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Osteological features in pure-bred dogs predisposing to cervical spinal cord compression

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ABSTRACT

Relative to body size, midsagittal and interpedicular diameters of the cranial and caudal aspects of cervical vertebral foramina (C3–C7) were found to be significantly ($P < 0.05$) larger in small breeds than in large breeds and Dachshunds, and also larger in Dachshunds ($P < 0.05$) than in large breeds. This condition increases the risk for spinal cord compression resulting from relative stenosis of the cervical vertebral foramina, especially in large dogs, and this is also exacerbated by the typical shape of the vertebral foramina (i.e. dorsoventrally flattened cranially and bilaterally narrowed caudally). Within large dogs those breeds highly predisposed to cervical spinal cord compression were Great Danes (the breed with the smallest midsagittal vertebral foramen diameters from cranial C6 to cranial T1) and Doberman Pinschers, because of the most strikingly cranially dorsoventrally narrowed cone-shaped vertebral foramina at C6 and C7. The existence of a small midsagittal diameter in the cranial cervical spine was a high risk factor predisposing to spinal cord compression in small breeds and Dachshunds. Remarkable consistency was noted between the spinal level of the maximum enlargement of the spinal cord which previously was reported to be at C6, and the site of maximum enlargement of the vertebral canal currently stated in Dachshunds and small breeds. In large breeds the maximum enlargement of the vertebral canal tended to be located more caudally at the caudal limit of C7. The average age at which large dogs were most susceptible to noxious factors causing abnormal growth of the pedicles was determined to be 16 wk.

Key words: Vertebral canal; osteology; cervical myelopathy; dog.

INTRODUCTION

Compression of the cervical spinal cord is common in the dog. Suggested aetiological factors include congenital or acquired changes of the vertebral canal such as malformations of the cervical vertebrae (e.g. deformities of articular processes, vertebral laminae and vertebral bodies), vertebral instability, prolapse/protrusion of intervertebral discs, and hypertrophy of soft tissue components (i.e. interarcual ligaments, dorsal longitudinal ligament, capsules of the zygapophyseal joints) (Geary, 1969; Raffe & Knecht, 1980; Rendano & Smith, 1981; Betts, 1982; Seim & Withrow, 1982; Jaggy & Lang, 1986; Jaggy et al. 1988; VanGundy, 1989; Lewis 1991, 1992). In man, acromegaly (Epstein et al. 1982; Parikh et al. 1987; Woo, 1988; Epstein & Schwall, 1994) and chondrodysplasia (Rogoll et al. 1990; Hunter et al. 1998) are also known to cause spinal stenosis.

The most common radiographic features in dogs are dorsoventral stenosis of the cranial opening and/or dorsolateral narrowing of the vertebral foramen (VF) (Wright et al. 1973; Trotter et al. 1976; Mason, 1977, 1979; Raffe & Knecht, 1980; Betts, 1982; Seim & Withrow, 1982; Lincoln & Pettit, 1985; VanGundy, 1989; Lewis, 1992; Sharp et al. 1992; Massicotte et al. 1999). Acquired vertebral deformity is suspected to develop at 6–12 wk of age (Burbidge et al. 1994). Unlike vertebral compression, which is commonly present in large dogs at C6–C7 (Wright et al. 1973; Trotter et al. 1976; Mason, 1977, 1979; Raffe & Knecht, 1980; Rendano & Smith, 1981), disc prolapse/protrusion occurs in both large and small breeds (Jurina, 1996). However, the incidence of

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clinically symptomatic intervertebral disc involvement decreases in a cranial to caudal direction in chondrodystrophic and small breeds and increases in large breeds (Dallman et al. 1992; Jurina, 1996).

Susceptibility to spinal cord compression owing to the development of any space-occupying condition of the vertebral canal is inversely related to canal diameter. In previous reports dealing with canine vertebral canal morphometry (Morgan et al. 1987; Jones et al. 1995), differences in breed-related body size were addressed by calculating vertebral canal to vertebral body height ratios. Thus different ratios between breeds might have been influenced by different vertebral body heights, making it difficult to compare the size of the vertebral canal in different breeds. There has been much disagreement about vertebral canal diameters (Lincoln & Pettit, 1985; Bailey & Morgan, 1992), the shape and physical size of the cross-sectional area of the spinal cord are reported to differ between the cranial and caudal cervical spine (Fletcher, 1993), but it is not yet known if and to what extent these values are associated with vertebral canal dimensions. In cases of disproportion, this condition might predispose to spinal cord compression resulting from relative stenosis of the vertebral canal.

In the present study a new method was introduced to relate normal values to body size. By comparing midsagittal and interpedicular diameters of the cervical vertebral foramina obtained from clinically asymptomatic dogs, we set out to determine those breeds and spinal sites which are predisposed to spinal cord compression because of relative stenosis of the vertebral foramina.

MATERIALS AND METHODS

This study was based on a random sample of regular spines of 139 adult (age $\geqslant$ 52 wk) and 21 juvenile (age $<$ 52 wk) neurologically asymptomatic dogs obtained from the Department of Pathology of the University of Veterinary Medicine Vienna. The number of dogs, their sex, age, breed, and the groups of breeds are listed in Table 1. The ages ranged between 1 and 15 y in all groups of adults, and between 4 and 32 wk in the group of juvenile dogs.

Calculation of the body size normalisation factor in adult dogs

The maximal ventral craniocaudal length (i.e. the anterior intervertebral disc height in man) of each intervertebral disc (ID) from C2/3 to L7/S1 was determined on lateral radiographs. The vertebral body length (VBL) of each bacterially macerated vertebra from C3 to L7 was then determined in the median ventral line. The lengths of C1 and C2 were not included because of the poor delineation between the dens and vertebral body of the axis. The lengths of the sacrum and the coccygeal vertebrae also were not determined because of the high variability in the individual number of vertebrae. Each spine was then corrected to a standardised length of 400 mm by the body size normalisation factor $(f) = \{(\sum \mathrm{ID}_{\mathrm{C2/3-L7/S1}} + \sum \mathrm{VBL}_{\mathrm{C3-L7}})/400\}$. The length of 400 mm was chosen because this represents the approximate length obtained in Dachshunds.

