Original Article

Population reference range for developmental lumbar spinal canal size

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Background: Considerable variability exists in normal developmental lumbar spinal canal size. This impacts the likelihood of neural compromise. Spinal canal development is complete by 17 years. As diseases incurred thereafter do not knowingly affect the developmental size of the spinal canal, it is reasonable to use a selected population undergoing abdominopelvic computed tomography (CT) examination to determine developmental lumbar spinal canal size.

Methods: Study approval was granted by the Clinical Research Ethics Committee. Between Feb 2014 and Jan 2015, mid-vertebral spinal canal cross-sectional area (CSA), depth, width, and vertebral body CSA at each level from L1–L5 was measured, using a semi-automated computerized method in 1,080 ambulatory patients (540 males, 540 females, mean age, 50.5±17 years). Patient height and weight was measured.

Results: A reference range for developmental lumbar spinal canal dimensions was developed at each lumbar level for each sex. There was a 34% variation in spinal canal CSA between smallest and largest quartiles. Developmental spinal canal CSA and depth were consistently smallest at L3, enlarging cranially and caudally. Taller people had slightly larger lumbar spinal canals ($P<0.0001$). Males had larger spinal canal CSAs than females though relative to vertebral body CSA, spinal canal CSA was larger in females. There was no change in spinal canal CSA with age, weight or BMI ($P<0.05$).

Conclusions: A population reference range for developmental lumbar spinal canal size was developed. This allows one to objectively determine the degree of developmental spinal canal stenosis present on an individual patient basis.

Keywords: Lumbar spine; spinal canal; developmental stenosis; computed tomography (CT); population; reference range

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Introduction

Spinal canal stenosis is the most common indication for lumbar surgery in patients older than 65 years (1). Factors governing spinal stenosis are the pre-existing developmental size of the spinal canal and the degree of acquired spinal canal narrowing (mainly from degenerative disease). Developmental size of the spinal canal is measured at the mid-pedicular level removed from any acquired narrowing that occurs at the discovertebral level (2). Anteroposterior spinal canal development is fully complete by 5 years of age while transverse spinal canal diameter increases until 15–17 years (3,4). Pre-natal (gestational age, placenta size, nutrition, birth weight) and maternal (age, parity, socioeconomic class, smoking) factors may all potentially influence spinal canal development (5-7). Once spinal canal development is complete by 17 years, further growth of the

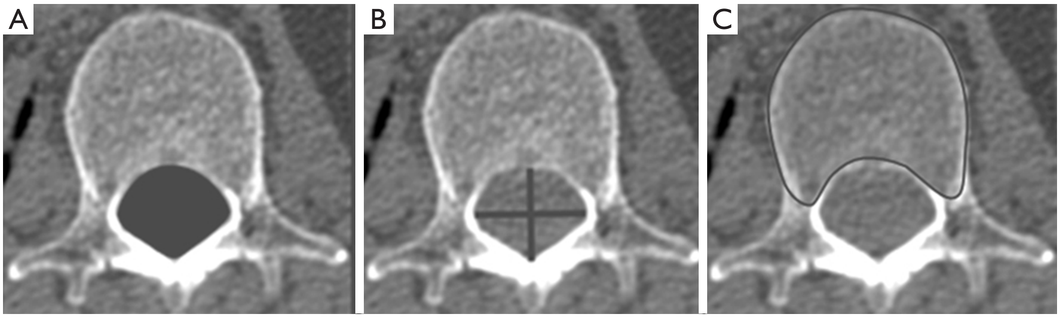

Figure 1 Reformatted axial CT image at mid-pedicular level showing measurement of (A) spinal canal crosssectional area, (B) spinal canal depth and width and (C) vertebral body cross-sectional area. CT, computed tomography.

spinal canal will not occur. Other than uncommon spinal diseases, such as dural ectasia, intraspinal tumours or intradural cysts, no other disease or metabolic condition knowingly affects developmental size of the lumbar spinal canal (2).

Considerable variation in the developmental size of the normal lumbar spinal canal exists within and between populations such that each population needs to develop its own reference range (2). Little large scale population data on normal spinal canal dimensions exists, particularly with regard to cross-sectional area (CSA). The purpose of this study was to develop a population range for developmental lumbar spinal canal dimensions using a template that can be readily applied to all other populations. This was undertaken by measuring the spinal canal dimensions in patients undergoing abdominopelvic computed tomography (CT) examination. Although these patients were clearly not healthy at the time of the examination, it is nevertheless valid to use this population to determine developmental spinal canal size as spinal canal development is complete by adulthood and systemic diseases incurred thereafter do not knowingly affect spinal canal dimension at the mid-pedicular level.

Methods

Patients

Study was approved by the Clinical Research Ethics Committee of our institution (CRE-2013.058). Lumbar spinal canal dimensions were prospectively measured on ambulatory patients undergoing abdominopelvic CT examinations between Feb 2014 and Jan 2015. Over 99% of the patient population was ethnically Chinese. Patients with non-Chinese names were not included as were patients with (I) skeletal orders such as dwarfism or scoliosis; (II) prior lumbar surgery; and (III) childhood chronic inflammatory condition; (IV) major lumbar morphological abnormality such as vertebral fracture or dysraphism.

The height (centimeters) and weight (kg) of all patients was recorded prior to CT examination. One thousand and eighty patients aged between 21 and 80 years were studied, comprising 540 males (mean 50.53±16.98 years) and 540 females (mean 50.65±17.02 years). Patients were selected to yield 90 patients from each sex in each 10-year age group (20–29, 30–39 years etc.). Subgroup recruitment stopped once the required 90 patients were recruited.

