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Radiographic Morphometry of the Lumbar Spine in Munich Miniature Pigs†

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The incidence of human spinal column disease remains high, and animal models still play important roles in prophylactic, diagnostic, and therapeutic research. Because of their similar size to humans, pigs remain an important spine model. For pigs to serve as a model for the human spine, basic similarities and differences must be understood. In this study, morphometric data of the lumbar spine of Munich miniature pigs (Troll) were recorded radiologically, evaluated, and compared with recorded human data. Whereas humans have a constant number of 5 lumbar vertebrae, Munich minipigs had 5 or 6 lumbar vertebrae. Compared with their human counterparts, the lumbar vertebral bodies of the minipigs were remarkably larger in the craniocaudal (superior–inferior) direction and considerably smaller in the dorsoventral and laterolateral directions. The porcine vertebral canal was smaller than the human vertebral canal. The spinal cord extended into the caudal part of the porcine lumbar vertebral canal and thus did not terminate as cranial, as seen in humans. The lumbar intervertebral spaces of the pig were narrower in craniocaudal direction than human intervertebral spaces. These differences need to be considered when planning surgical actions, not only to avoid pain and irreversible damage to the minipigs but also to achieve accurate scientific results.

Abbreviations: CCD, craniocaudal distance; DVD, dorsoventral distance; LLD, laterolateral distance.

The nonspecific symptom of back pain occurs frequently in industrialized countries. In European countries the 12-mo prevalence showed a large range, varying from 36.1% in Great Britain,[62] 40.5% in Norway, 47.2% in Sweden,[25] to 71.7% in Germany.[33] The point prevalence of back pain was 13.4% in Norway and 18.2% in Sweden,[25] whereas it was 39% in Germany.[33] The lifetime prevalence in Great Britain was 53.1%,[62] in Norway 60.7% and in Sweden 69.6%.[25] In the United States, an analysis of the data of the 2002 National Health Interview Survey indicated a 3-mo prevalence of back pain of 31%.[57]

In addition to causing the patient discomfort, back pain is a major expense of national health insurance companies. In the United States, back pain resulted in direct annual costs for personal medical care of $17.9 billion in 1988[12] and increased to $85.9 billion in 2005.[38] This background information alone emphasizes the importance of investigations concerning the etiology, prophylaxis, diagnosis, and therapy of diseases of the human back. Therefore, experimental research and surgical training are essential, both of which still require animal models. To comparatively investigate the biomechanics of the back and the effects of stress on the spine, the size of the animal species must be similar to humans.[39] Therefore, pigs (*Sus scrofa domestica*)—both young standard farm pigs and mature miniature pigs—play an important role as animal models for the human spine.[39] This importance is reflected in numerous articles—for example, from 1990 to 2006, the medical journal *Spine* published 120 articles involving investigations on pigs.[48] Moreover, the animal welfare report for Germany noted that 9571 pigs were used as laboratory animals in 1996;[16] this number increased to 14,004 pigs in 2005[17] and reached a maximum of 16,255 pigs in 2007.[18] Numerically, pigs used for research were in fifth place, behind 3 rodent species and rabbits. In the members of the European Union, a total of 66,305 pigs were used for examinations in 2005.[9]

A basic requirement for using a specific species or breed as an experimental animal with the goal of extrapolating the results from the animal model to human patients is understanding the similarities as well as the anatomic and morphometric differences between humans and the model species. Therefore, the intention of the present study was to compare the lumbar spine of Munich minipigs with that of humans. Radiologic images were recorded and used to analyze the morphometry of the lumbar spine of minipigs. These data then were compared with data from humans and the anatomic differences quantified. To avoid confusion, especially regarding the word 'height,' which applies to the craniocaudal distance of human vertebrae but the dorsoventral distance of those in animals, we adopted the same nomenclature to the vertebrae of both minipigs and humans: craniocaudal distance (CCD), dorsoventral distance (DVD), and laterolateral distance (LLD).

Materials and Methods

The study population comprised 16 (11 barrows, 5 sows; Table 1) mature Munich miniature pigs (Troll) from the Central Unit for Animal Research and Animal Welfare Duties of Heinrich–Heine University (Düsseldorf, Germany). The minipigs had been euthanized after the completion of other experiments that did not affect the lumbar spine region. Before radiography, the skin, abdominal wall, and intestines were removed to improve radiographic quality. To define the soft tissues within the vertebral canal, contrast medium (dose, 150 mg/kg body weight; iodine concentration, 300 mg/mL; Jopamidol, Solutrast 300M, Byk Gulden, Zürich, Switzerland) was injected into the subarachnoid space. Because of the postmortem condition of

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Table 1. Age and body weight of the Munich minipigs in the study

	Age (mo)	Body weight (kg)
Male, castrated (*n* = 11)	27.9 ± 6.4 (18–38)	80.4 ± 15.2 (48–97)
Female (*n* = 5)	22.6 ± 4.4 (18–29)	68 ± 23.3 (40–88)
Total (*n* = 16)	26.3 ± 6.3 (18–38)	76.5 ± 18.3 (40–97)

Data are shown as mean ± 1 SD (range).

the specimens, the contrast medium was administered by inserting a feeding tube (length, 50 cm; outer diameter, 2.1 mm) into the cerebellomedullary cistern and directing it caudally. The contrast medium was administered in 0.5-mL increments to improve distribution in the subarachnoid space and to avoid backflow. To help the contrast medium to flow caudally, the head of each minipig was lifted by tilting the operating table approximately 30%.