To determine the intervertebral disc lengths, the head, limbs, and muscles were removed from the spines and pelvic bones of adult specimens. After trimming the ribs, the specimens were wrapped in plastic and frozen (12–24 h, −25 °C) by hanging in a vertical position. According to Hickey & Hukins (1979) and Pflaster et al. (1997), freezing alters neither the arrangement of annular collagen fibrils nor the water content of intervertebral discs within 24 h. The ribs then were band-sawed to the same length as the transverse processes of the lumbar segment in order to receive a plan area. This treatment was required to decrease the distance between the spine and the x-ray film and to allow standardised positioning in the following strictly transverse radiographic examination, avoiding the effect of even small amounts of lateral tilt or longitudinal axis rotation which together with the bias introduced by different observers may lead to a loss of accuracy in radiographic morphometry of intervertebral discs of 35% (Saraste et al. 1985) up to 50% (Andersson et al. 1981). In order to decrease dispersion, 6 radiographs were taken in large dogs (central x-ray beam focused at C4/5, T1/2, T5/6, T11/12, L2/3, and L6/7). Five radiographs were taken in Dachshunds (C4/5, T2/3, T7/8, T12/13, L3/4), and 4 in small dogs (C5/6, T4/5, T10/11, L3/4). Radiographs were made with fixed film-to-focus (FFD = 100 cm) and specimen-to-film distances (SFD = 5 cm measured from the midsagittal plane to the film). The radiographic magnification correction factor (C = 0.95) was calculated as $C = (\mathrm{FFD}-\mathrm{SFD})/\mathrm{FFD}$ (van Bodegom et al. 1998). All measurements were performed by a single person with the help of a calliper and evaluated to the accuracy of 0.1 mm. In a random sample of 20 dogs, osteological and radiographic morphometry was performed twice to analyse the effect of intraobserver measurement variation on the calculated body size normalisation

Table 1. *Number of dogs, sex and age (mean ± standard deviation) with respect to breed*

Groups of breeds	Breed	n	Male/female	Mean age ± S.D.
Adult dogs				
Large breeds (L)	Bernese Mountain Dog (BMD)	9	6/3	5.4 ± 2.7 y
	Rough Collie	6	2/4	8.2 ± 3.5
	Doberman Pinscher	6	2/4	6.7 ± 2.8
	Great Dane	7	3/4	5.5 ± 2.8
	German Shepherd Dog (GSD)	39	23/16	7.6 ± 4.3
	Rottweiler	11	5/6	7.9 ± 3.5
	Large breeds total	78	41/37	7.2 ± 4.2
Dachshunds (D)	Dachshunds total	28	10/18	8.9 ± 3.6
Small breeds (S)	Maltese	8	2/6	6.7 ± 3.1
	Yorkshire Terrier	25	10/15	8.5 ± 4.3
	Small breeds total	33	12/21	8.1 ± 4.7
Juvenile dogs	GSD	5	3/2	11.4 ± 7.4 wk
	Rottweiler	16	12/4	10.9 ± 7.3
	Juvenile dogs total	21	15/6	11.0 ± 7.1

factor. The precision was regarded as good when the coefficient of variation was less than 5%. The coefficient of variation of the radiographic disc length measurements was 3.7% and the coefficient of variation of the osteological vertebral body length measurements was 0.4%. The effect of intraobserver measurement variation on the calculated body size correction factor was 0.2%.

Osteological cervical spine morphometry

The midsagittal diameter (vertebral foramen height, VFH), and the maximal interpedicular diameter of the vertebral foramen (vertebral foramen width, VFW) were evaluated at the cranial and caudal limits of the vertebral foramina from C2 caudal (cd) up to T1 cranial (cr) in the specimens of adult and juvenile dogs (vertebrae were cleaned by a colony of *Dermestes maculatus* larvae). The cranial and caudal width to height ratios (WHcr-ratio, WHcd-ratio) of the vertebral foramina as well as the caudal to cranial height (VFHcd/cr) and width ratios (VFWcd/cr) were calculated to characterise the shape of the vertebral foramen at the cranial (WHcr-ratio) and caudal (WHcd-ratio) aspect as well as in a lateral (VFHcd/cr) and sagittal view (VFWcd/cr). The maximum width of the caudal vertebral endplates (VBW) and the maximum midsagittal length of the vertebral laminae (ARCL) from C3 to C7 also were evaluated to determine the relation between VFW and VBW, and the ratio between VBL and ARCL (VBL/ARCL-ratio) dimensions. Multiplication of these variables with the body size normalisation factor (f) allowed comparison between breeds.

Using the statistical analysis programme SPSS v. 6.0.1 for Windows (SPSS, Chicago, 1994), all values were tested for normal distribution (Kolmogorov-Smirnov test) and for significant differences between breeds as well as differences within large and small breeds (Scheffé test, significance level $P < 0.05$; Student's t test, 95% confidence limits, significance level $P < 0.05$). A discriminant analysis (direct method) was performed to determine those variables best appropriate to classify individual breeds and the 3 groups of breeds. Independent variables included all body size corrected VFW and VFH values.

The association between age and vertebral foramen dimensions (original values VFH, VFW) was determined by regression analysis, the goodness-of-fit was denoted by R^2.

RESULTS

Canonical discriminant functions (Fig. 1) allowed 92.8% (129/139) of specimens to be classified to the correct breed. The canonical correlation coefficients were 0.96 (function 1) and 0.86 (function 2). Wilks' lambda indicated significant differences between the mean values of the discriminant function in all breeds ($P < 0.001$). The VF dimensions with the highest variable loading on the 2 canonical discriminant functions were the cranial VFH values at C6, C7, C5 (function 1), and the cranial VFH at T1, and the caudal VFH at C7 (function 2). Those dogs classified incorrectly were 1 Dachshund (1/28) predicted to the group of Rough Collies, 1 Rottweiler (1/11) classified as Great Dane, 2 BMDs (2/9) classified as Rough Collie or GSD respectively, and 2 GSDs (2/39)

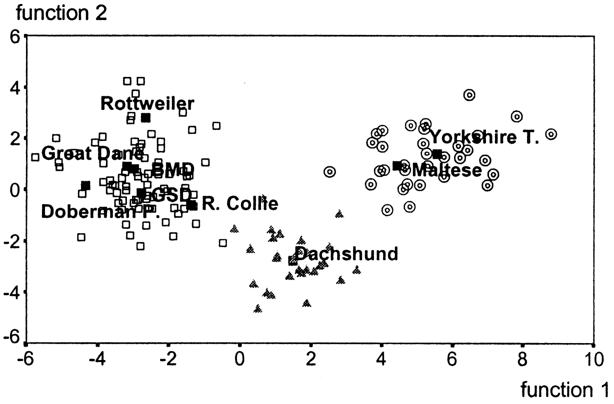

Fig. 1. Classification of breeds by means of the canonical discriminant functions and breed centroids.

classified as Doberman Pinscher or Rottweiler respectively. Yorkshire Terrier (2/25) and Maltese (1/8) were predicted interchangeably to the incorrect breed. Grouping dogs as Dachshunds, large and small breeds in the following discriminant analysis allowed 100% of dogs to be classified correctly.

