VIA MEDICA

ORIGINAL ARTICLE

Vol. 63, No. 4, pp. 431–438

ISSN 0015–5659
www.fm.viamedica.pl

Geometrical assessment of the foetal lumbar vertebral column — clinical implications

Marcin Czyż, Alicja Kędzia

Department of Normal Anatomy, Medical University of Wrocław, Poland

[Received 24 March 2004; Revised 18 June 2004; Accepted 7 July 2004]

The neural arches, transverse processes, spinous processes, and superior and inferior articular processes of each of the 5 lumbar vertebrae can often be found under the common heading of 'posterior element'. The aim of our study was to assess the changes in geometry of the posterior elements of the foetal lumbar vertebrae during the foetal period. A total of 50 human foetuses, both female and male, from natural abortions, C-R length ranging from 58 to 220 mm, were examined. The methodology of the research included classical anatomical preparation, detailed measurements of the structural elements of the lumbar vertebrae and statistical analysis. Geometrical reconstruction was subsequently performed. The shape of the posterior elements changed gradually from wide and massive to slender. We observed a descending sequence of these alterations, the first vertebra to change being L_1, with L_5 the last. The dynamic of the change was at its greatest during the first 4 weeks of the period evaluated. On the basis of our observations we concluded that the geometry of the posterior elements of the lumbar vertebrae undergoes a process of a great transformation during the foetal period, a process which progresses dynamically until the 14th week of intra-uterine development. The associations with micro-angiogenesis, the ossification process and the notion of structural adaptation of the lumbar spine to heightening mechanical stress are also discussed.

Key words: lumbar vertebra, morphometry, foetus, anatomy

INTRODUCTION

Internally the posterior column of the lumbar vertebral column consists of the neural arches, transverse processes, spinous processes and superior and inferior articular processes of each of the 5 vertebrae. These elements can often be found under a common heading 'posterior element' [17, 28]. In the light of the high prevalence of congenital lumbar spine defects, studies in the field of this structure's development are profoundly significant from the clinical point of view. Structural and the functional abnormalities of the lumbar vertebral column are common signs of a number of developmental pathologies. Spina bifida and the most common trisomy 21, 18 and 13 are often revealed in congenital pathology of this part of the axial skeleton [10, 11, 15, 20, 21]. The defects emerging in the foetal period are usually discovered *in utero*, in the neonatal period or in early childhood [4, 6, 18, 19, 31, 35]. Disorders of this kind are also found to be a factor increasing the probability of the occurrence of back pain syndrome among adults [7, 13, 14, 25, 28, 32]. In recent years significant development has been witnessed in the areas of 3D ultrasonography [6, 12, 29, 31] and ultra-fast NMR [1, 33, 36] used in the prenatal diagnosis of congenital pathologies of the axial skeleton. These methods have

Address for correspondence: Alicja Kędzia, Department of Normal Anatomy, Medical University of Wrocław, ul. Chałubińskiego 6a, 50–368 Wrocław, Poland, tel: +48 71 784 00 80, e-mail: m.czyz@poczta.fm

now rendered feasible a detailed visualisation of the morphology of the developing foetal structures. Their ongoing development is expected to enable earlier detection, more precise qualification and better prognosis of the evolution of the possible pathologies to be achieved. However, the indispensable condition of a proper interpretation of the diagnostic pictures obtained remains a thorough knowledge and good understanding of the proper anatomical relations and developmental tendencies of the area to be assessed.

The issue of the development of the spine in the early foetal period has aroused considerable interest among researchers for over a century [2, 13, 22]. Apart from our own data [8, 16], we have not encountered any articles in the available literature in which an attempt has been made to provide a systematic and detailed description of the developing lumbar vertebra metrology. The aim of our study, therefore, was to analyse the development of the lumbar posterior elements with special emphasis on the clinical significance of the results achieved.