Immediately after contrast administration, the lumbar region was radiographed in supine position for ventrodorsal images and in right lateral position for laterolateral images. When necessary, foam cushions were used to support the neck and lumbar region to align the vertebral column parallel to the image plane. The radiographs were obtained by using an analog X-ray system (generator: Optimus, Philips, Hamburg, Germany; tube: PCS 2000, Philips), including a Bucky grid. The source-to-image distance was 1.15 m. X-ray films (24 × 30 cm; XDA Trimax, Kodak, Stuttgart, Germany) were used with an intensifying screen (3M Trimax 6, Kodak) and were developed in an automatic processor (Fuji, Düsseldorf, Germany) using the Kodak developer (RP X-Omat EX) and fixer (RP X-Omat Lo). The parameters for exposure to X-ray varied between 7 kV at 32 mAs to 66 kV at 32 mAs. The correction factor for the source-to-image distance was 0.9.

All measurements from radiographs were performed twice by the same person using a digital caliper (measurement accuracy, ± 0.1 µm; Mahr, Göttingen, Germany). When a radiographic outline was double, one measurement was taken for each outline and the mean value was determined. For each lumbar vertebra, the DVD and LLD of the vertebral bodies and the DVD and LLD of the vertebral canal were measured at cranial, central, and caudal points (Figure 1). These same points were used for the DVD and LLD measurements of the vertebral canal and the soft-tissue structures (the subarachnoid space and spinal cord; Figure 1). The CCD of the vertebral body was measured as the largest dorsal distance, the CCD of the intervertebral space as the largest distance at midcorpus. For all DVD and LLD values, the largest distance at the level of the cranial and caudal vertebral endplates was measured; at the central measuring point, the smallest distance was recorded. Data are displayed as mean ± 1 SD, and the values were graphed to compare data along the lumbar spine.

Subsequently, the measurements of the minipig lumbar spine were compared with published data regarding humans. Specifically, the values for the human vertebral body and canal were taken from reference 46 (age of subjects: mean, 46.3 y; range, 19 to 59 y), those regarding the human subarachnoid space from references 31 (mean age of subjects, 43.7 y) and 45 (subject age: mean, 33.8 y; range, 17 to 50 y), and those for intervertebral spaces from reference 42 (adults younger than 40 y).

Results

Number of lumbar vertebrae. In the examined Munich minipigs, the first vertebra with no rib contact was considered to be the first lumbar vertebra; the vertebra directly cranial to the sacrum was defined as the last lumbar vertebra. The number of lumbar vertebrae differed among the minipigs: 12 of the 16 animals had 5 lumbar vertebrae; the remaining 4 pigs had 6 lumbar vertebrae. Male and female minipigs showed a similar variation in the number of vertebrae (Table 2).

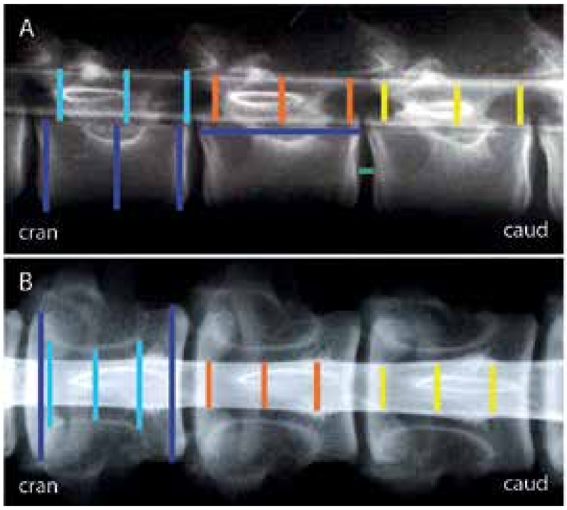

Figure 1. Measurements of the lumbar spine from myelographs of Munich minipigs (Troll). (A) Measurements of craniocaudal distances of vertebral bodies (dark-blue horizontal line) and intervertebral space (green horizontal line) and dorsoventral distances of vertebral bodies (dark-blue vertical lines: cranial, central, caudal), vertebral canal (light blue: cranial, central, caudal), subarachnoid space (orange: cranial, central, caudal), and spinal cord (yellow: cranial, central, caudal) on a right lateral radiograph. (B) Measurements of laterolateral distances of vertebral bodies (dark blue: cranial, caudal), vertebral canal (light blue: cranial, central, caudal), subarachnoid space (orange: cranial, central, caudal), and spinal cord (yellow: cranial, central, caudal) on a ventrodorsal radiograph.

Measurements of the lumbar vertebrae and their soft tissue contents. The average CCD of the lumbar vertebral bodies increased from 36.2 mm at L1 to a maximum of nearly 39 mm at L4 (Table 3). However, the mean CCD at L5 and L6 decreased to 36.7 and 36.5 mm, respectively, which are nearly the same as that for L1.

The mean DVD in the minipigs differed only slightly from L1 to L5. In vertebrae L1 to L5, mean vertebral body DVD was largest at the cranial measuring point, varying from 17.3 mm at L5 to a maximum of 18.4 mm at L3. The central part of vertebral bodies was smallest in all lumbar vertebrae; mean values ranged from 13.0 mm at L4 to 13.7 mm at L1. The mean DVD of the vertebral body's caudal endplate varied only slightly between vertebrae: 16.5 mm at L2 to 16.8 mm at L5. An exception was L6 (when present), whose caudal endplate averaged 18.3 mm, which slightly exceeded the mean DVD of the cranial endplate, measuring 18.0 mm. The central part of L6 was the smallest (average, 15.4 mm).

Along the lumbar spine, the LLD of the vertebral bodies showed an overall increase in the caudal direction. The smallest mean value was measured at the caudal endplate of L1 (25.5 mm), with the cranial endplate being slightly wider (26.1 mm). At L2, both ends had almost the same LLD (cranial, 26.3 mm; caudal, 26.1 mm). From L3 to L6, the caudal endplate was always wider than the cranial end of the same vertebra. In addition, from L3 to L5, the cranial endplate of the following vertebra was wider than the caudal endplate of the previous one.