Statistical evaluation of the body size corrected vertebral foramen heights (VFHs) and widths (VFWs) are listed in Table 2. None of these values were significantly different between Maltese dogs and Yorkshire Terriers. This is why these breeds, for further calculations, were combined as small breeds. Values of separate large breeds exclusively are listed in case of significant differences ($P < 0.05$) within the group of large breeds. Any association between sex and VF diameters could not be confirmed statistically.

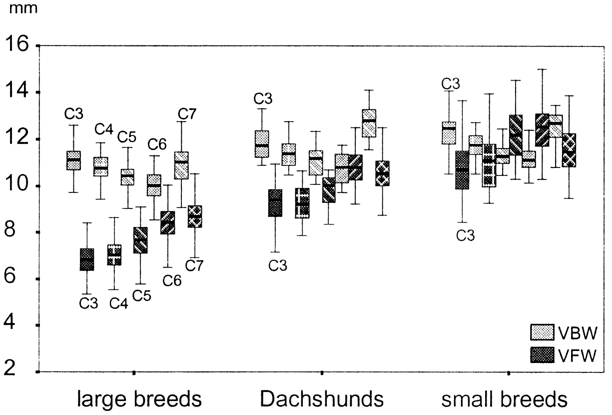

Fig. 2. Illustration of the body-size corrected caudal vertebral foramen width (VFW) relative to the caudal vertebral body width (VBW) from C3 to C7 (boxes mark the central 50% of observations and the median, whiskers indicate the 2.5th and 97.5th centiles).

The caudal VFWs were associated with the corresponding caudal VBWs (Fig. 2). From C3 up to C7 R^2 varied between 0.32 and 0.37 ($P < 0.001$) Therefore, like the VFHs and VFWs (Table 2), all VBWs were also smaller in large compared with small breeds and Dachshunds, and those in Dachshunds again were smaller relative to small breeds. However, Figure 2 illustrates that the disproportions between the caudal VFWs relative to the caudal VBWs were considerably greater in large breeds. The VBL to

Table 2. *Mean ± standard deviation of the body size corrected vertebral foramen height (VFH) and width (VFW) relative to the cranial and caudal limits.*

VFHcr	C2	C3	C4	C5	C6	C7	T1
Large breeds (L)		$4.9 \pm 0.5^{(D,S)*}$	$4.9 \pm 0.5^{(D,S)}$	$5.1 \pm 0.6^{(D,S)}$	$5.5 \pm 0.6^{(D,S)}$	$5.6 \pm 0.8^{(D,S)}$	$5.7 \pm 0.8^{(S)}$
Great Dane (2)					$4.5 \pm 0.4^{(3,6,D,S)}$	$4.4 \pm 0.2^{(3,D,S)}$	$4.8 \pm 0.6^{(3,S)}$
Rottweiler (3)					$5.9 \pm 0.4^{(2,D,S)}$	$6.3 \pm 0.5^{(2,D,S)}$	$6.7 \pm 0.7^{(2,5,S)}$
Dachshund (D)		$6.0 \pm 0.7^{(2,5,L,S)}$	$5.9 \pm 0.5^{(1,2,5,L,S)}$	$6.4 \pm 0.6^{(1-5,L,S)}$	$7.2 \pm 0.5^{(1-6,L,S)}$	$7.0 \pm 0.7^{(1-5,L,S)}$	$6.1 \pm 0.5^{(S)}$
Small breeds (S)		$8.3 \pm 1.0^{(1-6,L,D)}$	$6.9 \pm 0.9^{(1-6,L,D)}$	$8.5 \pm 0.9^{(1-6,L,D)}$	$9.6 \pm 1.0^{(1-6,L,D)}$	$9.8 \pm 1.0^{(1-6,L,D)}$	$9.3 \pm 1.2^{(1-6,L,D)}$
VFHcd							
Large breeds (L)	$6.0 \pm 0.6^{(D,S)}$	$5.8 \pm 0.6^{(S)}$	$5.8 \pm 0.6^{(D,S)}$	$6.1 \pm 0.6^{(D,S)}$	$6.6 \pm 0.8^{(D,S)}$	$5.7 \pm 0.7^{(D,S)}$	
Great Dane (2)					$5.2 \pm 0.3^{(1,3,D,S)}$	$5.7 \pm 0.6^{(1,3,S)}$	
Rottweiler (3)					$7.5 \pm 0.6^{(2,S)}$	$7.7 \pm 0.6^{(2,S)}$	
Dachshund (D)	$6.7 \pm 0.7^{(5,L,S)}$	$6.0 \pm 0.6^{(S)}$	$6.4 \pm 0.8^{(5,L,S)}$	$7.1 \pm 0.6^{(2,5,L,S)}$	$7.7 \pm 0.7^{(2,4,5,L,S)}$	$7.1 \pm 0.6^{(L,S)}$	
Small breeds (S)	$8.9 \pm 0.9^{(1-6,L,D)}$	$8.1 \pm 0.9^{(1-6,L,D)}$	$8.5 \pm 0.7^{(1-6,L,D)}$	$9.6 \pm 1.1^{(1-6,L,D)}$	$10.3 \pm 1.0^{(1-6,L,D)}$	$9.8 \pm 1.2^{(1-6,L,D)}$	
VFWcr							
Large breeds (L)		$7.0 \pm 0.5^{(D,S)}$	$7.4 \pm 0.5^{(D,S)}$	$7.7 \pm 0.6^{(D,S)}$	$8.4 \pm 0.7^{(D,S)}$	$9.0 \pm 0.8^{(D,S)}$	$8.7 \pm 0.5^{(D,S)}$
Dachshund (D)		$8.4 \pm 0.7^{(2,3,5,L,S)}$	$9.0 \pm 1.0^{(2-5,L,S)}$	$9.5 \pm 0.9^{(1-6,L,S)}$	$10.3 \pm 0.9^{(1-6,L,S)}$	$10.8 \pm 0.8^{(1-6,L,S)}$	$10.2 \pm 0.6^{(2-5,L,S)}$
Small breeds (S)		$10.8 \pm 1.4^{(1-6,L,D)}$	$11.0 \pm 1.3^{(1-6,L,D)}$	$11.7 \pm 1.1^{(1-6,L,D)}$	$12.3 \pm 1.1^{(1-6,L,D)}$	$12.4 \pm 1.0^{(1-6,L,D)}$	$11.6 \pm 1.0^{(1-6,L,D)}$
VFWcd							
Large breeds (L)	$6.8 \pm 0.5^{(D,S)}$	$6.8 \pm 0.6^{(D,S)}$	$7.0 \pm 0.6^{(D,S)}$	$7.6 \pm 0.9^{(D,S)}$	$8.3 \pm 0.9^{(D,S)}$	$8.6 \pm 0.9^{(D,S)}$	
Dachshund (D)	$8.5 \pm 0.7^{(1-6,L,S)}$	$9.4 \pm 0.9^{(1-6,L,S)}$	$9.2 \pm 0.8^{(1-6,L,S)}$	$9.9 \pm 0.8^{(1-6,L,S)}$	$10.8 \pm 0.8^{(1-6,L,S)}$	$10.5 \pm 1.0^{(2-5,L,S)}$	
Small breeds (S)	$10.5 \pm 1.3^{(1-6,L,D)}$	$10.9 \pm 1.3^{(1-6,L,D)}$	$11.1 \pm 1.3^{(1-6,L,D)}$	$12.1 \pm 1.2^{(1-6,L,D)}$	$12.5 \pm 1.1^{(1-6,L,D)}$	$11.6 \pm 1.2^{(1-6,L,D)}$	