CT examination and image analysis

CT examinations were performed on a 64-slice multidetector CT machine (LightSpeed VCT, GE Healthcare, Buckinghamshire, UK) with a reconstructive resolution of 0.6 mm. Spinal canal and vertebral body measurements were made on volumetric CT data reconstructed on bone windows in an axial plane though the mid-pedicles for each vertebral body from L1 to L5 inclusive (5,400 levels assessed). All analysis was performed by one operator. First, the volumetric image dataset for each lumbar vertebral level was adjusted to yield an image at right angles to the vertebral body. The mid-pedicle axial image was then automatically determined orthogonal to the mid-sagittal plane of the vertebral body.

Spinal canal CSA

Following rigid co-registration, a seed-growing image segmentation program was used to measure osseous spinal canal CSA. Thereafter, manual modification was performed to ensure correct demarcation of the spinal canal boundary (*Figure 1*).

Spinal canal depth and width

Spinal canal depth was measured from the posterior margin of the vertebral body to the cortex of the neural arch at the base of the spinous process (*Figure 1*). Spinal canal width was measured from the inner margin of one pedicle to the inner margin of the contralateral pedicle (*Figure 1*).

Vertebral body CSA

Vertebral body CSA was measured using a semi-automatic approach. A threshold technique defined vertebral body CSA based on attenuation differences between the vertebral body and the surrounding soft tissues followed by manual modification of this CSA and demarcation of the pedicle base (8) (*Figure 1*).

Spinal canal CSA/vertebral body CSA

Spinal canal CSA/vertebral body CSA ratio was determined to assess how consistently one was related to the other.

Thresholds demarcating the smallest 25% of the population

Histograms were drawn separately for each measure and sex to ensure a normal distribution. A cut-off point demarcating the smallest 25% (quartile) of the population was arbitrarily used as an indicator of a developmentally small spinal canal CSA, depth or width.

Comparison of smallest and largest quartiles

To gauge variation within the population, the 2 patient quartiles (25%) with the largest and smallest spinal canal dimension at each level from L1 to L5 for both males and females were selected and compared. These subgroups were matched for patient height.

Reliability and concordance for computerized and manual measurements

For computerized measurements, one reader selected the appropriate image and measured spinal canal CSA, depth and width at five levels (L1–L5) on 20 randomly selected subjects (100 axial levels) on two separate occasions 1 week apart blinded to previous results. Another reader independently selected and manually measured the same parameters at five levels (L1–L5) on the same 20 subjects. Results of the second computerized readings were compared to the manual readings.

Statistical analysis

Statistical analyses were performed using SPSS version 22.0 (SPSS Inc., Chicago, Illinois, US). Intraclass correlation was used to test reliability and independent 2-samples *t*-test for gender and inter-quartile differences. Pearson correlation was used to determine associations between spinal canal dimensions and age, height, weight and BMI. A P value <0.05 was considered statistically significant.

Results

Gender and age-related differences

Males were taller (168.1±6.8 *vs.* 157.0±5.9 cm, P<0.0001), heavier (66.9±12.8 *vs.* 55.5±10.6 kg, P<0.0001) and had a higher BMI (23.7±4.1 *vs.* 22.5±4.0, P<0.0001) than females. With increasing age, both sexes had a slight reduction in mean height, males had a slight decrease in mean weight, while females had a slight increase in BMI (*Table 1*).

Spinal canal CSA

Developmental spinal canal CSA was smallest at L3 for both sexes increasing in size both cranially and caudally (*Table 2*). Average spinal canal CSA at L3 was about 9% smaller than at L1 and about 23% smaller than at L5 (*Table 2*).

The spinal canal CSA was larger in males at all levels, other than L2 (*Table 2*). However, after adjustment for height and weight, spinal canal CSA was larger in females at L1, L2 and L3 and in males at L5 (*Table S1*).

For each gender, there was no detectable change in spinal canal CSA with age (*Table 1*). There was a weak but highly significant positive correlation between increasing height and increasing overall lumbar spine CSA (*Table 1*). For females only, there was a very slight increase in spinal CSA with increasing weight (*Table 1*).

Spinal canal depth

Developmental spinal canal depth was also smallest at L3, increasing cranially and caudally (*Table 3*). After height and weight adjustment, spinal canal depth was larger in females at L1, L2 and L3 and in males at L5 (*Table S2*). Overall, spinal change depth did not change with increasing age

Table 1 Correlation between clinical and spinal measurements

Variable	Age	Height	Weight	BMI	SC CSA L1–L5	Spinal canal depth L1–L5	Spinal canal width L1–L5	VB CSA L1–L5
Male								
Height	−0.355 (<0.001)							
Weight	−0.095 (0.027)	0.416 (<0.001)						
BMI	0.048 (0.268)	<0.001 (1.000)	0.905 (<0.001)					
Spinal canal CSA L1–L5	0.071 (0.101)	0.186 (<0.001)	0.071 (0.098)	−0.012 (0.781)				
Spinal canal depth L1–L5	0.008 (0.860)	0.163 (<0.001)	0.045 (0.302)	−0.032 (0.459)	0.871 (<0.001)			
Spinal canal width L1–L5	0.281 (<0.001)	0.126 (0.003)	0.005 (0.912)	−0.061 (0.154)	0.769 (<0.001)	0.610 (<0.001)		
Vertebral body CSA L1–L5	0.165 (<0.001)	0.331 (<0.001)	0.255 (<0.001)	0.118 (0.006)	0.293 (<0.001)	0.287 (<0.001)	0.439 (<0.001)	
SC CSA/VB CSA L1–L5	−0.031 (0.474)	−0.043 (0.321)	−0.108 (0.012)	−0.098 (0.022)	0.761 (<0.001)	0.644 (<0.001)	0.450 (<0.001)	−0.376 (<0.001)
Female								
Height	−0.370 (<0.001)							
Weight	0.079 (0.065)	0.347 (<0.001)						
BMI	0.243 (<0.001)	−0.048 (0.261)	0.917 (<0.001)					
Spinal canal CSA L1–L5	−0.040 (0.349)	0.298 (<0.001)	0.092 (0.033)	−0.033 (0.444)				
Spinal canal depth L1–L5	−0.102 (0.018)	0.255 (<0.001)	0.044 (0.313)	−0.066 (0.128)	0.865 (<0.001)			
Spinal canal width L1–L5	0.267 (<0.001)	0.143 (<0.001)	0.102 (0.018)	0.045 (0.294)	0.761 (<0.001)	0.553 (<0.001)		
Vertebral body CSA L1–L5	0.294 (<0.001)	0.264 (<0.001)	0.269 (<0.001)	0.177 (<0.001)	0.250 (<0.001)	0.196 (<0.001)	0.372 (<0.001)	
SC CSA/VB CSA L1–L5	−0.249 (<0.001)	0.047 (0.275)	−0.138 (0.001)	−0.174 (<0.001)	0.692 (<0.001)	0.625 (<0.001)	0.397 (<0.001)	−0.507 (<0.001)