In the Munich minipigs we evaluated, the vertebral canal's mean LLD increased caudally (Table 4). However, every lumbar

Table 2. Number of lumbar vertebrae in mature Munich minipigs

	No. of lumbar vertebrae	
	5	6
Male, castrated (*n* = 11)	8 (73%)	3 (27%)
Female (*n* = 5)	4 (80%)	1 (20%)
Total (*n* = 16)	12 (75%)	4 (25%)

Data are given as no. of minipigs (% of population).

vertebra showed central retraction of the LLD of the vertebral canal and thus the central LLD was smallest measure of vertebral canal among all lumbar vertebrae. This central LLD increased sequentially from 13.2 mm at L1 to 19.3 mm at L5 and 19.5 mm at L6 (when present). At L1 and L2, the mean LLD of the vertebral canal was almost the same as that at the cranial and caudal ends but increased slightly from L1 to L2 (L1, 18.0 mm and 17.8 mm; L2, 18.5 mm and 18.4 mm, respectively). From L3 to L5 (or L6), the mean LLD of the vertebral canal was always smaller at the cranial measuring point than at the caudal point.

Throughout the entire lumbar spine, the mean DVD of the vertebral canal was nearly the same at all 3 measurement points (cranial, central, and caudal) of a respective vertebra. The DVD of the vertebral canal increased slightly from L1 to L4, remained the same at L5, and decreased at L6 (when present) to a similar value as cranial L1.

The cranial DVD of the subarachnoid space at L1 averaged 9.3 mm (Table 5). The mean DVD achieved a maximum of 10.7 mm at the cranial measuring point of L4, which was similar to that at the central point of L4, but began to decrease at caudal L4. The mean DVD of the subarachnoid space reached a minimum value of 7.3 mm at the caudal point of L5. When L6 was present, the minimal mean DVD value (4.3 mm) occurred at the caudal end of that vertebra.

Regarding the average LLD of the subarachnoid space, these values progressed in a similar manner as DVD values, starting with 9.1 mm at cranial L1 and increasing caudally to a maximum of 11.9 mm at the central point of L4. The caudal point of L4 had almost the same LLD (11.6 mm) as the cranial region. Thereafter the value decreased rapidly to a caudal L5 value of 5.6 mm or of 3.0 mm at caudal L6. In some minipigs, the subarachnoid space at L5 and L6 was impossible to measure, because the ileal alae were superimposed onto the vertebral region in the X-ray images. This situation occurred during measurements of the spinal cord, too.

Beginning at the cranial measuring point of L1, the mean spinal cord LLD increased from 7.7 mm to a maximum of 10.4 mm centrally at L4 (Table 6). Afterward, the LLD decreased rapidly to a minimum of 4.1 mm at caudal L5 or of 1.7 mm at caudal L6. The mean DVD of the spinal cord was 7.0 mm at the cranial point of L1 and reached its maximum of 7.4 mm at the cranial end of L3; the central and caudal points had nearly the same DVD. Beginning at the cranial point of L4, the cord DVD decreased gradually to a minimum of 2.8 mm at caudal L5 or of 1.1 mm at caudal L6.

The mean value of the CCD of the intervertebral spaces varied between 3.3 and 3.4 mm. The mean CCD was 3.4 mm (± 0.7, *n* = 16) at the intervertebral space between L1 and L2, 3.3 (± 0.6, *n* = 16) at L2-L3, 3.4 (± 0.5, *n* = 16) at L3-L4, 3.3 (± 0.6 *n* = 16) at L4-L5, and 3.4 (± 0.5 *n* = 16) at L5-L6. Only the intervertebral disc between L6 and the sacrum was slightly smaller 3.0 mm (± 0.4, *n* = 4).

The graph of the DVD values (Figure 2 A) shows that the values of the cranial and caudal points of the vertebral body were greater than that of the vertebral canal. At the central point of the lumbar vertebrae, the DVD of the vertebral body and canal were similar, with the body slightly larger at L1 and at L2 and with the canal slightly larger at L3 and L4; L6 was an exception, where the body was 3.2 mm larger than the canal. The DVD values of the subarachnoid space and the spinal cord showed a parallel development from the cranial point of L1 to the caudal point of L3, with a difference of approximately 2.3 mm. After that point, the values slightly diverged: the subarachnoid space had its highest value at the cranial end of L4, whereas the maximal value of the spinal cord was at the cranial point of L3.

The graph of the LLD values (Figure 2 B) shows that both the vertebral body and canal had slightly larger cranial LLD values at L1 and L2; from L3 to L6, the caudal values of body and canal were larger than the cranial values. The difference between the values for the body and canal was largest (approximately 8 mm) at L1 and L2. This difference became smaller in the caudal direction and was 4.8 mm caudally at L5. Along the lumbar spine the LLD values for the subarachnoid space and spinal cord demonstrated a proportionate rise and fall, with the spinal cord being approximately 1.3 mm narrower than the subarachnoid space.

Comparison of the human and minipig lumbar spines. The values of the human vertebral body and vertebral canal are represented in Table 7, and the data regarding the human subarachnoid space and intervertebral spaces are summarized in Table 8. The ratio between the CCD of a lumbar vertebral body in humans and the corresponding measurement in minipigs varied from 0.6 to 0.7 because the vertebral body in minipigs was approximately 1/3 longer than that in humans. In contrast, the DVD of the vertebral bodies of the minipigs was approximately half that of humans, such that the human:minipig ratio was approximately 2 (range, 1.9 to 2.1). The LLD of the vertebral body was also much smaller in minipigs than in humans, yielding a human:minipig ratio between 1.5 and 1.7.

The comparison of the values of the vertebral canal in the lumbar region showed that the values of the minipigs were smaller than those of humans. Therefore, the DVD ratio (human:minipig) of the vertebral canal increased from 1.3 at L3 to 1.4 at L1 and L5. The human:minipig ratio of the spinal canal LLD decreased from 1.8 at L1 in the caudal direction to a minimum of 1.4 at L5. Therefore, the ratios of DVD and LLD were nearly the same at L5.