*Symbols in parentheses indicate significant different values ($P < 0.05$). Large breeds (L) are coded as follows: Doberman Pinscher (1), Great Dane (2), Rottweiler (3), BMD (4), GSD (5), R. Collie (6). Values in small breeds (S) and Dachshunds (D) always were significantly higher than in the coded large breeds. Singular significant values within large breeds additionally were noticed in the R. Collies (VFHC6cr $6.1 \pm 0.4^{(2,D,S)}$), GSDs (VFHT1cr $5.4 \pm 0.6^{(3,S)}$), Doberman Pinscher (VFHC6cd $7.0 \pm 0.8^{(2,S)}$; VFHC7cd $7.4 \pm 0.7^{(2,S)}$).

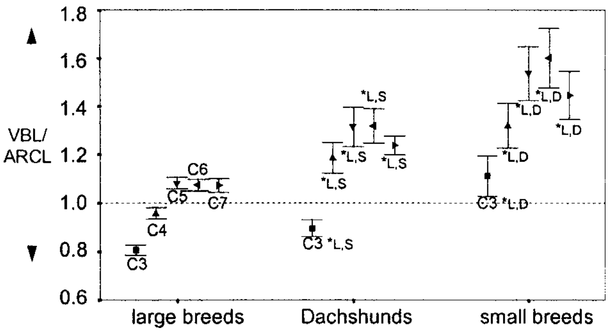

Fig. 3. Mean and 95% confidence limits of the mean of the vertebral body length (VBL) to vertebral lamina length (ARCL) ratios. Symbols indicate significant differences ($P < 0.05$). L, large breeds; D, Dachshunds; S, small breeds.

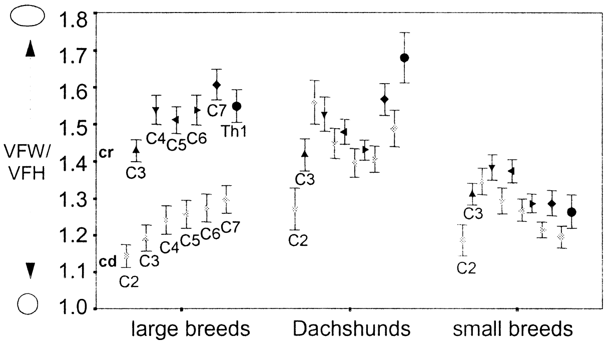

Fig. 4. Mean and 95% confidence limits of the mean of the width to height ratios (WHcr-ratio, WHcd-ratio) illustrating the shape of the cranial and caudal limits of the vertebral foramina.

ARCL-ratios and statistical results are given in Figure 3.

The shapes of the cranial and caudal limits of the

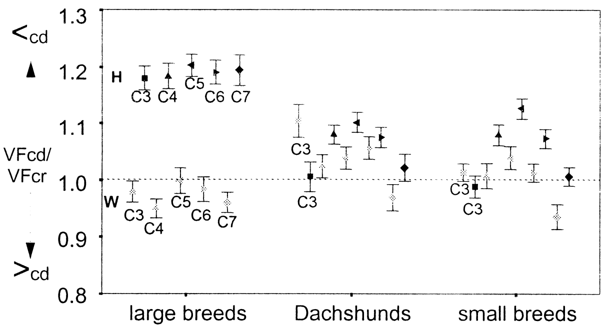

Fig. 5. Mean and 95% confidence limits of the mean of the caudal to cranial width (VFWcd/cr) and height (VFHcd/cr) ratios.

vertebral foramina relative to the vertebral position are indicated by the width to height ratios (WHcr-ratio, WHcd-ratio) shown in Figure 4. Unlike ratios > 1, which reveal dorsoventrally flattened oval-shaped orifices, a ratio of 1 represents a circular shape. Mean values of the ratios and statistical results are given in Table 3. The caudal to cranial width (VFWcd/cr) and height (VFHcd/cr) ratios shown in Figure 5 indicate the shape of the vertebral foramen in a lateral and sagittal view, i.e. the shape expected in radiographs. Ratios 1 represent funnel-shaped foramina narrowed cranially in a lateral (VFHcd/cr) and sagittal view (VFWcd/cr) respectively. Mean values of the ratios and statistical results are listed in Table 4. Anatomical specimens which are representative for the typical shape of the VF in a dorsal and lateral view

Table 3. *Mean of the width to height ratios at the cranial (WHcr-ratio) and caudal limits (WHcd-ratio) of the vertebral foramina*