MATERIAL AND METHODS

Foetal material

A total of 50 human foetuses were examined, of both sexes (26 male and 24 female) and with a crown-rump length (C-R length) ranging from 58 mm to 220 mm (11th to 23rd week of intra-uterine development). All the foetuses were derived from spontaneous abortions and did not show macroscopic developmental defects. The preparations had been stored for at least 8 weeks in a 10% formaldehyde solution with 98% alcohol added. During careful preparation via a stereoscopic microscope the occipital bone and the dorsal part of the vertebral column of each foetus were exposed.

Measurements

Detailed measurements were made with the use of a Digital Mitutoyo slide ruler to enable feedback to be obtained from the computer (0.01 mm scale). The following parameters were measured: X — the total length of the vertebral column and Y — the length of the lumbar vertebral column and for each vertebra A — the distance between the apices of the superior articular processes (upper width), B — the distance between the apices of the inferior articular processes (lower width), C — the distance between the apex of the superior and inferior articular processes on both sides and D — the distance between the apex of the superior articular process and the central point of the spinous process on both sides. The scheme of measurements is presented in Figure 1.

Statistical analysis

The results obtained were subjected to statistical analysis with the significance level set at $p < 0.05$. The variance homogeneity was assessed using a Brown and Forysthe test and the normality of distribution using a Shapiro-Wilk W test.

Student's t-test did not reveal any significant differences between the results of C-left vs. C-right and D-left vs. D-right measurements. After exclusion of the asymmetry the results of the relevant measurements were averaged. The significance of the differences between

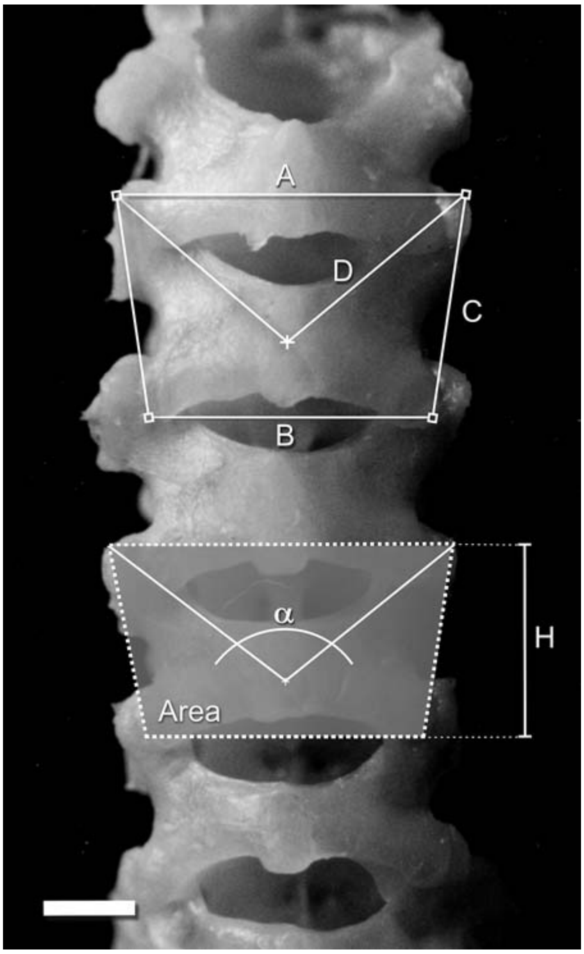

Figure 1. Scheme of the detailed foetal lumbar vertebrae measurements. Male foetus, C-R length 178 mm. The bar indicates 3 mm. A — distance between the apices of the superior articular processes; B — distance between the apices of the inferior articular processes; C — distance between the apex of the superior and inferior articular process; D — distance between the apex of the superior articular process and the central point of the spinous process. α — the angle between the neural arch laminae; H — the axial dimension of the vertebra; area — the area of the dorsal surface of the vertebra.

the areas examined of the posterior elements of the particular lumbar vertebrae was evaluated with the use of one-way ANOVA. The correlation between C-R length and diameters X and Y was tested by the determination of Pearson's correlation coefficient. A simple linear regression of the A, B, C and D diameters in relation to C-R length was carried out. Statistica version 6 software was used for the necessary calculations.