Depending on the study [31,45] (Table 8), the human:minipig ratio for the DVD of the subarachnoid space either ranged from 1.2 at central L4 to 1.6 at central L1 or from 1.4 at (central) L4 to 1.8 at caudal L5. At L3 and L4, the ratios of the subarachnoid space LLD were less than 2 (1.9 and 1.5, respectively), whereas they were greater than 2 (that is, 2.3 and 2.4) at L5 and L5–S1, respectively. Because the spinal cord of humans typically terminates between T12 and L2 (at the latest, in the upper third of L3),[11] there were an insufficient number of human spinal cord values to calculate ratios between the human and minipig spinal cord dimensions. The lumbar intervertebral discs of the minipigs were considerably thinner than those of humans; therefore, the human:minipig ratios ranged between 3 (that is, 3.1 at L5–S1) and 4 (3.9 at L4–L5).

Discussion

For diagnosing lumbar spinal disease, such as spinal stenosis, several radiologic methods including plain radiography, myelography, CT,[1,14] and MRI[56] are used currently. Measurements taken from CT images differ only slightly from those taken from MRI.[29,44] However, the distinction between bone

Table 3. Dimensions (mm) of the lumbar vertebral bodies in Munich minipigs

	L1			L2			L3		
	Cranial	Central	Caudal	Cranial	Central	Caudal	Cranial	Central	Caudal
Craniocaudal distance		36.2 ± 3.2			37.6 ± 3.2			38.3 ± 3.0	
n		14			16			16	
Dorsoventral distance	17.9 ± 1.1	13.7 ± 1.2	16.7 ± 1.3	18.2 ± 1.2	13.7 ± 1.3	16.5 ± 1.3	18.4 ± 1.5	13.5 ± 1.7	16.5 ± 1.3
n	16	16	16	16	16	16	16	16	16
Laterolateral distance	26.1 ± 2.2		25.5 ± 1.5	26.3 ± 1.8		26.1 ± 1.6	26.5 ± 1.8		27.6 ± 1.8
n	16		16	16		16	16		16

	L4			L5			L6		
	Cranial	Central	Caudal	Cranial	Central	Caudal	Cranial	Central	Caudal
Craniocaudal distance		38.9 ± 3.5			36.7 ± 4.1			36.5 ± 3.7	
n		16			14			3	
Dorsoventral distance	17.8 ± 1.5	13.0 ± 1.2	16.6 ± 1.2	17.3 ± 1.5	13.4 ± 1.4	16.8 ± 1.4	18.0 ± 1.9	15.4 ± 2.0	18.3 ± 1.4
n	16	16	16	15	14	14	4	4	4
Laterolateral distance	27.6 ± 1.5		29.5 ± 1.5	30.0 ± 1.8		32.3 ± 2.4	31.4 ± 2.7		32.3
n	16		16	15		14	3		1

Each vertebra was measured at 3 points: cranial, central, and caudal. Data are shown as mean ± 1 SD.

Table 4. Dimensions (mm) of the lumbar vertebral canal in Munich minipigs

	L1			L2			L3		
	Cranial	Central	Caudal	Cranial	Central	Caudal	Cranial	Central	Caudal
Dorsoventral distance	12.6 ± 1.4	13.3 ± 1.5	13.3 ± 1.7	12.7 ± 1.5	13.5 ± 1.3	13.8 ± 1.8	13.2 ± 1.5	14.0 ± 1.5	14.3 ± 1.8
n	16	16	16	16	16	16	16	16	16
Laterolateral distance	18.0 ± 1.3	13.2 ± 0.7	17.8 ± 1.0	18.5 ± 1.0	13.8 ± 0.8	18.4 ± 1.4	19.6 ± 1.0	14.8 ± 0.9	21.1 ± 1.7
n	16	16	16	16	16	16	16	16	16

	L4			L5			L6		
	Cranial	Central	Caudal	Cranial	Central	Caudal	Cranial	Central	Caudal
Dorsoventral distance	14.2 ± 1.9	14.2 ± 1.6	14.8 ± 1.9	14.2 ± 1.9	13.8 ± 1.9	14.4 ± 2.1	12.9 ± 1.3	12.3 ± 0.8	12.3 ± 1.2
n	16	16	16	14	14	13	4	4	4
Laterolateral distance	21.2 ± 1.0	16.7 ± 0.9	24.1 ± 1.3	23.8 ± 1.3	19.3 ± 1.3	27.5 ± 1.8	24.4 ± 2.1	19.5 ± 1.2	29.2 ± 1.3
n	16	16	16	16	16	16	4	4	4

Data are shown as mean ± 1 SD.

and soft tissue in CT myelography is superior to that of MRI.[44] In the present study, the measurements were obtained by using plain myelographic imaging, which sufficiently highlights the borderlines between bone, subarachnoid space, and spinal cord. In addition, both osseous and soft tissues can be measured in the same pass, without massive and invasive dissection of the lumbar vertebral column.

Because the published human measurements were obtained from adults,[31,42,45,46] only mature minipigs (that is, 18 mo and older) were used. Sexual maturity for all porcine breeds occurs between 4 and 6 mo of age.[58] However, the epiphyses of the long bones close at different times in farm breeds compared with miniature pig, for example, at 3 to 4 y in farm pigs compared with 1.5 to 2 y in Yucatan minipigs.[58] Depending on the strain or breed, ossification of the epiphyseal cartilage of the vertebral endplates occurs until the age of 4 to 7 y in domestic pigs.[65] This process is highly variable; for example, in German Landrace pigs, epiphyseal closure occurs at 26 to 36 mo.[63] In the Munich minipigs used in the current study, we noted that the epiphyses of the lumbar vertebrae were frequently open at 24 mo of age.