WHcr-ratio	C2	C3	C4	C5	C6	C7	T1
Large breeds (L)		$1.43^{(S)}$*	$1.54^{(S)}$	$1.51^{(S)}$	$1.54^{(D,S)}$	$1.61^{(S)}$	$1.55^{(S,D)}$
Doberman P. (1)		**	$1.75^{(3,4,S)}$	$1.60^{(S)}$	$1.64^{(2,3,D,S)}$	$1.70^{(3,S)}$	$1.51^{(S)}$
Great Dane (2)		$1.63^{(3,6,D,S)}$	$1.76^{(3,4,S)}$	$1.62^{(S)}$	$1.80^{(1,3–6,D,S)}$	$1.82^{(3,S)}$	$1.78^{(3,S)}$
Rottweiler (3)		$1.28^{(2)}$	$1.40^{(1,2)}$		$1.34^{(1,2,5)}$	$1.38^{(1,2,4,5)}$	$1.29^{(2,5,D)}$
BMD (4)			$1.45^{(1,2)}$		$1.48^{(2)}$	$1.62^{(3,S)}$	$1.48^{(S)}$
GSD (5)				$1.54^{(S)}$	$1.57^{(2,3,D,S)}$	$1.63^{(3,S)}$	$1.61^{(3,S)}$
Rough Collie (6)		$1.37^{(2)}$			$1.41^{(2)}$	$1.54^{(S)}$	$1.60^{(S)}$
Dachshund (D)		$1.42^{(2,S)}$	$1.53^{(S)}$	$1.48^{(S)}$	$1.43^{(1,2,5,L,S)}$	$1.57^{(S)}$	$1.68^{(3,L,S)}$
Small breeds (S)		$1.31^{(2,L,D)}$	$1.39^{(1,2,L,D)}$	$1.38^{(1,2,5,L,D)}$	$1.28^{(1,2,5,L,D)}$	$1.29^{(1,2,4–6,L,D)}$	$1.26^{(1,2,4–6,L,D)}$
WHcd-ratio							
Large breeds (L)	$1.14^{(D)}$	$1.19^{(D,S)}$	$1.24^{(D)}$	$1.26^{(3)}$	$1.27^{(D,S)}$	$1.30^{(D,S)}$	
Doberman P. (1)		$1.30^{(3,D)}$	$1.36^{(3)}$	$1.35^{(3,D)}$		$1.24^{(D)}$	
Great Dane (2)		$1.24^{(D)}$	$1.20^{(D)}$	1.26	$1.34^{(3)}$		
Rottweiler (3)	$1.06^{(D)}$	$1.02^{(1,5,D,S)}$	$1.04^{(1,5,D,S)}$	$1.06^{(1,5,D,S)}$	$1.06^{(2,4,5,D)}$	$1.11^{(5,6,D)}$	
BMD (4)		$1.09^{(D,S)}$	$1.14^{(D)}$		$1.29^{(3)}$		
GSD (5)		$1.23^{(3,D)}$	$1.30^{(3,D)}$	$1.31^{(3)}$	$1.33^{(3)}$	$1.32^{(3,D,S)}$	
Rough Collie (6)	$1.01^{(D)}$	$1.19^{(D)}$				$1.48^{(3,S)}$	
Dachshund (D)	$1.27^{(3,6,L,S)}$	$1.56^{(1–6,L,S)}$	$1.45^{(2–5,L,S)}$	$1.40^{(1,3,L,S)}$	$1.41^{(3,L,S)}$	$1.49^{(1,3,5,L,S)}$	
Small breeds (S)	$1.18^{(D)}$	$1.34^{(3,4,L,D)}$	$1.29^{(3,D)}$	$1.27^{(3,D)}$	$1.21^{(L,D)}$	$1.19^{(5,6,L,D)}$	

*Symbols in parentheses indicate significant different values ($P < 0.05$). Large breeds (L) are coded as follows: Doberman Pinscher (1), Great Dane (2), Rottweiler (3), BMD (4), GSD (5), R. Collie (6). Small breeds are coded as (S) and Dachshunds as (D). **Individual breed ratios, which were not significantly different from values of the large breeds group, are not listed.

Table 4. *Mean of the caudal to cranial width (VFWcd/cr) and height (VFHcd/cr) ratios*

VFWcd/cr-ratio	C3	C4	C5	C6	C7
Large breeds (L)	$0.98^{(D)}$*	$0.95^{D,S}$	1.00	$0.98^{(D)}$	0.96
Great Dane (2)	**			$0.86^{(D)}$	
Rottweiler (3)		$0.90^{D,S}$			
Dachshund (D)	$1.10^{(1-6,L,S)}$	$1.02^{(3,L)}$	1.04	$1.06^{(2,L)}$	0.97
Small breeds (S)	$1.01^{(D)}$	$1.00^{(3,L)}$	1.04	1.01	0.94
VFHcd/cr-ratio					
Large breeds (L)	$1.18^{(D,S)}$	$1.18^{(D,S)}$	$1.20^{(D,S)}$	$1.19^{(D,S)}$	$1.19^{(D,S)}$
Doberman P. (1)		$1.22^{(2,D,S)}$	$1.22^{(D,S)}$	$1.31^{(2-6,D,S)}$	$1.34^{(5,6,D,S)}$
Great Dane (2)	$1.26^{(D,S)}$	$1.37^{(1,3-6,D,S)}$	$1.26^{(D,S)}$	$1.16^{(1)}$	$1.29^{(6,D,S)}$
Rottweiler (3)	$1.17^{(D,S)}$	$1.21^{(2,D,S)}$	$1.24^{(D,S)}$	$1.28^{(1,4-6,D,S)}$	$1.22^{(6,D,S)}$
BMD (4)	$1.17^{(D,S)}$	$1.18^{(2)}$		$1.10^{(1,3)}$	$1.22^{(D,S)}$
GSD (5)	$1.20^{(D,S)}$	$1.15^{(2)}$	$1.20^{(D)}$	$1.18^{(1,3,D,S)}$	$1.17^{(1,D,S)}$
Rough Collie (6)		$1.17^{(2)}$		$1.11^{(1,3)}$	$1.04^{(1-3)}$
Dachshund (D)	$1.01^{(2-5,L)}$	$1.08^{(1-3,L)}$	$1.10^{(1-3,5,L)}$	$1.07^{(1,3,5,L)}$	$1.02^{(1-5,L)}$
Small breeds (S)	$0.99^{(2-5,L)}$	$1.08^{(1-3,L)}$	$1.13^{(1-3,L)}$	$1.07^{(1,3,5,L)}$	$1.01^{(1-5,L)}$

*Symbols in parentheses indicate significant different values ($P < 0.05$). Large breeds (L) are coded as follows: Doberman Pinscher (1), Great Dane (2), Rottweiler (3), BMD (4), GSD (5), R. Collie (6). Small breeds are coded as (S) and Dachshunds as (D). **Individual breed ratios, which were not significantly different from values of the large breeds group, are not listed.