Geometrical assessment

During the geometrical analysis the values of measurements A, B, C and D, obtained according to C-R length during simple linear regression (Table 1), were used. The L_1, L_3 and L_5 vertebrae were chosen as representative for the part of the vertebral column under examination. The dorsal surface of each posterior element was schematically represented by an isosceles trapezium with an inscribed isosceles triangle (Fig. 1). Diameters A and B corresponded to the upper and the lower bases of the trapezium respectively. Diameter C represented a trapezium side and diameter D corresponded to a side of the inscribed triangle. Diameter H, the axial dimension of each vertebra (the height of the trapezium) was calculated using the following geometrical formula:

$$H = \sqrt{C^2 + \left(\frac{A-B}{2}\right)^2}$$

The area of the dorsal surface of each vertebra was calculated after using the measures of A, B and H in the formula for the area of the trapezium.

Table 1. Linear regression of the detailed L_1, L_3 and L_5 vertebrae measurements. All results significant with $p < 0.00001$

Diameter	Vertebra	Regression equation	R^2	SeE
A	L_1	A_R = 0.97 + 0.058*CRL	0.91	0.75
	L_3	= 0.64 + 0.059*CRL	0.92	0.72
	L_5	= 0.36 + 0.057*CRL	0.90	0.78
B	L_1	B_R = 0.88 + 0.049*CRL	0.88	0.68
	L_3	= 0.59 + 0.048*CRL	0.86	0.73
	L_5	= 0.19 + 0.050*CRL	0.87	0.75
C	L_1	C_R = –0.63 + 0.044*CRL	0.89	0.64
	L_3	= –0.64 + 0.044*CRL	0.86	0.71
	L_5	= –0.74 + 0.038*CRL	0.86	0.62
D	L_1	D_R = –1.32 + 0.045*CRL	0.92	0.59
	L_3	= –1.07 + 0.048*CRL	0.91	0.63
	L_5	= –1.20 + 0.046*CRL	0.89	0.64

CRL — crown-rump length, R^2 — coefficient of determination, SeE — standard error of the estimation

The value of parameter α, the angle between the laminae of the neural arches (the angle between the sides of the inscribed triangle) was calculated using trigonometrical dependency:

$$\alpha = 2\arcsin\left(\frac{A}{2 \times D}\right)$$

In order to render the geometrical analysis objective, the following parameters were used: 1) Shape Factor (SF), which expressed the relation H/A. Low values of the SF were characteristic for the wide and the low vertebrae (Fig. 2A); values close to 1 corresponded to the posterior elements, the shapes of which were quadrant-like (Fig. 2B).

