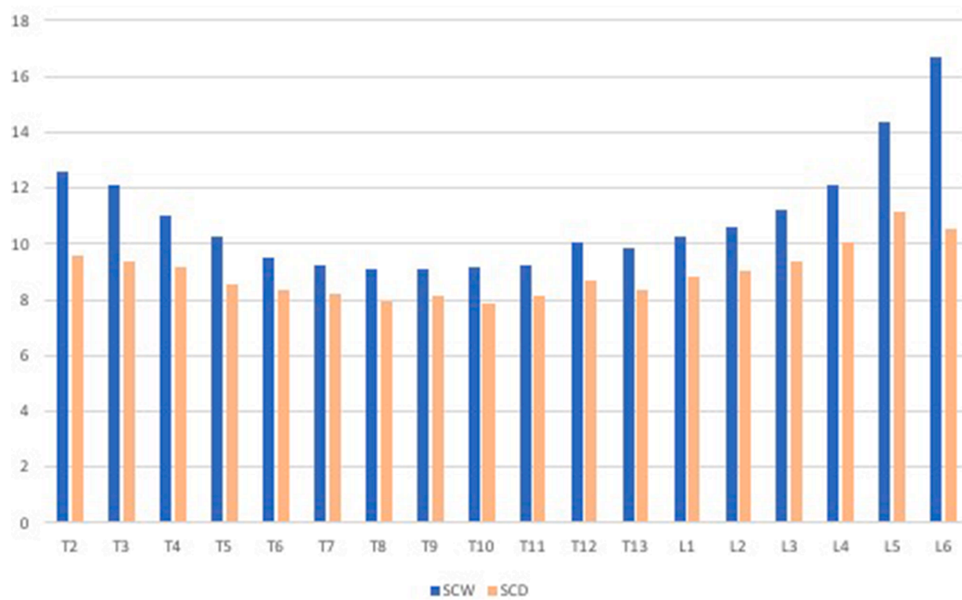

Fig. 7. Variation of the spinal canal width (SCW) and spinal canal depth (SCD) (mean values).

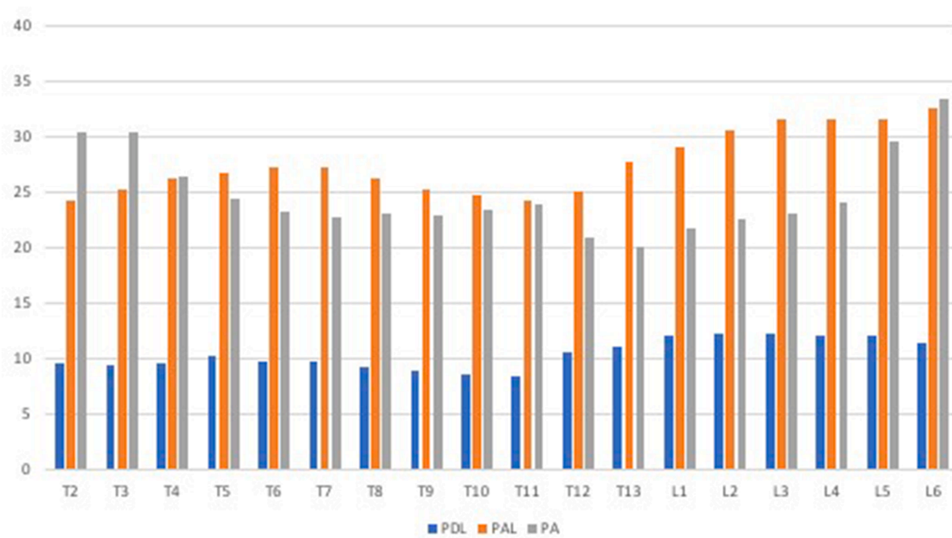

Fig. 8. Variation of the pedicle length (PDL), pedicle axis length (PAL) and pedicle angle (PA) (mean values).

Table 5
Means and standard deviations of the CT measurement dimensions and angles related to the pedicles of 11 healthy goat thoracolumbar spines.