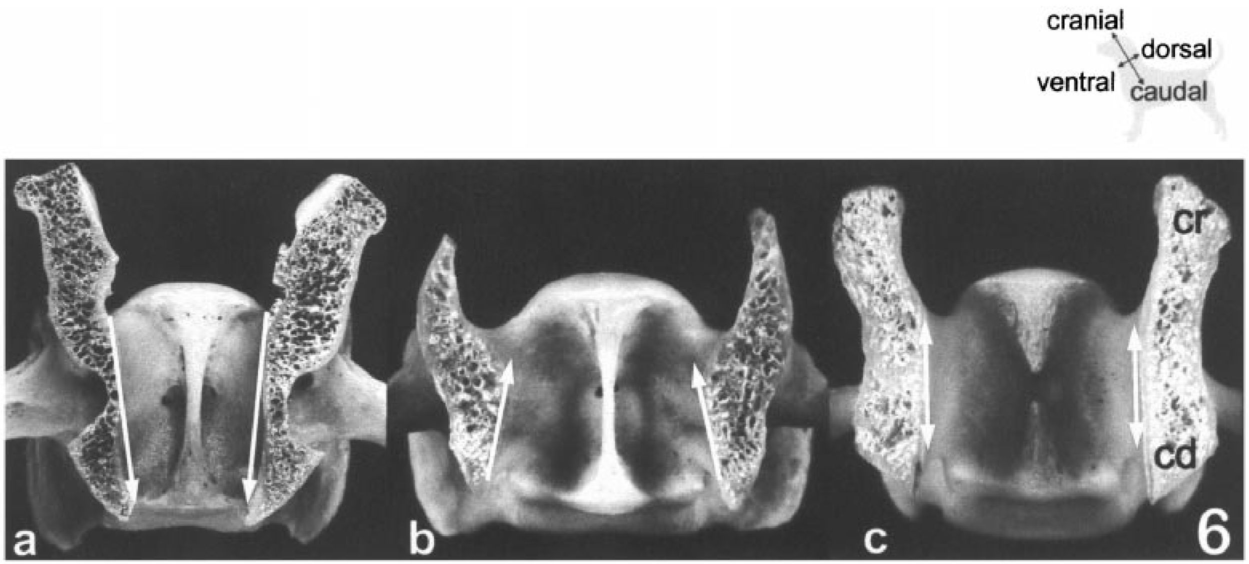

Fig. 6. Anatomical specimens of C6 in a dorsal view after removing the vertebral lamina indicating the caudally narrowed vertebral foramen in an 8-y-old female Great Dane (*a*), the cranially narrowed vertebral foramen in a 5-y-old male Dachshund (*b*), and the parallel position of the vertebral pedicles in a 6-y-old female Yorkshire Terrier (*c*). Note the disproportions of the vertebral foramen width between *a*, *b* and *c*. cr, cranial; cd, caudal.

in Dachshunds, large and small dogs are shown in Figures 6 and 7.

The earliest indication of dorsomedian fusion of both ossification centres of the vertebral arch was evident by 4 wk and complete by 8 wk of age. The onset of fusion of the vertebral arch with the vertebral body from C3 to C6 was noted by 10 wk and at C7 by 16 wk. This process was complete by 16–18 wk (C3–C6) and 18 wk of age (C7) respectively. Delay of the ossification process was noted to progress down the cervical spine (C3–C7). The best possible relationship between age and the variables VFH and VFW is illustrated by a quadratic model after logarithmic transformation of age is shown in Figure 8. This figure is also representative for findings in other vertebrae. Depending on the vertebra, R^2 varied between 0.71 and 0.89 ($P < 0.001$). The age period at which VF diameters of juvenile specimens correspond to the lowest values observed in adult specimens was of special interest. This age period is expressed by the mean age and the upper and lower limits of the 95% CI of the mean. From C2cd up to T1cr this period on

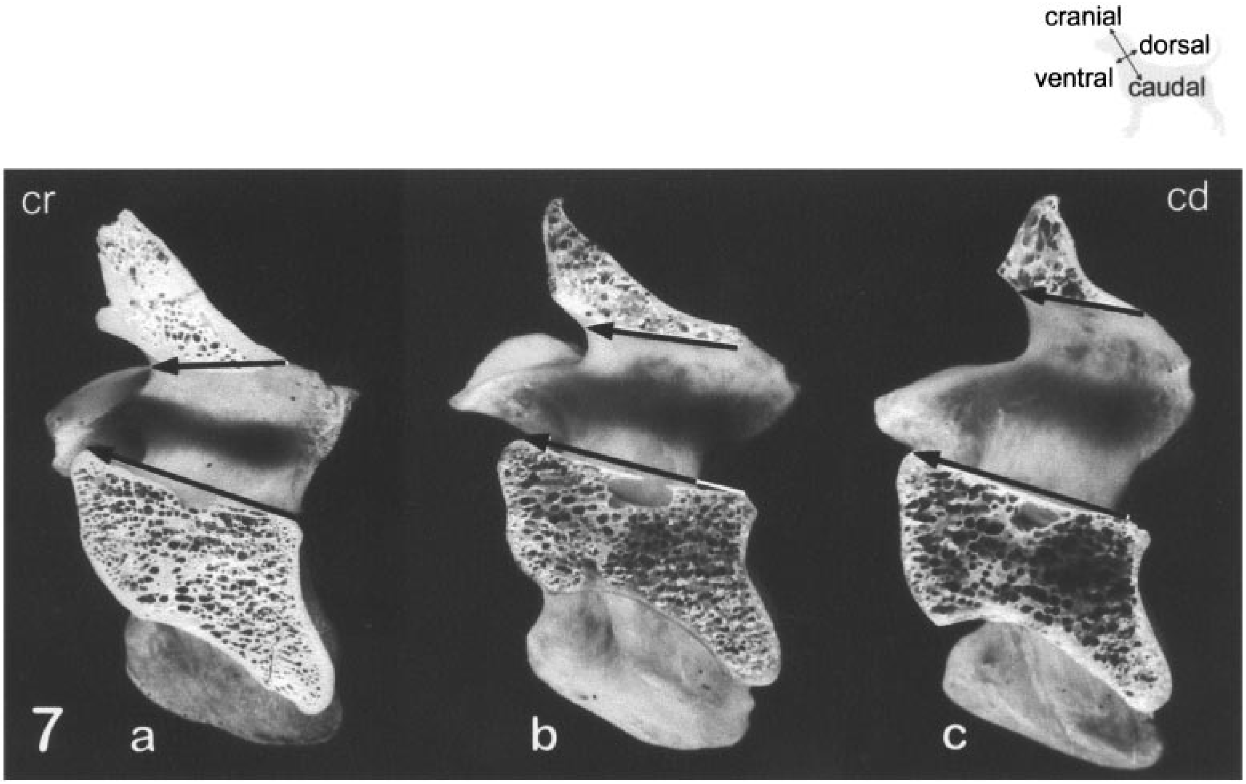

Fig. 7. Midsagittal sections of anatomical specimens of C6 in a lateral view indicating cranial narrowing of the vertebral foramina. Distinct narrowing is evident in the 1-y-old female Doberman Pinscher (*a*), slight cranial narrowing is present in the 4-y-old male Dachshund (*b*), and the 10-y-old male Yorkshire Terrier (*c*). Note also the disproportions between vertebral body length and vertebral lamina length in the 3 specimens. cr, cranial; cd, caudal.