Pearson correlation coefficient between different clinical and spinal measurements. All statistically significant correlations are bolded. SC, spinal canal; VB, vertebral body; CSA, cross-sectional area.

Table 2 Mean spinal canal CSA for males and females

Variable	Mean (SD)		P value
	Males (N=540)	Females (N=540)	
L1	273.7 (49.0)	264.8 (42.5)	0.002
L2	256.3 (52.1)	252.7 (42.6)	0.212
L3	247.8 (53.3)	241.8 (43.6)	0.043
L4	276.3 (64.4)	258.1 (55.1)	<0.0001
L5	338.3 (82.6)	296.9 (72.4)	<0.0001
L1–L5	278.5 (50.3)	262.8 (42.5)	<0.0001

Mean spinal canal CSA for both sexes at each level from L1 to L5 and overall for L1–L5. All statistically significant differences are bolded. SD, standard deviation; CSA, cross-sectional area.

Table 4 Spinal canal width in males and females

Variable	Mean (SD)		P value
	Males (N=540)	Females (N=540)	
L1	20.87 (2.50)	19.83 (2.16)	<0.0001
L2	21.19 (2.62)	20.13 (2.28)	<0.0001
L3	22.13 (2.70)	20.96 (2.35)	<0.0001
L4	24.55 (3.24)	22.95 (2.90)	<0.0001
L5	29.55 (4.25)	27.41 (3.69)	<0.0001
L1–L5	23.66 (2.59)	22.26 (2.25)	<0.0001

Spinal canal width. Mean transverse diameter (width) of the spinal canal in males and females at each level from L1 to L5 and overall for L1–L5. All statistically significant differences are bolded. SD, standard deviation; CSA, cross-sectional area.

Table 3 Spinal canal depth in males and females

Variable	Mean (SD)		P value
	Males (N=540)	Females (N=540)	
L1	15.46 (2.13)	15.58 (2.02)	0.363
L2	14.58 (2.36)	14.87 (1.97)	0.033
L3	14.04 (2.45)	14.18 (2.08)	0.300
L4	15.34 (2.99)	15.03 (2.75)	0.077
L5	19.67 (3.76)	18.12 (3.28)	<0.0001
L1–L5	15.82 (1.96)	15.55 (1.72)	0.019

Spinal canal depth. Mean anteroposterior diameter (depth) of the spinal canal in males and females at each level from L1 to L5 and overall for L1–L5. All statistically significant differences are bolded. SD, standard deviation; CSA, cross-sectional area.

Table 5 Vertebral body CSA for males and females

Variable	Mean (SD)		P value
	Males (N=540)	Females (N=540)	
L1	1,201.0 (172.3)	961.7 (138.1)	<0.0001
L2	1,273.4 (179.3)	1,030.0 (145.0)	<0.0001
L3	1,399.3 (194.5)	1,144.6 (159.5)	<0.0001
L4	1,511.5 (206.7)	1,251.9 (173.9)	<0.0001
L5	1,711.4 (240.9)	1,426.5 (206.4)	<0.0001
L1–L5	1,419.3 (185.5)	1,162.9 (153.7)	<0.0001

Vertebral body CSA. Mean vertebral body CSA in males and females at each level from L1 to L5 and overall for L1–L5. All statistically significant differences are bolded. SD, standard deviation; CSA, cross-sectional area.

in males (*Table 1*) though did reduce slightly in females (*Table 1*). There was a weak but highly significant positive correlation between increasing height and increasing overall lumbar spine depth for both sexes (*Table 1*).

Spinal canal width

As opposed to spinal canal CSA and depth, which were smallest at L3, developmental spinal canal width gradually increased from L1 to L5 (*Table 4*). Spinal canal width was larger in males at all levels (*Table 4*), even after adjustment for height and weight (*Table S3*).

Thresholds demarcating the smallest 25% of the population for developmental spinal canal CSA, depth or width

The values demarcating the smallest 25% of the population for developmental spinal canal CSA, depth or width for each level and gender are shown in *Figures S1-S3*.

Vertebral body CSA

Vertebral body CSA was significantly larger in males at all levels (*Table 5*). This difference remained true even after adjustment for height and weight (*Tables S4,S5*). Vertebral

Table 6 Spinal canal CSA/vertebral body CSA ratio

Variable	Mean (SD)		P value
	Males (N=540)	Females (N=540)	
L1	0.23 (0.05)	0.28 (0.06)	<0.0001
L2	0.20 (0.05)	0.25 (0.05)	<0.0001
L3	0.18 (0.04)	0.21 (0.05)	<0.0001
L4	0.18 (0.04)	0.21 (0.05)	<0.0001
L5	0.20 (0.05)	0.21 (0.05)	0.0002
L1–L5	0.20 (0.04)	0.23 (0.04)	<0.0001

Spinal canal CSA/vertebral body CSA ratio. Mean spinal canal CSA/vertebral body CSA ratio in males and females at each level from L1 to L5 and overall for L1–L5. All statistically significant differences are bolded. SD, standard deviation; CSA, cross-sectional area.

body CSA increased with age in both sexes with the rate of increase being almost twice as great in females (*Table 1*). For both sexes, there was a weak but highly significant positive correlation between increasing vertebral body CSA and increasing height, weight and BMI (*Table 1*).