Table 5. Dimensions (mm) of the lumbar subarachnoid space in Munich minipigs

	L1			L2			L3		
	Cranial	Central	Caudal	Cranial	Central	Caudal	Cranial	Central	Caudal
Dorsoventral distance	9.3 ± 0.7	9.4 ± 0.6	9.2 ± 0.6	9.5 ± 0.5	9.6 ± 0.6	9.4 ± 0.6	9.9 ± 0.5	10.0 ± 0.6	10.0 ± 0.4
n	16	16	16	16	16	16	16	16	16
Laterolateral distance	9.1 ± 0.5	9.1 ± 0.5	9.5 ± 0.5	9.3 ± 0.3	9.4 ± 0.3	9.8 ± 0.5	9.9 ± 0.4	10.4 ± 0.6	11.1 ± 0.5
n	16	16	16	16	16	15	16	16	15

	L4			L5			L6		
	Cranial	Central	Caudal	Cranial	Central	Caudal	Cranial	Central	Caudal
Dorsoventral distance	10.7 ± 0.9	10.6 ± 1.4	10.0 ± 2.00	9.6 ± 1.3	8.5 ± 2.1	7.3 ± 1.2	6.2 ± 0.2	5.6 ± 0.2	4.3 ± 0.6
n	16	15	14	12	11	9	3	3	3
Laterolateral distance	11.7 ± 0.6	11.9 ± 1.1	11.6 ± 1.8	8.8 ± 2.6	7.0 ± 2.5	5.6 ± 1.4	4.3	3.2	3.0
n	15	15	14	14	14	10	2	1	1

Data are shown as mean ± 1 SD.

Table 6. Dimensions (mm) of the lumbar spinal cord in Munich minipigs.

	L1			L2			L3		
	Cranial	Cenral	Caudal	Cranial	Central	Caudal	Cranial	Central	Caudal
Dorsoventral distance	7.0 ± 0.3	7.1 ± 0.6	7.0 ± 0.4	7.1 ± 0.4	7.2 ± 0.4	6.9 ± 0.6	7.4 ± 0.4	7.4 ± 0.5	7.3 ± 0.8
n	16	16	16	16	16	16	16	16	16
Laterolateral distance	7.7 ± 0.4	7.8 ± 0.4	8.1 ± 0.5	8.0 ± 0.5	8.1 ± 0.3	8.3 ± 0.4	8.4 ± 0.4	8.8 ± 0.6	9.3 ± 0.5
n	16	16	16	16	16	15	16	16	15

	L4			L5			L6		
	Cranial	Central	Caudal	Cranial	Central	Caudal	Cranial	Central	Caudal
Dorsoventral distance	7.3 ± 1.0	6.6 ± 1.5	5.7 ± 1.8	5.0 ± 1.4	4.0 ± 1.5	2.8 ± 1.0	2.2 ± 0.6	1.9 ± 0.5	1.1 ± 0.5
n	16	15	14	12	11	9	3	3	3
Laterolateral distance	10.0 ± 0.5	10.4 ± 1.0	9.8 ± 1.8	7.1 ± 2.5	5.4 ± 2.5	4.1 ± 1.4	2.7	2.3	1.7
n	15	15	14	14	14	10	2	1	1

Data are shown as mean ± 1 SD.

Therefore, the describing pigs as 'adult' or 'mature' is unclear, and studies should always report the breed and actual age of the pigs used, as has been suggested by previous authors,[59] who emphasize the importance of describing the type of pig, including breed, sex, weight, age, and health status.

The normal weight of human adults is between 60 and 90 kg, similar to that of mature miniature pigs—for example, Yucatan micropigs reach a mature weight of 70 to 90 kg.[39] The Munich minipigs (Troll) used in the present study weighed between 63 and 97 kg at 24 mo or older. Adult weight is reached at approximately 2 y of age in minipigs.[60] In comparison, standard farm pigs weigh between 200 and 350 kg at full maturity,[7] depending on the breed. Therefore, standard farm pigs with a weight similar to normal human weight are still growing rapidly.[58] This situation must be considered, especially when surgical devices that should remain in place for a prolonged period of time are implanted.[58]

In addition, the trabecular bone density of the vertebrae changes remarkably between young (mean, 1.2 y) and mature (mean, 4.2 y) minipigs.[5] For example, bone mineral density continued to increase in Göttingen miniature pigs until 20 to 30 mo of age.[27] In comparison, the density of goat lumbar vertebrae is about twice that in humans.[55] Therefore, depending on the experimental purpose, not only the size of the vertebrae and the ossification of the epiphyseal cartilage but also the density of the vertebral bone might be of interest.

To have a broadly similar animal group, we examined only female and castrated male pigs in the current study, because the growth rate of these animals is similar, whereas noncastrated male pigs grow more rapidly.[51] Therefore the dimensions for the lumbar spine of intact male minipigs likely will exceed the values measured in the present study.

Whereas 2/3 of the evaluated Munich minipigs had 5 lumbar vertebrae, the remaining 1/3 had 6. Unfortunately, published

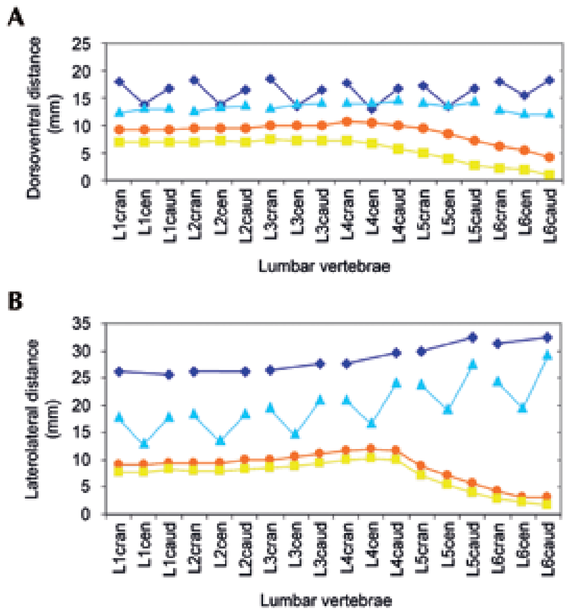

Figure 2. Mean measurements of the lumbar spine in Munich minipigs (Troll). (A) Dorsoventral distance. (B) Laterolateral distance. Dark blue, vertebral body; light blue, vertebral canal; orange, dural sac; yellow, spinal cord; caud, caudal; cen, central; cran, cranial.