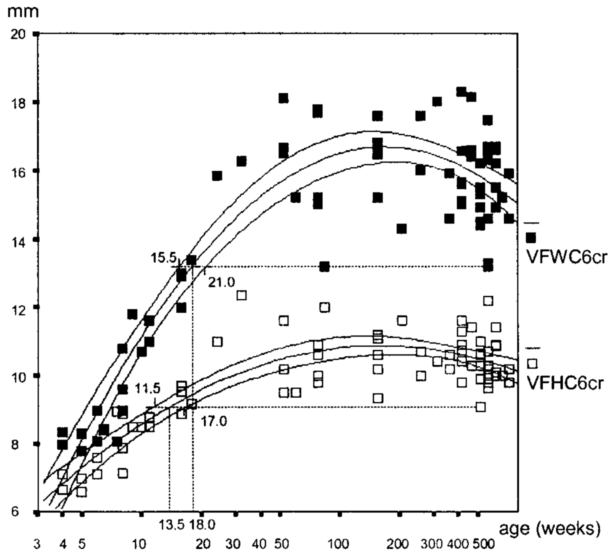

Fig. 8. Association between age and vertebral foramen height (VFH), and between age and vertebral foramen width (VFW) in a sample of Rottweilers and GSDs. Curves indicate the mean and the upper and lower limits of the 95% CI of the mean. (VFH: $y = -1.5754x^2 + 6.9515x + 3.2089$, $R^2 = 0.72$; $P < 0.001$; VFW: $y = -3.6487x^2 + 16.28x - 1.4867$, $R^2 = 0.84$, $P < 0.001$).

average ranged between 10 and 26 wk of age (mean 16 wk) (VFHcr: 11.5–17.0, mean 13.5; VFHcd: 14.2–21.9, mean 17.5; VFWcr: 17.6–25.4, mean 20.7; VFWcd: 10.5–15.4, mean 12.7).

DISCUSSION

For the interpretation of the present findings the differentiation between absolute and relative stenosis is important. According to Bailey & Morgan (1992), absolute stenosis indicates a vertebral canal diameter that is sufficiently narrow to result in direct neural compression. Relative stenosis implies a diameter that is less than 'normal' but asymptomatic, although it carries a risk of becoming symptomatic on the development of space-occupying conditions of the vertebral canal (Bailey & Morgan, 1992) resulting in increased susceptibility of the spinal cord to undergoing compression (Lincoln, 1992).

The present results indicate that, relative to body size, the midsagittal as well as interpedicular diameters of the vertebral canal from C2cd up to C7cd were largest in small breeds and smallest in large breeds ($P < 0.05$). The high disproportion between interpedicular diameter and vertebral body width in large relative to small breeds suggests an association between interpedicular and pedicular diameters. Increase of the pedicular diameters which becomes necessary in large breeds to increase loading capacity apparently results in reduction of both the interpedicular and midsagittal diameters. Böhme (1992) determined the mean spinal cord length and weight to be 78 cm/33 g in GSDs and 48 cm/14 g in Dachshunds. Therefore the ratio of the spinal cord weight per unit length in GSDs relative to Dachshunds may be estimated as 1.45 to 1. Taking into account that the weight of the spinal cord per unit length is proportional to the cross-sectional area, and assuming that GSD values are representative of other large breeds, functionally this suggests a greater discrepancy between cross-sectional areas of the spinal cord and cervical vertebral foramen diameters in large breeds. The present results suggest that this osteological feature in general increases the risk of cervical spinal cord compression in large breeds and decreases the risk in small breeds and chondrodystrophic Dachshunds, confirming the clinical experience of Lincoln & Pettit (1985). In their opinion decompressive laminectomy in chondrodystrophic dogs affected with intervertebral disc disease is rarely necessary because of the relative large size of the cervical vertebral canal. In contrast, Bailey & Morgan (1992) suggest that relative stenosis in chondrodystrophic dogs may be part of the reason that clinical disc protrusion is more common in these than in nonchondrodystrophic dogs.

The risk that space-occupying conditions causing dorsoventral narrowing (e.g. disc protrusion) of the vertebral canal becomes clinically significant primarily depends on the sagittal vertebral foramen diameters. In Dachshunds and small breeds this diameter increased from cranial to caudal, being maximum on average at C6cd, and thus is inversely related to earlier reported incidences of disc space involvement in these breeds (Dallman et al. 1992; Jurina, 1996). Although the midsagittal vertebral foramen diameters also increased from cranial to caudal in large breeds, spinal cord compression is reported to occur most commonly between C5 and C7 (Wright et al. 1973; Trotter et al. 1976; Mason, 1977, 1979; Raffe & Knecht, 1980; Rendano & Smith, 1981; Jaggy & Lang, 1986; VanGundy, 1988; Jurina, 1996). The present anatomical results suggest that the following causative agents play a major role for this clinical finding.

1. Considerably ($P < 0.05$) lower vertebral body length to vertebral arch length ratios in large dogs indicate that the cervical vertebral canal dorsally is bordered by a higher amount of bone reducing decompression potential.
2. The cervical enlargement of the spinal cord formed by the sixth cervical up to the first thoracic spinal cord segment extends from the middle of the vertebral body of C5–C7cd with a maximum at C6 (Goller, 1959; Fletcher & Kitchell, 1966; De Lahunta, 1977; Böhme, 1992). Thus lesions at C5–C7 may be more significant. The expected larger cross-sectional area of the spinal cord may also exacerbate compression.
3. Although the mean midsagittal vertebral foramen diameter was maximal at C6cd in large breeds, Table 2 indicates that the maximum diameter in several breeds (Doberman Pinschers, Great Danes, Rottweilers) was located more caudally at C7cd. This is in accordance with the findings of Lincoln (1992), who noted the C7 vertebral foramina in lateral radiographs to be larger than those at C6.
4. Although all midsagittal vertebral foramen diameters were smaller in large breeds, statistical analysis identified the cranial vertebral foramen heights of caudal cervical vertebrae (C5–C7) to be those variables allowing the best possible discrimination between breeds. However, differences also were noticed within the group of large breeds. From C6cr to T1cr the vertebral foramen height on average was smallest in specimens of Great Danes: relative to Rottweilers the difference was statistically significant ($P < 0.05$). This might explain why Great Danes are among those breeds most commonly affected by clinically symptomatic cervical spinal cord compression (Trotter et al. 1976; Mason, 1977, 1979; Raffe & Knecht, 1980; Lewis, 1992).
5. Unlike in Dachshunds and small breeds, the caudal to cranial vertebral foramen height ratios from C3 to C7 were higher ($P < 0.05$) in large breeds, indicating dorsoventral narrowing of the cranial limit of the vertebral foramina. Accordingly, the high degree of cranial narrowing diminishes the functional importance of the true dimension of the caudal vertebral foramen diameter predisposing to spinal cord compression. Dorsoventral flattening of the cranial limit of the vertebral foramen is reported to be the most common clinically symptomatic cervical vertebral malformation (Wright et al. 1973; Trotter et al. 1976; Mason, 1977, 1979; Raffe & Knecht, 1980; Betts, 1982; Seim & Withrow, 1982; Lincoln & Pettit, 1985; VanGundy, 1989; Lewis, 1992; Sharp et al. 1992; Massicotte et al. 1999). In a lateral radiograph, the vertebral foramen then appears funnel-shaped (Trotter et al. 1976; Massicotte et al. 1999). This feature may be noticed from C4 to C7 but is usually present at C6 and C7 (Wright et al. 1973; Trotter et al. 1976; Mason, 1977, 1979; Raffe & Knecht, 1980; Rendano & Smith, 1981). However, in accordance with the findings of Lewis (1991), cranial stenosis of the vertebral foramen occurs to some extent in all large dogs. Strikingly high ratios were found in Great Danes (exacerbated by the smallest vertebral foramen heights), Rottweilers (favoured by the largest vertebral