Spinal canal CSA/vertebral body CSA

Developmental spinal canal CSA was approximately one-fifth that of vertebral body CSA (*Table 6*). Although spinal canal CSA (*Table 2*) and vertebral body CSA (*Table 5*) were both larger in males, the spinal canal CSA/vertebral body CSA ratio was consistently larger in females (*Table 6*) indicating that, relative to the CSA of the vertebral body, the CSA of the spinal canal is actually larger in females than males, even after adjusted for height and weight (*Table S6*).

The spinal canal CSA/vertebral body CSA ratio decreased with age only in females as female vertebral body CSA tended to increase more with age than males (*Table 1*). The spinal canal CSA/vertebral body CSA ratio did decrease slightly with increasing weight and BMI (*Table 1*).

Comparison of smallest and largest quartiles

Patients in the smallest quartile had a spinal canal CSA about 34% smaller than those in the largest quartile (*Table 7*). This variation was ~24% for spinal canal depth, and ~22% for spinal canal width (*Table 7*), after adjustment for height and weight (P<0.0001).

Reliability and concordance for computerized and manual measurements

Intra-operator reliability of computerized measurements was 0.85, 0.87, 0.91, 0.85, and 0.96 respectively for each level from L1–L5. Reliability between computerized and manual readings was 0.80, 0.89, 0.88, 0.83 and 0.95 respectively.

Discussion

Symptomatic lumbar spinal canal stenosis is a function of both the developmental size of the spinal canal (i.e., how large the spinal canal is to begin with) and the degree of superimposed (i.e., acquired) bony and soft tissue spinal canal encroachment, usually from degenerative disease. Developmental size of the spinal canal has considerable bearing on the likelihood of nerve root compression (9), spinal canal stenosis (9), or the need for decompressive surgery (10). The larger the developmental size of the spinal canal, the lower the risk of neurological compromise (2).

Geographic, racial and gender differences in developmental size of the spinal canal do exist such that each region, race and gender should have its own reference range (2). Such normative reference data will become routine with the automated availability of quantitative spinal canal size data during routine MR spine examination (11-14). This study utilized abdominopelvic CT data to establish a population reference range for developmental lumbar spinal canal size. This provides a good template for comparative studies from other populations given that over 100 million abdominopelvic CTs are performed yearly around the world (15). This is by far the largest study of developmental spinal canal size undertaken to date.

This study confirms previous findings that nearly all developmental spinal canal dimensions are smaller in females (16-19). Spinal canal CSA and depth were consistently smallest at L3 from where they enlarged cranially and caudally. Spinal canal width gradually increased from L1 to L5. Spinal canal depth rather than width is the primary contributor to developmental CSA (3,20).

Considerable variation in developmental spinal canal dimensions that exist within a single population with a 34% difference in spinal canal CSA and a 24% difference in depth between the largest and smallest quartiles. No accepted definition as to what defines normal and abnormal spinal canal development exists (21). Anteroposterior diameters from <10 to <14 mm have been quoted as

Table 7 Comparison of smallest and largest quartiles

Variable	Male			Female		
	25% largest	25% smallest	Percentage difference* (%)	25% largest	25% smallest	Percentage difference* (%)
Spinal canal CSA						
L1	335.3 (26.8)	214.1 (32.1)	–36.1	319.5 (23.6)	213.4 (24.2)	–33.2
L2	323.1 (30.7)	193.3 (27.9)	–40.2	308.8 (25.4)	202.5 (25.1)	–34.4
L3	316.2 (39.9)	186.4 (26.9)	–41.0	297.9 (26.4)	190.4 (23.5)	–36.1
L4	361.0 (46.8)	202.9 (30.6)	–43.8	330.3 (42.3)	195.9 (24.0)	–40.7
L5	446.3 (47.8)	236.8 (37.5)	–46.9	394.7 (50.5)	215.7 (27.8)	–45.4
L1–L5	341.4 (32.3)	218.7 (31.6)	–35.9	318.4 (28.3)	214.7 (23.6)	–32.6
Spinal canal depth						
L1	18.19 (1.15)	12.54 (1.36)	–31.0	18.31 (0.93)	12.82 (1.15)	–30.0
L2	17.51 (1.49)	11.54 (1.11)	–34.1	17.39 (1.20)	12.68 (1.15)	–27.1
L3	17.33 (1.82)	11.29 (1.14)	–34.9	16.84 (1.21)	11.71 (1.19)	–30.5
L4	19.41 (2.03)	11.84 (1.10)	–39.0	18.71 (2.05)	11.94 (1.27)	–36.2
L5	24.35 (2.15)	14.87 (1.78)	–38.9	22.25 (1.86)	14.03 (1.58)	–36.9
L1–L5	18.27 (1.24)	13.49 (1.22)	–26.2	17.71 (1.05)	13.53 (1.11)	–23.6
Spinal canal width						
L1	23.86 (1.38)	17.83 (1.88)	–25.3	22.35 (1.22)	17.24 (1.28)	–22.9
L2	24.88 (1.38)	18.37 (1.72)	–26.2	22.76 (1.50)	17.59 (1.42)	–22.7
L3	25.54 (1.42)	18.76 (1.84)	–26.6	23.96 (1.38)	18.11 (1.34)	–24.4
L4	28.49 (1.70)	20.56 (2.02)	–27.8	26.79 (1.64)	19.20 (1.49)	–28.3
L5	34.91 (2.14)	24.28 (2.42)	–30.4	32.19 (2.14)	22.86 (1.89)	–29.0
L1–L5	26.80 (1.21)	20.50 (1.94)	–23.5	25.08 (1.30)	19.55 (1.42)	–22.0
Vertebral body CSA						
L1	1,413.1 (132.6)	1,007.6 (119.6)	–28.7	1,137.5 (89.6)	797.4 (77.1)	–29.9
L2	1,493.9 (110.6)	1,062.6 (126.0)	–28.9	1,214.4 (82.2)	852.4 (78.2)	–29.8
L3	1,635.8 (123.2)	1,172.3 (145.6)	–28.3	1,347.3 (88.1)	952.2 (94.1)	–29.3
L4	1,764.9 (133.4)	1,271.7 (156.3)	–27.9	1,471.1 (101.4)	1,043.6 (103.6)	–29.1
L5	2,009.6 (152.3)	1,428.6 (167.0)	–28.9	1,690.2 (118.6)	1,178.3 (111.1)	–30.3
L1–L5	1,643.9 (116.3)	1,202.0 (142.8)	–26.9	1,355.5 (85.5)	977.2 (93.4)	–27.9
Spinal canal CSA/vertebral body CSA						
L1	0.30 (0.03)	0.17 (0.02)	–41.8	0.36 (0.03)	0.21 (0.02)	–40.6
L2	0.27 (0.03)	0.15 (0.02)	–45.1	0.32 (0.03)	0.19 (0.02)	–41.3
L3	0.23 (0.03)	0.13 (0.02)	–44.1	0.28 (0.03)	0.16 (0.02)	–42.0
L4	0.24 (0.03)	0.14 (0.02)	–43.3	0.27 (0.03)	0.15 (0.02)	–43.6
L5	0.26 (0.03)	0.14 (0.02)	–45.3	0.28 (0.03)	0.15 (0.02)	–46.3
L1–L5	0.25 (0.03)	0.16 (0.02)	–37.4	0.29 (0.03)	0.18 (0.02)	–36.8