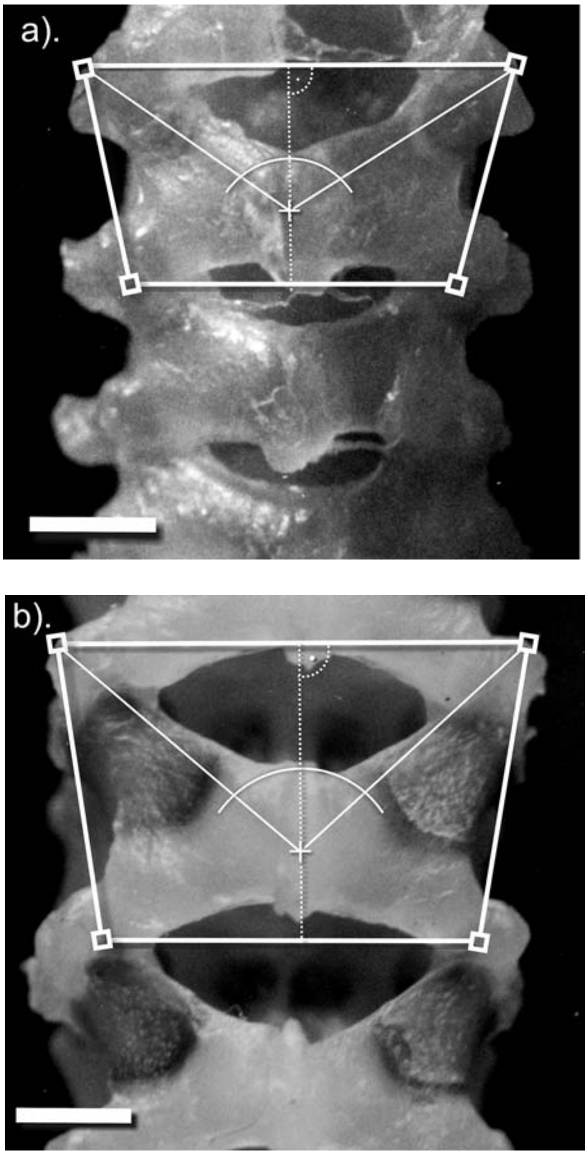

Figure 2. Age-related changes in the shape of the posterior elements of the lumbar vertebrae; **A** — L_3 vertebra; female foetus, C-R length 87 mm. The bar indicates 1 mm; **B** — L_3 vertebra; male foetus, C-R length 180 mm. The bar indicates 2 mm.

The second parameter was the 2) Wide Ratio (WR), which provided information about the relation B/A. An increase in the value of the WR proved that there was a decrease in the difference between the length of the upper (A) and lower (B) widths, and a change in the shape of the posterior element from trapezoidal to rectangular.

The diameters derived from the direct measurements (A, B, C, D) and the values calculated for α, H and area of the posterior elements was compared to the computed adequate measurements. The digitalised photographs of 30 lumbar vertebrae (6 foetuses of different ages) which had undergone a typical metrological procedure were analysed using Scion for Windows 4.0 software. In none of the cases was the difference between the traditional methods and the digital measurements greater than 5%.

RESULTS

The results of the direct measurements of the lumbar vertebrae are shown in Table 2. The values surveyed of the α, H and area are presented in Table 3.

In Table 1 the results of the simple linear regression of the direct measurements in relation to C-R length have been introduced. High values of the determination coefficients (R^2) of the regression equations indicate a proper adjustment of the model. All diameters have been given in mm.

The data analysis showed that the axial growth of the total vertebral column (X) and its lumbar part (Y) strongly correlates with the C-R length changes ($R_x = 0.98$; $R_Y = 0.97$; $p < 0.00001$) (Fig. 3).

Comparison of the particular areas of the posterior elements of the vertebrae revealed that the L_2 vertebra was the largest and the L_5 vertebra

Table 2. The results of the detailed survey of the lumbar vertebral column in particular months of the intra-uterine development