foramen heights within large breeds), and Doberman Pinschers (characterised by the highest caudal to cranial vertebral foramen height ratios at C6 and C7). The extreme funnel-shape of these vertebral foramina in Doberman Pinschers is supposed to be a high risk factor for spinal cord compression and might explain why, in addition to Great Danes, Doberman Pinschers are also among the high risk breeds affected by cervical spinal cord compression (Trotter et al. 1976; Mason, 1977, 1979; Raffe & Knecht, 1980; Lewis, 1992).

In all breeds the caudal to cranial vertebral foramen height ratios increased from cranial to caudal. They were maximal at C5, indicating caudal enlargement of the vertebral foramen because of the presence of the cervical enlargement of the spinal cord, and then decreased. These results disagree with the findings of Lewis (1991), who noted that the difference between the cranial and caudal sagittal vertebral foramen diameters steadily increased down the cervical spine. Unlike in large dogs, cylindrical vertebral foramina, due to similar midsagittal diameters at the cranial and caudal limits, were typical in small breeds and Dachshunds.

The interpedicular diameters also were observed to increase from cranial to caudal cervical vertebrae. Like the maximal midsagittal diameter, the maximal interpedicular diameter was at C6cd in Dachshunds and small breeds, and at C7cd in large breeds. Large dogs, which had the smallest ($P < 0.05$) mean interpedicular values in our sample, also tended to have lower caudal to cranial vertebral foramen width ratios, indicating vertebral foramina which were slightly bilaterally narrowed caudally. In contrast, the inverse shape predominated in small breeds and Dachshunds. Considering that the C6 and C7 spinal nerve roots are the only cervical nerve roots which have to pass a remarkable distance to reach their respective intervertebral foramen (Fletcher & Kitchell, 1966), small interpedicular diameters caudally at C6 and C7 are suspected to be of major functional importance and thus to be risk factors in large dogs. Especially in cases of articular facet overgrowth with encroachment upon the lumen of the vertebral canal, the additional reduction of the interpedicular diameters of the vertebral foramina may result in pronounced nerve root and dorsolateral (Sharp et al. 1992) or lateral compression of the spinal cord (Wright et al. 1973; Trotter et al. 1976; Rendano & Smith, 1981; Seim & Withrow, 1982; VanGundy, 1989; Lewis, 1991; Lincoln, 1992; Massicotte et al. 1999). Previously this was seen most commonly at C5/6 and C6/7 (Sharp et al. 1992; Massicotte et al. 1999) in Great Danes but also in other large breeds (Wright et al. 1973; Lewis, 1992; Sharp et al. 1992).

Predisposition to spinal cord compression not only depends on the diameters of the vertebral foramina, but also on the shape of the cross-sectional area of the spinal cord. According to Fletcher (1993), the spinal cord is a dorsoventrally flattened oval-shape at C2 (spinal segment C3, width to height = 1.36 to 1) and more circular at T1 (spinal segment T2, width to height = 1.29 to 1). From C3 to C7 this change in shape is directly related to the change in shape of the caudal limits of the vertebral foramina in small breeds and inversely related in large breeds (Fig. 3). Relative to the cranial limit of the vertebral foramina, the caudal limit on average was more circular in all groups of breeds. With the exception of Rottweilers, the cranial limit of the vertebral foramen was significantly ($P < 0.05$) more flattened dorsoventrally in large than in small breeds. High agreement between the width to height ratio of the spinal cord (Fletcher, 1993) and the cranial vertebral foramen width to height ratios evaluated in the present study was evident in small breeds, while low agreement was seen in large breeds—especially in Great Danes and also partly in Doberman Pinschers. The degree of change in shape within one vertebra was highest in large breeds (Fig. 3). Generally, the cervical vertebral canal is formed by the union of cranially dorsoventrally and caudally bilaterally narrowed cones in large breeds, by rather circular tubes in small breeds, and by dorsoventrally flattened tubes in Dachshunds.

Vertebral malformations resulting in stenotic vertebral foramina have been attributed to genetic, nutritional, and biomechanical factors (Wright et al. 1973; Mason, 1977; Jaggy & Lang, 1986; Jaggy et al. 1988; VanGundy, 1988; Lewis, 1991, 1992) affecting maturation of the juvenile spine during the early formative months of life (Lewis, 1991, 1992). The earliest radiological observation of stenotic vertebral abnormalities has been made in puppies over 3 mo of age (Trotter et al. 1976; Burbidge et al. 1994). Lincoln (1992) suspected that shortening of the vertebral pedicles occurs during growth of clinically affected dogs. According to Burbidge et al. (1995), bony fusion of the lamina (C5–C7) is complete by 4 wk, while the present results show it is complete by 8 wk of age, and that fusion of the vertebral arch with the vertebral body is complete by 18 wk. Thus this period of life is highly susceptible for factors causing abnormal growth of the pedicles. Later on, the shape of the vertebral arch can only be influenced by remodelling of bone formed by intramembranous ossification (Burbidge et al. 1995). Excessive appositional bone growth and depressed bone remodelling are considered to be the cause of stenotic vertebral foramina (VanGundy, 1989) in the older dog. Burbidge et al. (1994) suspected that vertebral deformity occurs between 6 and 12 wk of age. The smallest vertebral foramen diameters in adult dogs in the current study were comparable to those expected in puppies aged on average 16 wk. This age also corresponds with the period of maximum body weight gain in large dogs, which in Great Danes occurs between 13.0 and 14.3 wk of age (Schulze et al. 1997).

Clinical signs in dogs affected with stenosis of the cervical vertebral canal are insidious in onset (Lewis, 1992) and marked neurological signs are often present only in older dogs (Burbidge et al. 1994). This is probably indicative of the progressive degeneration of the cervical spinal cord which results from the continued or increased compression of the cord by the vertebral column deformity (Jaggy & Lang, 1986; VanGundy, 1988; Burbidge et al. 1994). The presence of relative stenosis of cervical vertebral foramina stated in various breeds and spinal sites may be clinically unsuspected, but may also exacerbate any further space-occupying condition.

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