*, percent of difference between 25% largest and 25% smallest group, P value <0.0001. Comparison of smallest and largest quartiles for different spinal canal and vertebral body dimensions. Mean (SD) of spinal canal CSA, spinal canal depth, spinal canal width, vertebral body CSA, spinal canal CSA/vertebral body CSA in both sexes. SD, standard deviation; CSA, cross-sectional area.

measures of mid-vertebral spinal canal 'stenosis' (21-23) with a value of <11 mm at L2 and L3 being the most widely accepted (23). The current study uses an arbitrary cut-off of the lowest quartile to represent a developmentally narrow canal. For the study population, an anteroposterior value of <13 mm in males and <14 mm in females at L2 indicates the lowest 25% of the population range with different values for other levels. From a US-based study, Peter F. Ullrich Jr *et al.* suggested <145 mm^2 as a measure of 'developmental stenosis' at L3. This value is too low for the current population where a mid-vertebral spinal canal CSA of <212 mm^2 in males and <213 mm^2 in females indicates a patient in the smallest 25% of the population.

Taller patients were slightly more inclined to developmentally have a spinal canal with a larger CSA and depth. No change in developmental spinal canal CSA or depth was apparent with increasing age. Vertebral body CSA did, however, increase slightly in old age, particularly in females. This is not unexpected as reduced bone mineral density has a recognized association with increased lumbar vertebral CSA, probably as an inherent compensatory mechanism for reduced bone strength (24,25). Although males have a larger spinal canal CSA and vertebral body CSA than females, relative to vertebral body CSA, the spinal canal CSA is actually larger in females. This relative difference lessened in older females as overall vertebral body CSA increased.

One similar smaller scale study performed in Lausanne, Switzerland (2) showed a similar trend with males having larger spinal canal dimensions and the smallest lumbar CSA being at L3. The CSA of the lumbar spinal canal was generally 8–16% larger in Swiss subjects than in the current population. In contrast, the current study found no increase in lumbar canal CSA with age.

In conclusion, a population reference range for normal developmental size of the spinal canal was developed using data from abdominopelvic CT examinations from a large patient cohort. The reference range developed will be useful for gauging individual spinal canal development and ultimately adopting a more quantitative approach to the assessment of developmental spinal canal narrowing. The template used in this study is suited to cross-comparison with CT databases from other populations. An accurate relevant population reference range is critical to defining what constitutes a developmentally narrow canal, its clinical significance and to exploring, in great detail, the factors governing the aetiology of developmental spinal canal stensosis.

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None.

Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

Ethical Statement: The study was approved by the Joint Clinical Research Ethics Committee of The Chinese University of Hong Kong (CRE-2013.058) and written informed consent was obtained from all patients.

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Supplementary

Table S1 Adjusted spinal canal CSA

Variable	Estimated mean (SE)		P value
	Males (N=540)	Females (N=540)	
L1	264.1 (2.3)	274.4 (2.3)	0.005
L2	247.8 (2.4)	261.2 (2.4)	0.0004
L3	240.9 (2.4)	248.6 (2.4)	0.0498
L4	268.5 (3.0)	265.9 (3.0)	0.589
L5	324.0 (3.9)	311.2 (3.9)	0.040
L1–L5	269.1 (2.3)	272.3 (2.3)	0.386

Estimated mean for spinal canal CSA at each level from L1 to L5 and overall for L1–L5 after adjusting for height and weight. All statistically significant differences are bolded. SE, standard error; CSA, cross-sectional area.