Fetal age [month]	n	Vertebra	Diameters (mean ± SD)					
			A	B	C		D	
					Left	Right	Left	Right
III	6	L_1	6.55 ± 1.05	4.27 ± 0.50	2.46 ± 0.30	2.50 ± 0.31	2.65 ± 0.32	2.79 ± 0.27
		L_2	6.38 ± 0.93	4.15 ± 0.48	2.58 ± 0.40	2.55 ± 0.33	2.77 ± 0.22	2.88 ± 0.21
		L_3	6.15 ± 1.05	4.06 ± 0.69	2.39 ± 0.27	2.45 ± 0.29	2.81 ± 0.20	2.85 ± 0.26
		L_4	5.97 ± 1.02	3.79 ± 0.41	2.20 ± 0.20	2.21 ± 0.22	2.75 ± 0.31	2.87 ± 0.30
		L_5	5.66 ± 0.97	3.49 ± 0.72	2.04 ± 0.17	2.01 ± 0.17	2.51 ± 0.47	2.65 ± 0.44
IV	18	L_1	7.87 ± 1.28	6.55 ± 1.05	4.57 ± 0.79	4.46 ± 0.77	4.30 ± 0.77	4.32 ± 0.76
		L_2	7.94 ± 1.16	6.38 ± 0.93	4.79 ± 0.93	4.68 ± 0.82	4.73 ± 0.83	4.76 ± 0.79
		L_3	7.67 ± 1.17	6.15 ± 1.05	4.64 ± 0.88	4.50 ± 0.76	4.50 ± 0.80	4.58 ± 0.81
		L_4	7.37 ± 1.13	5.97 ± 1.02	4.21 ± 0.81	4.20 ± 0.81	4.30 ± 0.76	4.30 ± 0.71
		L_5	6.97 ± 1.19	5.66 ± 0.97	3.82 ± 0.77	3.80 ± 0.73	4.10 ± 0.73	4.05 ± 0.70
V	19	L_1	10.52 ±1.24	8.61 ± 0.98	6.38 ± 1.01	6.34 ± 1.00	6.57 ± 0.85	6.60 ± 0.87
		L_2	10.62 ± 1.21	8.59 ± 1.05	6.55 ± 0.95	6.48 ± 0.92	6.88 ± 0.88	6.92 ± 0.95
		L_3	10.36 ± 1.10	8.34 ± 1.00	6.40 ± 0.97	6.34 ± 0.95	6.69 ± 1.01	6.71 ± 1.01
		L_4	10.11 ± 1.16	8.26 ± 1.10	5.78 ± 0.85	5.89 ± 0.88	6.39 ± 0.92	6.38 ± 0.90
		L_5	9.83 ± 1.16	7.89 ± 1.05	5.29 ± 0.83	5.34 ± 0.86	6.14 ± 0.93	6.07 ± 0.95
VI	7	L_1	11.84 ± 1.54	10.24 ± 1.06	8.14 ± 1.03	8.14 ± 1.03	9.17 ± 1.30	9.20 ± 1.25
		L_2	12.07 ± 1.33	9.87 ± 1.04	7.93 ± 0.93	7.94 ± 0.90	9.00 ± 1.37	9.00 ± 1.37
		L_3	11.97 ± 1.30	9.88 ± 1.32	7.87 ± 1.03	7.85 ± 1.04	8.80 ± 1.12	8.80 ± 1.16
		L_4	11.55 ± 1.20	9.69 ± 1.34	7.52 ± 0.98	7.52 ± 0.98	8.46 ± 1.05	8.48 ± 1.07
		L_5	11.11 ± 1.09	9.78 ± 1.34	7.16 ± 0.87	7.13 ± 0.81	8.17 ± 1.18	8.22 ± 1.23

A — distance between the apices of the superior articular processes, B — distance between the apices of the inferior articular processes, C — the distance between the apex of the superior and inferior articular process, D — the distance between the apex of the superior articular process and the central point of the spinous process

Table 3. The results of the survey of α, H parameters and the L_1, L_3 and L_5 vertebrae areas in particular months of the intra-uterine development

Fetal age [month]	n	Vertebra	Parameter (mean ± SD)		
			α	H	Area
III	6	L_1	163.44 ± 15.28	2.47 ± 0.41	11.89 ± 3.19
		L_3	141.26 ± 14.34	2.47 ± 0.41	11.28 ± 3.11
		L_5	148.10 ± 16.04	1.94 ± 0.36	7.82 ± 2.44
IV	18	L_1	119.13 ± 9.29	4.38 ± 0.49	32.39 ± 6.09
		L_3	110.51 ± 5.17	4.41 ± 0.46	30.59 ± 5.54
		L_5	117.65 ± 6.83	3.63 ± 0.41	23.56 ± 4.76
V	19	L_1	99.24 ± 3.19	6.45 ± 0.58	61.10 ± 9.45
		L_3	97.96 ± 2.36	6.36 ± 0.58	59.19 ± 9.91
		L_5	102.20 ± 2.76	5.36 ± 0.51	47.16 ± 8.30
VI	7	L_1	92.67 ± 1.90	7.94 ± 0.63	88.71 ± 10.20
		L_3	92.77 ± 1.02	7.98 ± 0.45	89.86 ± 9.73
		L_5	96.22 ± 1.15	6.78 ± 0.39	72.98 ± 8.24

α — the angle between the neural arch laminae, H — the axial dimension of the vertebra, area — area of the dorsal surface of the vertebra

the smallest. However, one-way ANOVA did not reveal any significance in the differences observed (p = 0.16).