Dimension (mm)	MEAN Lumbar	Thoracic
VBHd	**33.51** ± 2.5	**23.39** ± 3.2
VBHv	**31.27** ± 2.6	**22.91** ± 2.6
DT	**2.89** ± 0.7	**1.90** ± 0.4
VBW	**16.06** ± 2.3	**14.22** ± 1.9
VBD	**12.34** ± 1.0	**12.14** ± 0.8
SCW	**12.54** ± 2.4	**9.92** ± 1.2
SCD	**9.82** ± 1.1	**8.44** ± 0.7
TPL	**101.03** ± 10.7	**40.86** ± 3.1
PDL	**12.03** ± 1.3	**9.60** ± 1.1
PDW	**6.48** ± 1.1	**5.13** ± 0.5
PA	**25.737** ± 4.37	**23.796** ± 2.76
PAL	**25.9** ± 1.0	**31.2** ± 1.0

to establish safe implantation corridors for pedicular screws in the caprine thoracolumbar spine.

In humans, Roy-Camille et al. recommended that the pedicle screw should be inserted in a straight (vertical) direction (Roy-Camille, Saillant & Mazel, 1986). It is interesting to note that the pedicle angulation in goats is more oblique than in humans. Therefore, using a straight screw insertion technique could lead to a high misplacement rate in goats. Thus, an oblique trajectory should be used. This conclusion was also reported in sheep (Jahng et al., 2004).

The results of the present study show that the spinal canal and vertebral bodies in goats are wider than deep, especially in the lumbar region. However, the spinal canal tends to have a comparable width and depth in the caudal thoracic region. The intervertebral discs are the thickest in the lumbar region. Pedicles are higher and longer than wide throughout the entire thoracic and lumbar spine. The disc thickness is 65.7% thicker in the lumbar vertebrae than in the thoracic vertebrae. A thicker disc offers better mobility than a thinner disc (Haussler, 1999). Conversely, transverse processes are longer in the thoracic region than in the lumbar region. The latter findings may explain the limited lateral flexion and axial rotation of the lumbar region (Wilke, Kettler & Claes, 1997).

In humans, spinal canal dimensions have an influence on movement upon the coronal axis of the spine; for instance, larger dimensions facilitate bending movement (Inufusa, An, Lim, Hasegawa & Haughton, 1996; Schönström, Lindahl, Willén & Hansson, 1989). In the current study, the dimensions of the spinal canal were maximal at two points: L6 and T8. Based on these results, we expect the maximum flexion point to be at L6 and the minimal flexion point to be at T9. No biomechanical study of this nature has been carried out on the goat spine. To our knowledge, this is the first report of this value in the goat spine.

In a study conducted by Qui *et al.*, eleven goats with an average weight of 28 kg underwent magnetic resonance imaging for the caudal thoracic spine (T9-T13), and morphometrics data were measured (Qui et al., 2015). As an example, the T10 body height value was 23.7 mm vs 23 mm in the current study, which confirms the reliability of the results obtained. Moreover, the age of the goats used in the study of Qui et al. ranged between 26 and 32 months, while in our study, the age average was 48 months. These results support the fact that the vertebral column of goats reaches its maximum growth size between 26 and 32 months (Qui et al., 2015).

In humans, pedicles represent a maximum resistance site for the placement of screws. The trabeculae in the pedicles seem to be thicker and stronger than in the vertebral body. In addition, the pedicular cortex is thicker, allowing an effective holding of screws (Krag et al., 1988); thus, the pedicular morphometry plays an important role in vertebral fixation. The screw diameter should be 80% of the pedicle diameter (Zhou et al., 2000). Therefore, the current study provides the precise morphometric data needed for the use of goats as a research model for pedicular fixation.

To our knowledge, this is the first report of the pedicular implantation corridors of the entire thoracolumbar goat spine (except for the first thoracic vertebra T1). However, the majority of cases concern the segment T3-L5 due to the complexity of the surgical approaches for T1, T2, T3 and L6. Their description has little relevance for pedicle attachment but is provided to fill in the lack of the morphometric data for goats in the literature. Plus, our study provides the first reports of certain parameters, such as PDL, PDW, PAL and PA, for the goat's thoracolumbar spine.