Table S2 Adjusted spinal canal depth

Variable	Estimated mean (SE)		P value
	Males (N=540)	Females (N=540)	
L1	15.02 (0.10)	16.02 (0.10)	<0.0001
L2	14.24 (0.11)	15.21 (0.11)	<0.0001
L3	13.81 (0.11)	14.40 (0.11)	0.001
L4	15.06 (0.15)	15.31 (0.15)	0.294
L5	19.38 (0.18)	18.41 (0.18)	0.001
L1–L5	15.50 (0.09)	15.87 (0.09)	0.013

Estimated spinal canal depth. Mean estimated anteroposterior diameter (depth) of the spinal canal in males and females at each level from L1 to L5 and overall for L1–L5 after adjusting for height and weight. All statistically significant differences are bolded. SE, standard error; CSA, cross-sectional area.

Table S3 Adjusted spinal canal width

Variable	Estimated mean (SE)		P value
	Males (N=540)	Females (N=540)	
L1	20.63 (0.12)	20.07 (0.12)	0.003
L2	20.99 (0.12)	20.34 (0.12)	0.001
L3	21.89 (0.13)	21.20 (0.13)	0.001
L4	24.28 (0.16)	23.21 (0.16)	<0.0001
L5	29.09 (0.20)	27.87 (0.20)	0.0001
L1–L5	23.38 (0.12)	22.54 (0.12)	<0.0001

Estimated spinal canal width. Mean estimated transverse diameter (width) of the spinal canal in males and females at each level from L1 to L5 and overall for L1–L5 after adjusting for height and weight. All statistically significant differences are bolded. SE, standard error; CSA, cross-sectional area.

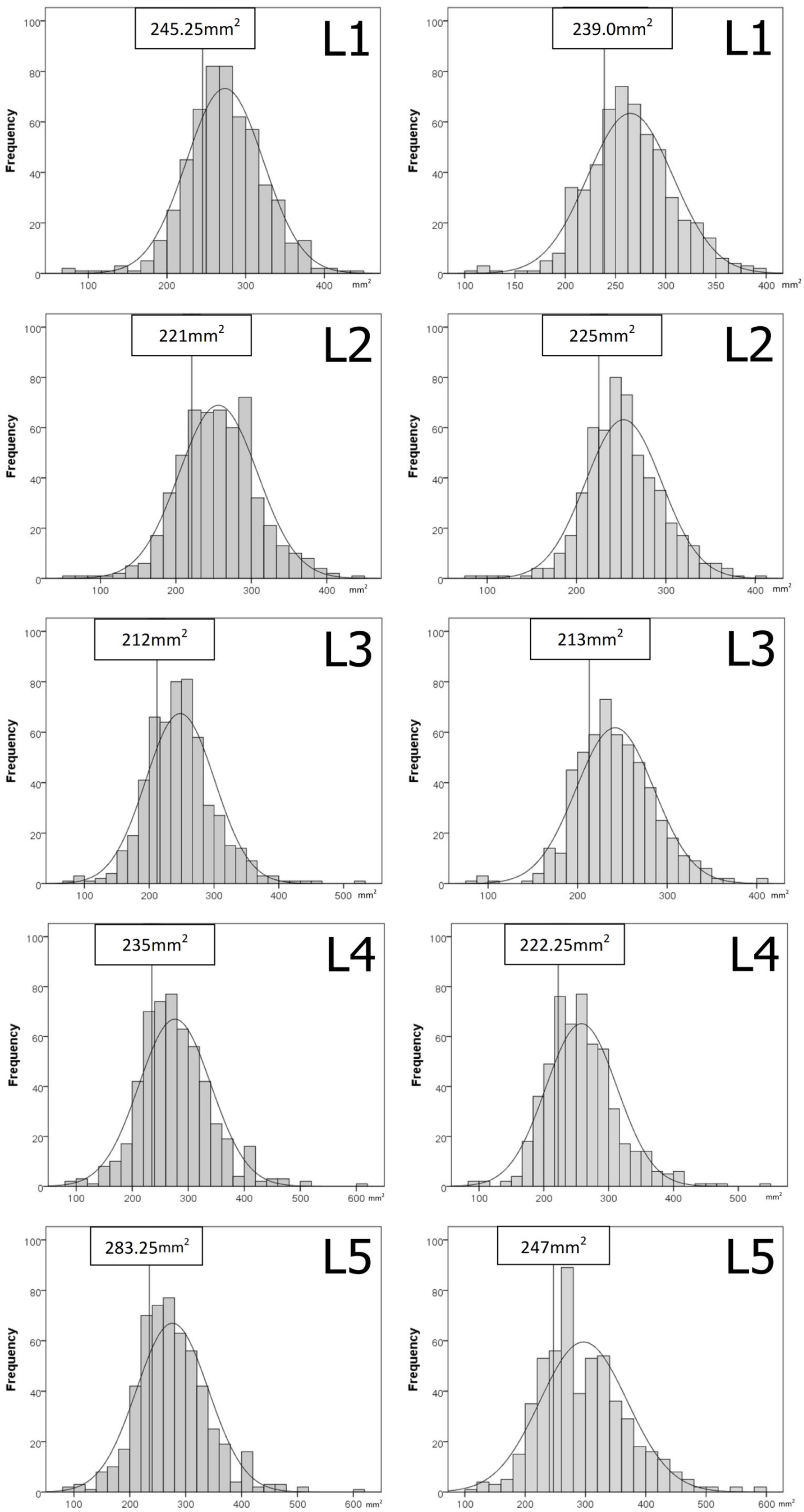

Figure S1 Spinal canal cross-sectional area from L1–L5 for males and females. This follows a normal distribution at each level. The value demarcating the smallest 25% of the population is shown for each level.