information regarding the number of lumbar vertebrae in various minipig breeds, such as Yucatan minipigs, is unavailable.[19] Wild boars consistently have 5 lumbar vertebrae,[41] whereas modern breeds of domestic pigs have between 5 and 7 (but usually 6) lumbar vertebrae.[2,6,40,41,54] Humans have 5 lumbar vertebrae,[22,34] but apparent increases or decreases in number arise due to a lengthened or shortened sacral bone (referred to as 'lumbalization' and 'sacralization,' respectively).[36] Therefore, researchers should remember that, in most cases, Munich minipigs and humans have the same number of lumbar vertebrate, but exceptions exist in Munich minipigs.

Along the lumbar spine, the CCD of the vertebral bodies increased slightly to a maximum at L4, and decreased again at L5 (and L6, when present). This general pattern also occurs in standard farm pigs, with the maximum of the CCD localized at L5.[35,49] In the present study, the ratios for the CCD values between humans[46] and minipigs remained almost constant along the entire lumbar vertebral spine, indicating similar patterns of change in humans and minipigs. The remarkable reduction in size from L4 to L5 also occurs in humans, such that L5 is between 5% and 12% smaller than L4.[3,43,46] The present study showed that the CCD of the lumbar vertebral bodies in Munich minipigs are approximately 1/3 larger than those of humans,[46] yielding a human:minipig ratio of approximately 0.6. However, the CCD of the vertebral bodies did not differ significantly between humans and Yucatan micropigs,[9] perhaps due to differences in the measuring points used in the 2 studies. Whereas a previous study[39] measured the ventral CCD of the vertebral body in humans and Yucatan micropigs, we evaluated the dorsal CCD in the present study so that we could compare the minipig data with the corresponding measurement (posterior vertebral height) in humans.[46] The ventral CCD in humans reaches its maximum (28.1 to 28.7 mm) at L5, thus exceeding the dorsal values by 2.6 to 5.6 mm.[3,43,52]

Regarding the DVD, the minipig vertebral bodies are only half the size of their human counterparts,[46] such that the human:minipig ratio is nearly 2. Furthermore, minipigs show an additional reduction in DVD at the middle of each vertebral body. Although human vertebral bodies also demonstrate a central DVD reduction, this parameter was not measured in the study[46] we used for comparison. Along the lumbar spine, the ratio of the DVD between humans and minipigs changed only slightly because the values are nearly constant in both species. The DVD values measured for humans were consistent among 3 previous studies,[3,43,46] with an additional study[52] reporting slightly smaller values.

The LLD of the lumbar vertebral body were remarkably larger in humans[46] than in Munich minipigs. Human vertebral bodies are 1/3 wider than those in minipigs, such that the human:minipig ratio is approximately 1.5. Again, these ratios remained nearly equal along the entire lumbar vertebral spine, because LLD increased caudally in both species. Moving caudally, the cranial LLD of the lumbar vertebral bodies increased by 14.8% in humans and 14.9% in minipigs. However, the caudal LLD of minipigs increased by 26.7% in the caudal direction, markedly exceeding the increase of 14.1%[46] or 19.4%[52] found in humans. The LLD and DVD values we obtained for Munich minipigs are in accordance with the results of a study in which the anatomy of L4 was compared between Yucatan micropigs and humans.[39] In that study,[39] the human DVD was more than twice that of micropig specimens, and LLD was 65% greater in human than micropig vertebrae.

The L2 CCD and LLD values of Göttingen minipigs[26] are smaller than those of Munich minipigs, consistent with the different mature body weights of these breeds: Göttingen miniature pigs reach a weight of 35 to 45 kg at the age of 24 mo,[23] whereas Munich minipigs used in the present study weighed between 63 and 97 kg at 24 mo or older. In addition, the different mean age of the pigs might also have contributed: the Göttingen minipigs had a mean age of 16.8 mo,[26] whereas the animals in the present study were 26.3 mo old on average. In comparison, 4-mo-old Landrace pigs (average weight, 40 kg)[8] had lumbar vertebral LLD and DVD values that were similar to the Munich minipig values but the CCD of their vertebral bodies (range, 23.4 to 25.0 mm) and intervertebral spaces (range, 2.6 to 3.0 mm) were somewhat smaller than those in Munich minipigs. Another study measured the lumbar vertebrae of adult (age, 18 to 24 mo; weight, 60 to 80 kg) Landrace hybrids,[10] in which the CCD (range, 33.0 to 37.2 mm) was similar to that of Munich minipigs. The LLD and DVD values of the Munich minipig values were approximately 25% smaller than those of the Landrace hybrid pigs.[10] Whether the reported data are typical for growing or adult Landrace and Landrace hybrid pigs is unclear, given that domestic farm pigs are expected to weigh up to 100 kg at the age of 4 mo.[58] For example, Duroc hybrid pigs have a body weight of 150 kg at the age of 171 d,[53] and Spanish Landrace hybrids weigh 120 kg at 189 d.[32]

Although the DVD of the human lumbar vertebral body was approximately twice that of the Munich minipigs, the human vertebral canal exceeded that of the minipigs by only 20% to 30%, consistent with results showing that the DVD of the canal of L4 was 23% narrower in minipigs than in human specimens.[39] Along the human lumbar spine, the DVD of the canal has 2 maxima at L1 and L5, measuring 16 to 19.7 mm depending on the study.[3,13,15,46,52] The minimal value in humans, found at L3, varied between 15 and 17.5 mm.[13,46,52] The DVD of the vertebral canal in minipigs showed a contrasting pattern: minimal values occurred at L1 and L6 (when present), with the maximum DVD at L4. Therefore, whereas the vertebral canal showed only a slight reduction at the caudal end of the lumbar spinal column in minipigs with 5 lumbar vertebrae, the DVD of the canal in