It is interesting to highlight that the pedicle width was thicker in the lumbar region than in the thoracic region. It is known that the widest pedicles allow thicker screws to be inserted, thus providing better stability and avoiding implant failure, as seen in the studies performed by Zhang et al. and Braun et al. (Braun et al., 2003; Zhang et al., 2009). In our study, PAL was longer in the lumbar vertebrae than in the thoracic vertebrae. Longer pedicles allow longer screw insertion in the lumbar vertebrae and could provide better stability.

Variation of pedicle angle has been evaluated. These data correspond to the "optimum" insertion angle, which means that the insertion angle can vary around this "optimal" value by four degrees without incurring a major risk. We can therefore simplify the results by estimating insertion angles of approximately 30 ° for the T2-T3 segments, 25 ° for the T4-T5 segments, 23 ° for the T6-T11 segments, 20 ° for the T12-T13 segments, 22 ° for the L1-L3 segments, 24° for the L4 segment and 30° for the L5-L6 segments.

Jahng et al. reported a significant difference between the insertion angle of the thoracic region and the lumbar region in a study performed in sheep; those findings correlate with the results obtained in the current study (Jahng et al., 2004). This significant difference between the lumbar and thoracic spine could be secondary to the type of vertebra (thoracic type I/ lumbar type II).

CT scan is the gold standard for the evaluation of the spine bony structures as seen in the current study. The quality of the perceived image depends on the calibration of the imaging parameters, the reconstruction algorithm of the reformatting parameters and the display mode (Tins, 2010). Dorsal recumbency is the position of choice for spinal computed tomography evaluation. This position reduces motion artifacts resulting from respiratory movements occurring during image acquisition (Tins, 2010). In the current study, goats were placed in sternal decubitus because it is the natural position of the spine and can mimic the same abnormalities, especially kyphosis in the lumbar spine. Goats were also euthanized before the study and CT scan; thus, breathing did not influence the image quality.

There are several limitations of our study. First, a data limitation is noted due to the limited number of available goat spines. To overcome this problem, the significance of the analysis was set using a low p value ($P < 0.05$); in addition, each goat has 19 thoracolumbar vertebrae, ultimately constituting a sample size of 198 thoracolumbar vertebrae. However, the animals were of the same age, weight, sex and breed. Furthermore, the measurements obtained in this study had a small variance around the mean, indicating that a larger sample was not necessary. In addition, a comparable sample number has been used in similar studies (Kumar, Kukreti, Ishaque & Mulholland, 2000; Mageed et al., 2013). Second, the positioning of goats, particularly regarding the alignment of the spine in a single plane, can lead to measurement errors of the segment's length; however, we did not measure the length of the segments. Third, this study is not a direct anatomical study. Measurements were performed on CT scans, which may lead to some approximation in the measurements. This technique was selected because CT is a noninvasive imaging modality and is a well-accepted method to assess spinal and vertebral morphometry in vivo. CT has been widely used in both humans and animal models (Bergmann, Graichen & Rohlmann, 1986; Riley et al., 2004; Wilke et al., 1997). The CT scan parameters (i.e., slice thickness, pitch, and window width) used in this study follow the recommendations for orthopedics studies and are consistent with published spinal CT imaging protocols. The validation of the results obtained would have required an anatomical comparison. Since goats were sacrificed for further studies, it was unfortunately not possible to make this comparison.

Conclusion

In conclusion, this study provides a quantitative database of pedicle screw implantation corridors and morphometric dimensions of the normal thoracolumbar goat spine. These results should be considered when using pedicle screws on goat spines in experimental studies (i.e., when testing new implants or surgical techniques) to provide correct and safer screw positions. Thus, these results may limit postoperative complications and thereby limit the use of live animals.

Ethical statement

This study is a morphometric analysis using computed tomography already performed on goats for another study with experience on live animals. The current study didn't use live animals.

Declaration of Competing Interest

The authors have declared that no competing interests exist.

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