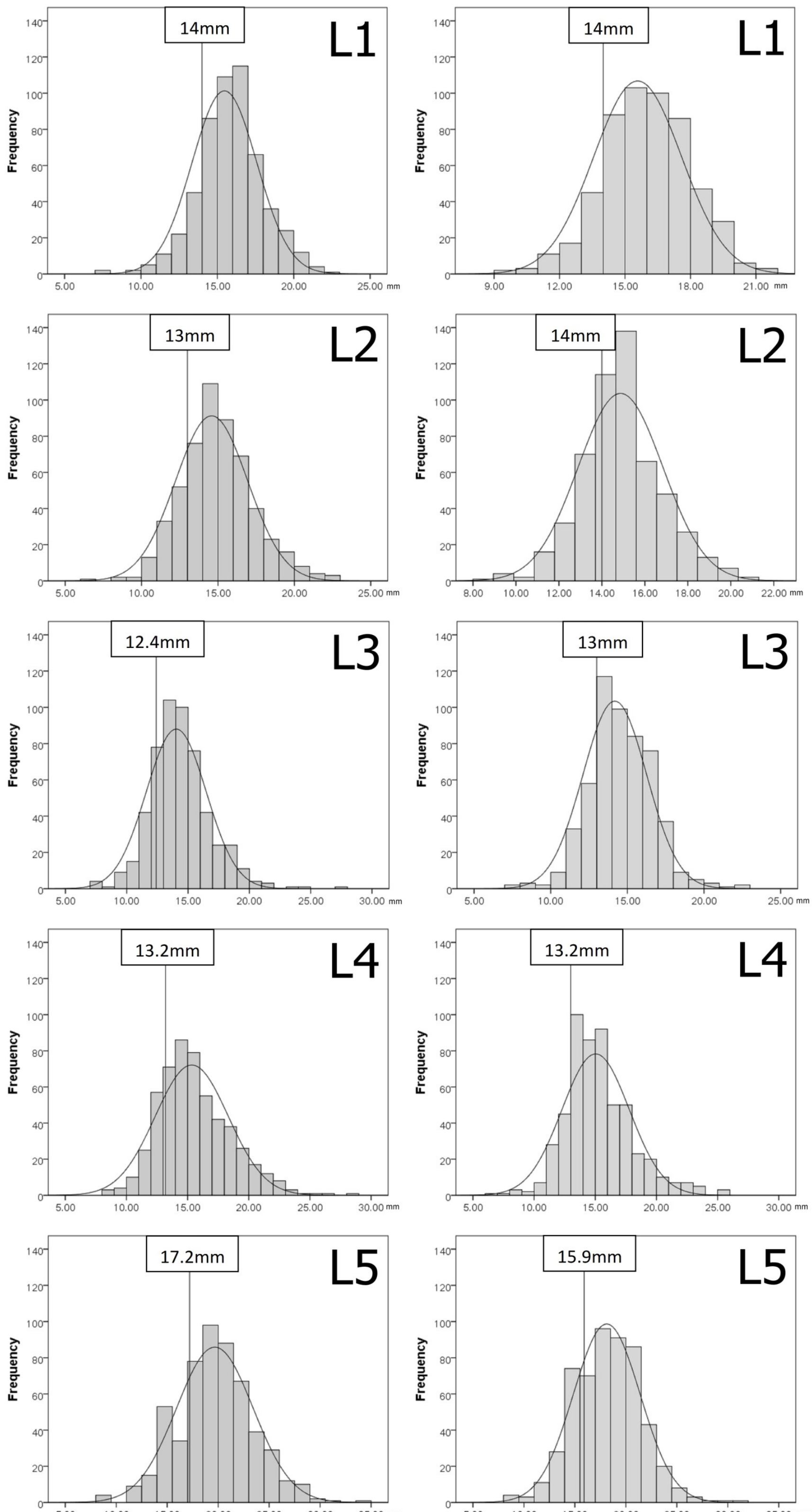

Figure S2 Spinal canal depth from L1–L5 for males and females. This follows a normal distribution for each level. The value demarcating the smallest 25% of the population is shown for each level.