Table 7. Ratio of dimensions (mm) of vertebral bodies and spinal canal between humans and minipigs, calculated by using published human data

Measured distance						
Human term	Veterinary term (present study)	L1	L2	L3	L4	L5
Posterior vertebral body height	Dorsal vertebral body length (CCD)	23.8 ± 1.0	24.3 ± 1.0	23.8 ± 1.1	24.1 ± 1.1	22.9 ± 1.0
Ratio, human:minipig		0.7	0.7	0.6	0.6	0.6
Upper end plate depth	Cranial vertebral body height (DVD)	34.1 ± 1.3	34.6 ± 1.1	35.2 ± 1.1	35.5 ± 0.9	34.7 ± 1.2
Ratio, human:minipig		1.9	1.9	1.9	2.0	2.0
Lower end plate depth	Caudal vertebral body height (DVD)	35.3 ± 1.3	34.9 ± 0.7	34.8 ± 1.2	33.9 ± 0.9	33.2 ± 0.9
Ratio, human:minipig		2.1	2.1	2.1	2.0	2.0
Upper end plate width	Cranial vertebral body width (LLD)	41.2 ± 1.0	42.6 ± 0.7	44.1 ± 0.9	46.6 ± 1.2	47.3 ± 1.2
Ratio, human:minipig		1.6	1.6	1.7	1.7	1.6
Lower end plate width	Caudal vertebral body width (LLD)	43.3 ± 0.8	45.5 ± 1.1	48.0 ± 1.2	49.5 ± 1.4	49.4 ± 1.4
Ratio, human:minipig		1.7	1.7	1.7	1.7	1.5
Spinal canal depth	Vertebral canal height (DVD)	19.0 ± 0.7	18.2 ± 0.5	17.5 ± 0.5	18.6 ± 0.7	19.7 ± 0.5
Ratio, human:minipig		1.4	1.4	1.3	1.3	1.4
Spinal canal width	Vertebral canal width (LLD)	23.7 ± 0.9	23.8 ± 0.7	24.3 ± 0.6	25.4 ± 0.5	27.1 ± 0.9
Ratio, human:minipig		1.8	1.7	1.6	1.5	1.4

Data are shown as mean ± 1 SD.
Human data were obtained from reference 46 ($n = 12$).

Table 8. Ratio of dimensions (mm) of lumbar subarachnoid spaces and intervertebral spaces between humans and minipigs, calculated by using published human data

Measured distance							
Human term	Veterinary term (present study)	L1	L2	L3	L4	L5	L5–S1
Dural sac, sagittal diameter[a]	Subarachnoid space height (DVD)	—	—	14.7 ± 0.2	14.4 ± 0.2	14.2 ± 0.3	12.8 ± 0.3
Ratio, human:minipig		—	—	1.5	1.4	1.7	1.8
Dural sac, frontal diameter[a]	Subarachnoid space width (LLD)	—	—	19.4 ± 0.2	17.8 ± 0.2	16.0 ± 0.3	13.5 ± 0.3
Ratio, human:minipig		—	—	1.9	1.5	2.3	2.4
		L1	L2	L3	L4	L5	
Dural sac diameter, midcorpus[b]	Central subarachnoid space height (DVD)	14.6 ± 1.4	13.3 ± 1.6	12.5 ± 1.9	12.2 ± 2.0	11.2 ± 2.6	—
Ratio, human:minipig		1.6	1.4	1.3	1.2	1.3	—
Dural sac diameter, lower end plate[b]	Caudal subarachnoid space height (DVD)	13.8 ± 1.8	13.1 ± 1.8	12.0 ± 1.8	11.6 ± 2.1	10.6 ± 3.0	—
Ratio, human:minipig		1.5	1.4	1.2	1.2	1.5	—
		L1–L2	L2–L3	L3–L4	L4–L5	L5–S1	
Intervertebral disc height[c]	Intervertebral space length (CCD)	11.1 ± 1.8	12.2 ± 1.8	12.9 ± 2.0	13.0 ± 2.1	10.4 ± 2.1	
Ratio, human:minipig		3.3	3.7	3.8	3.9	3.1	

CCD, craniocaudal distance; DVD, dorsoventral distance; LLD, laterolateral distance
Data are shown as mean ± 1 SD.
Human data were obtained from references 31[a] ($n = 121$), 45[b] (subarachnoid space, $n = 44$; data obtained from diagram by using GetData Digitizer 2.24), and 42[c] (intervertebral space, $n = 48$).

pigs with 6 lumbar vertebrae diminished to a greater extent. This different mode between humans and minipigs also is reflected in the changing human:minipig ratios: from 1.4 at L1 to 1.3 at L3 and 1.4 at L5.

In both humans and Munich minipigs, the LLD of the vertebral canal increased in the caudal direction, but the degree of the increase was quite different. In humans, the LLD increased by 14.3%[46] or 16.6% in men[52] and by as much as 22.6% in women.[52] In Munich minipigs, LLD increased by 46% from L1 to L5, with an additional increase of 6.1% when L6 was present. Accordingly, the human:minipig ratio decreased from 1.8 at L1 to 1.4 at L5.[46]

The ratio between DVD and LLD of the vertebral canal in Munich minipigs shows that in the center of the cranial lumbar vertebrae, L1 and L2, the canal is almost round, becoming increasingly transversely oval in the caudal direction. In humans, the LLD of the canal is larger than the DVD along the entire lumbar spine.[42] A comparison between the DVD values of the vertebral body and vertebral canal shows that in humans,[46] the body is almost twice as tall as the canal, whereas in minipigs, the central measurements of both structures are nearly the same size.