The value of the α parameter gradually decreased; the highest extension of this parameter was characteristic for the L_1 vertebra (the difference between the highest and the lowest values was over 73 degrees), while the lowest was for the L_5 vertebra (54 degrees) (Table 3). This angle reached half the final value relatively early, at C-R length 100 mm in the L_3 and at C-R length 110 mm in the L_1 and L_5 vertebrae. During the further period the process of decrease of the α angle continued, although less dynamically (Fig. 4).

The value of the Shape Factor (SF) increased from 0.43 to 0.65 in the L_1 and L_3 and from 0.38 to 0.59 in the L_5 vertebrae. The SF achieved half the final value at a C-R length of over 97 mm (Fig. 5A).

The Width Ratio (WR) only changed significantly in the L_5 vertebra, increasing from 0.74 to 0.83 and reaching half the final value at a C-R length of over 100 mm. We concluded that the decrease in the WR in L_1 from 0.85 to 0.83 was extremely small (Fig. 5B).

All the above-mentioned changes are visible in the geometrical reconstructions of the posterior elements of the lumbar vertebrae (Fig. 6). The schemes have been constructed on the basis of the relation of A, B, C, and D to C-R length.

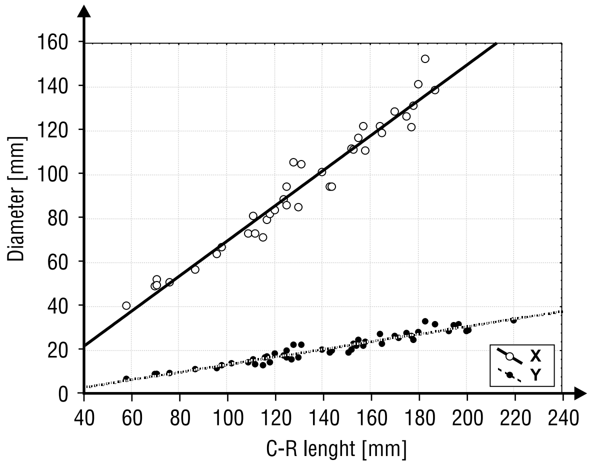

Figure 3. Linear relation between the length of the whole spine, the lumbar vertebral column and the age of the foetus.
$R_x = 0.98$; $R_Y = 0.97$; $p < 0.00001$.

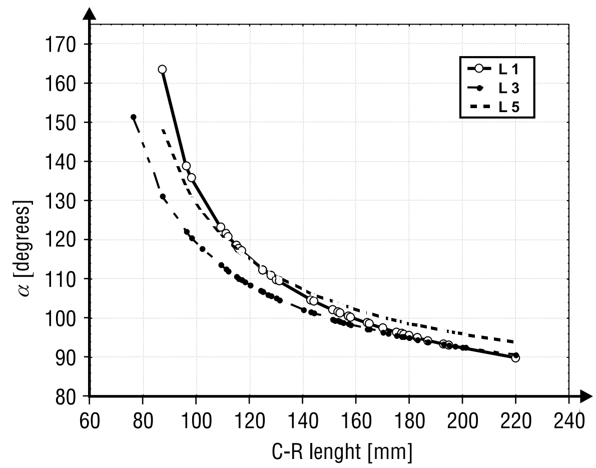

Figure 4. Changes in the angle between the neural arch laminae. Foetal vertebrae L_1, L_3 and L_5.