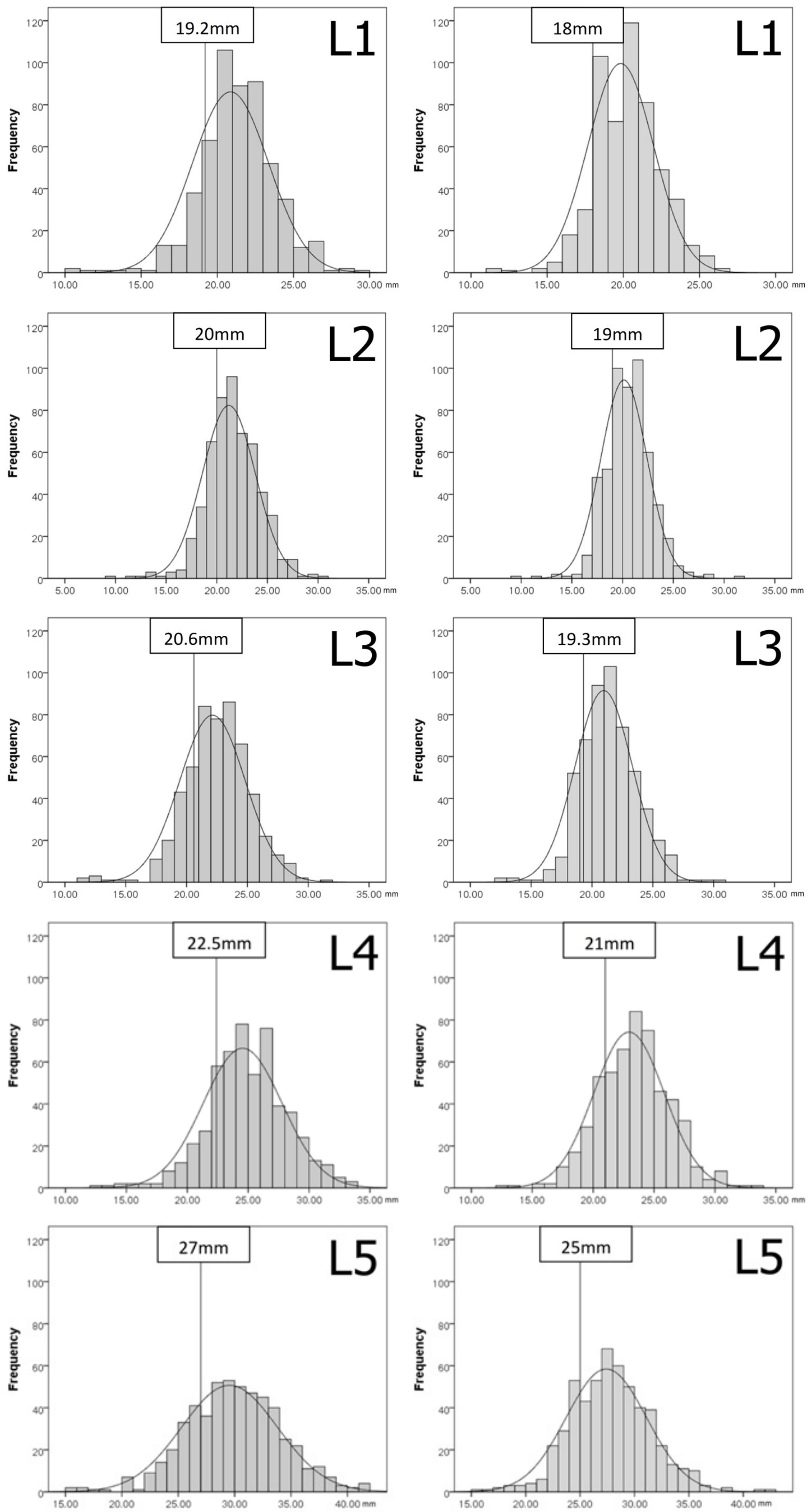

Figure S3 Spinal canal width from L1–L5 for males and females. This follows a normal distribution for each level. The value demarcating the smallest 25% of the population is shown for each level.

Table S4 Adjusted vertebral body CSA

Variable	Estimated mean (SE)		P value
	Males (N=540)	Females (N=540)	
L1	1,165.0 (7.6)	997.7 (7.6)	<0.0001
L2	1,231.6 (7.9)	1,071.7 (7.9)	<0.0001
L3	1,350.3 (8.6)	1,193.5 (8.6)	<0.0001
L4	1,456.7 (9.2)	1,306.7 (9.2)	<0.0001
L5	1,646.4 (10.7)	1,491.4 (10.7)	<0.0001
L1–L5	1,370.0 (8.2)	1,212.2 (8.2)	<0.0001

Estimated vertebral body cross-sectional area (CSA). Mean estimated vertebral body CSA in males and females at each level from L1 to L5 and overall for L1–L5 after adjusting for height and weight. All statistically significant differences are bolded. SE, standard error.

Table S5 Vertebral body CSA for different age groups

Variable	Mean (SD)		P value
	Males	Females	
21–40 years	N=180	N=180	
L1	1,159.5 (162.9)	926.4 (122.9)	<0.0001
L2	1,234.1 (181.7)	993.8 (136.9)	<0.0001
L3	1,358.0 (199.6)	1,113.7 (153.3)	<0.0001
L4	1,476.5 (212.8)	1,217.3 (165.8)	<0.0001
L5	1,666.0 (243.5)	1,397.8 (195.4)	<0.0001
L1–L5	1,378.8 (190.5)	1,129.8 (146.8)	<0.0001
41–60 years	N=180	N=180	
L1	1,203.1 (155.7)	957.0 (128.3)	<0.0001
L2	1,279.5 (170.8)	1,020.5 (137.6)	<0.0001
L3	1,406.0 (178.1)	1,127.1 (154.6)	<0.0001
L4	1,523.6 (191.1)	1,228.6 (165.9)	<0.0001
L5	1,743.4 (234.9)	1,396.6 (195.0)	<0.0001
L1–L5	1,431.1 (174.1)	1,146.0 (146.2)	<0.0001
61–80 years	N=180	N=180	
L1	1,240.4 (187.8)	1,001.8 (151.5)	<0.0001
L2	1,306.7 (178.6)	1,075.5 (148.9)	<0.0001
L3	1,433.8 (198.5)	1,192.9 (159.8)	<0.0001
L4	1,534.5 (211.9)	1,309.7 (176.0)	<0.0001
L5	1,724.7 (238.6)	1,485.0 (216.5)	<0.0001
L1–L5	1,448.0 (185.6)	1,213.0 (155.9)	<0.0001

Mean (SD) of vertebral body cross-sectional area (CSA) in males and females according to age. All statistically significant differences are bolded. SD, standard deviation.

Table S6 Adjusted spinal canal/vertebral body CSA ratio

Variable	Estimated mean (SE)		P value
	Males (N=540)	Females (N=540)	
L1	0.23 (0.003)	0.28 (0.003)	<0.0001
L2	0.21 (0.003)	0.25 (0.003)	<0.0001
L3	0.18 (0.002)	0.21 (0.002)	<0.0001
L4	0.19 (0.002)	0.21 (0.002)	<0.0001
L5	0.20 (0.003)	0.21 (0.003)	0.001
L1–L5	0.20 (0.002)	0.23 (0.002)	<0.0001

Estimated spinal canal CSA/vertebral body CSA ratio. Mean estimated spinal canal CSA/vertebral body CSA ratio in males and females at each level from L1 to L5 and overall for L1–L5 after adjusting for height and weight. All statistically significant differences are bolded. SE, standard error; CSA, cross-sectional area.