In Munich minipigs, both the DVD and LLD of the subarachnoid space were maximal at L4. Beginning at L1, the DVD increased in size by 14% and the LLD by 30%. From these maxima, DVD and LLD rapidly decreased to a minimum at the caudal end of L5: DVD decreased in size by 32%, and LLD lost more than half of its size (53%). Comparing the DVD and LLD values revealed that the transverse section area of the subarachnoid space is nearly round from L1 to the center of L3, transversely oval from the caudal end of L3 to the caudal end of L4, and finally LLD was smaller than DVD at L5 and L6 (when present). This pattern contradicts previous authors,[50] who reported that the subarachnoid space was longer in the transverse dimension at the lumbosacral junction. This difference might reflect differences in the age and breed of the animals evaluated; the previous study[50] did not mention the age or breed of the piglets involved. In addition, the radiographic images of L5 and L6 in some Munich minipigs were difficult to evaluate because the ileal wing was superimposed over L5 or L6 (or both), making delineation of the dura difficult. This artifact particularly affected the DVD measurements in these cases.

Compared with that in Munich minipigs, the human subarachnoid space showed a continuous reduction in the DVD value across the lumbar region.[31,45,64] The previously cited studies[31,45,64] report only the DVD value, and an additional work[31] demonstrated that the LLD likewise decreased from L3 to the lumbosacral junction. The termination of the human subarachnoid space is described as beginning at the cranial end of S1, typically in the region between the intervertebral discs of S1–S2 and S2–S3.[31,37,45] However, the subarachnoid space in humans sometimes continues until the intervertebral disc at S4–S5.[31] Therefore, it is unsurprising that the SD of subarachnoid space values increased in the caudal direction in humans.[30,31,45] In the Munich minipig, the point at which the subarachnoid space begins to narrow varies between animals: in one pig, it began at the central point of L4, whereas in most animals, narrowing started at central or caudal L5. Therefore, the SD of the subarachnoid space measurements from Munich minipigs became larger in the caudal direction, as did the human data.

For reasons similar to those accounting for the variations in the subarachnoid space measurements, the SD of the spinal cord values from Munich minipigs also increased in the caudal direction. Like that of the subarachnoid space, the maximal LLD of the spinal cord occurred at central L4. This maximum was due to an increase in the spinal cord LLD of 34.4%, beginning from the cranial end of L1. In contrast, the DVD of the spinal cord increased by only 5%, reaching the maximum at cranial L3 and remaining as such until the cranial part of L4. Subsequently, both the LLD and DVD of the minipig spinal cord decreased by more than 60% (LLD, 60.3%; DVD, 61.9%). Therefore, the transectional area of the lumbar spinal cord in Munich minipigs changes from transversely oval at the cranial end to almost rounded centrally and then back again to transversely oval at the caudal end.

The lumbar enlargement of the spinal cord in pigs is formed by the 4th to 6th segments of the lumbar spinal cord[21,28] and is situated in the vertebral canal of L4[4] or L5.[21,28] In Munich minipigs, the lumbar enlargement was located between the caudal part of L3 to the end of L4 (Figure 2 B). The level of the termination of the porcine spinal cord is described as being at the cranial half of the sacrum.[21,24,47,61] Therefore, pigs have a different type of soft tissue in the lumbar spinal canal in comparison to humans, given that the human spinal cord typically ends between T12 and L2, occasionally reaching L3.[11] In comparison, the minipig spinal cord extends well beyond L3 and into the sacrum, particularly in Munich minipigs with 5 vertebrae, but there are exceptions: in one animal, the filum terminale began at caudal L4. In Munich minipigs with 6 lumbar vertebrae, the medullary cone became very thin at cranial L6 (mean DVD, 2.2 mm), decreasing to a mean DVD of 1.1 mm at caudal L6, such that in minipigs with 6 vertebrae, the filum terminale lay in the vertebral canal of L6. In young farm pigs with 6 vertebrae, the medullary cone reportedly terminated in the first half of the sacrum, compared with between L5 and L6 in older pigs.[47] However, the exact age of the examined pigs was not indicated in the cited study.[47]

In accordance with previous findings,[20] our current results showed that the intervertebral spaces are much smaller in minipigs than in humans. The human:minipig ratio of the CCD values is almost 4, being smaller in the spaces between L1 and L2 and in the space cranial to the sacrum, where the ratio is closer to 3. This pattern reflects major changes in the human spaces at the beginning and end of the lumbar spine, whereas in minipigs, the measurements of the spaces are nearly equal throughout the lumbar spine. Minipigs with 6 lumbar vertebrae are an exception: they have a slight decrease in the intervertebral spaces value between the last lumbar vertebra and the sacrum. However, this difference might be due to small sample size: only 4 of the 16 minipigs we evaluated had 6 lumbar vertebrae.

In conclusion, our current data indicate substantial differences between the lumbar spines of minipigs and humans. However, all large standard laboratory animals (for example, dogs, sheep, goats) are quadrupeds, which are similar in vertebral anatomy to pigs, with a large CCD value and a small DVD value. This finding is in accordance with the authors of a previous study,[39] who stated that, because no animal truly reflects human vertebral anatomy, models for spine research must compromise. The lumbar spine of Munich minipigs can serve as a model in human medicine only when the anatomic differences have been studied and considered, especially when the studies involve the use of human-size implants. For those studies, precise measurements of the affected anatomic structures are extremely important. The current study provided these data for the entire lumbar spine of Munich minipigs, particularly demonstrating that the contents of the caudal lumbar vertebral canal differ strikingly between humans and minipigs: the spinal cord in minipigs does usually not terminate before this region. Therefore, careless surgical actions not only might cause irreversible damage to the experimental animals but also yield unreliable results. This situation must be avoided for the sake of the animal`s health as well as for scientific and even financial reasons.

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