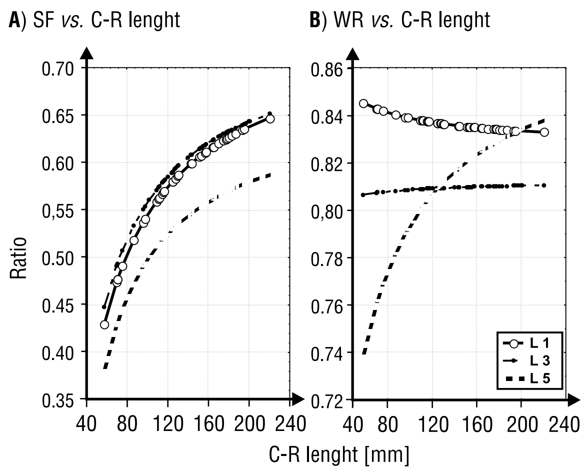

Figure 5. Relations between the age and the shape of the foetal lumbar vertebrae; **A**) Changes in the Shape Factor (SF); **B**) Changes in the Width Ratio (WR); (SF — the relation H/A; WR — the relation B/A; H — the axial dimension of each vertebra; **A** — the distance between the apices of the superior articular processes; **B** — the distance between the apices of the inferior articular processes).

DISCUSSION

The vast majority of the geometrical descriptions of lumbar vertebrae found in the literature have been based on the analyses of specimens derived from adults [17, 24, 26, 30]. Attempts to date to assess the metrology of the foetal lumbar vertebral column have been made mainly on the strength of ultrasonographic techniques [5, 27, 29, 34]. The authors of the publications referred to worked out the diagnostic norms, designated mainly for the evaluation of the development of the vertebral corpora and the spinal canal. Thus the detailed geometrical analysis of posterior elements of the lumbar vertebral column that we managed to carry out is, as far as we know, the first statement of this kind.

The results of our research prove that the growth of the particular lumbar vertebrae is a process of changeable dynamics proceeding according to a precise scheme. The comparison of the areas of the particular posterior elements did not prove the domination of the L_2 vertebra, which has previously been discussed [16]. However, it should be pointed out that the particular lumbar vertebrae of each individual also differed in the shape of the posterior element (Fig. 6).

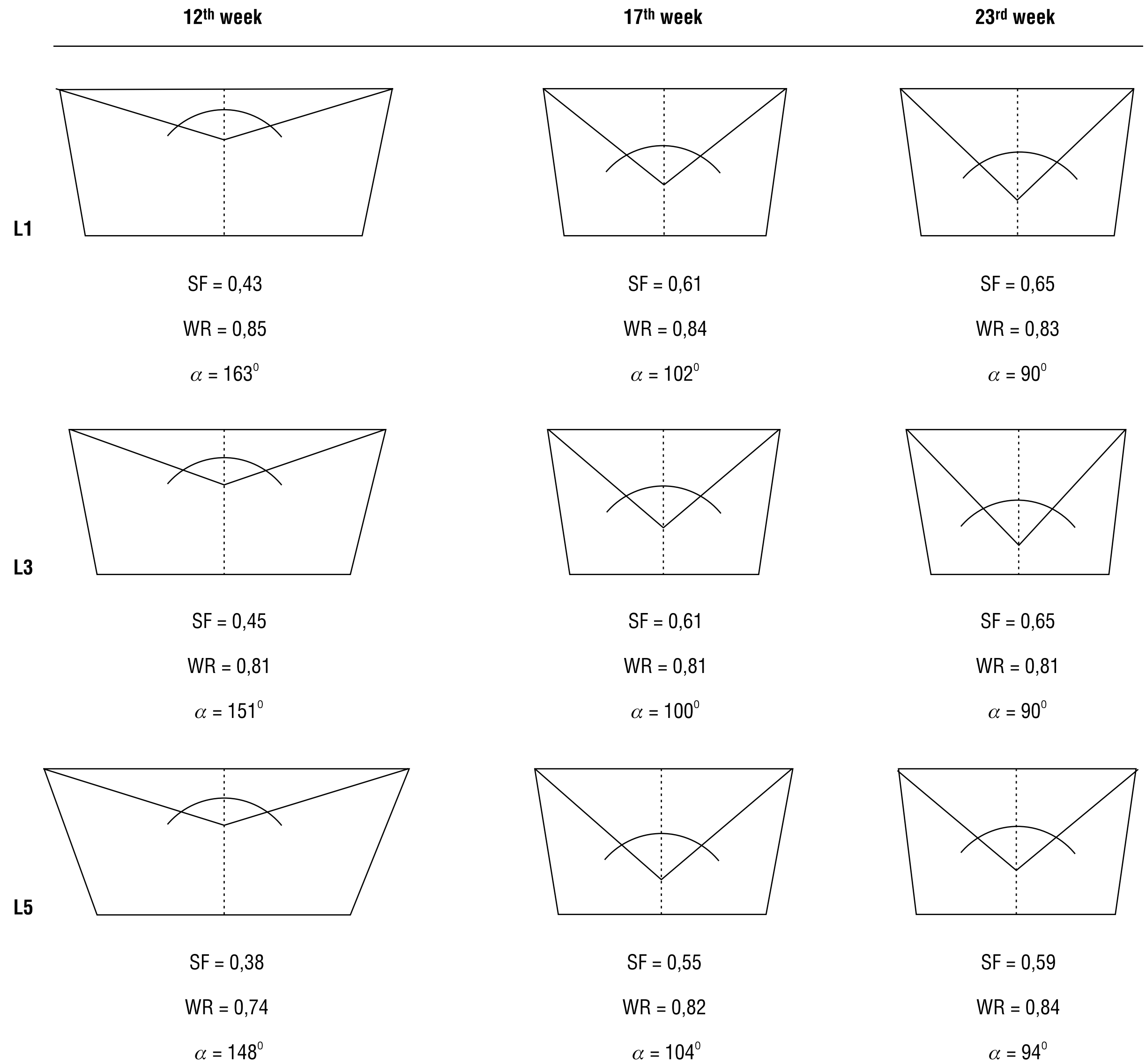

Figure 6. Geometrical reconstruction of the dorsal surfaces of the foetal lumbar vertebrae at different stages of the intra-uterine development. The graphical reconstructions were made uniform with respect to the height of the particular posterior elements. SF — Shape Factor expresses the relation H/A. WR — Wide Ratio expresses the relation B/A; α — the angle between the neural arch laminae; H — the axial dimension of each vertebra; A — the distance between the apices of the superior articular processes; B — the distance between the apices of the inferior articular processes.

In the first phase of the period analysed the posterior elements were characterised by low values for the SF and high values for the α angle; vertebrae were shaped like squat trapezia with broadly situated sides (Fig. 2A, 6). In the period between the 11th and 14th week of intra-uterine development (C-R length from 60 to 100 mm), from 2 to 5 weeks after the beginning of ossification of the vertebral column [3], the shape of the vertebrae changed. The diagonal growth was outdone in terms of dynamics by the growth in the long axis. This observation is in accordance with our previous research [9]. The change in the vertebrae form from squat (low SF, high α) into oblong (maximal SF, minimal α) proceeded in the case of each individual, like the ossification process, according to a descending sequence.

A period of intensified change in the morphology of the vertebrae coincides with the moment of intensified angiogenesis in the vicinity of their original ossification centres [16]. A dynamic development of the blood vessels is therefore a landmark for the changes described. The osseous tissue that develops in the area of the neural arches changes the matrix of the strains which influence a vertebra during the movements of a foetus [9, 23]. This probably leads to a change in the shape of the vertebra from squat to more slender.

The ossification of the neural arches is accompanied by a dynamic development of the inferior articular processes, which remain unossified for a long period of time [28]. In our survey their growth was manifested especially strongly in L_5, which resulted in a considerable increase in its WR value (Fig. 5B). It is vital to mention that the L_5 vertebra is situated on the lumbo-sacral border, which is especially loaded mechanically, and is the last lumbar vertebra to ossify [3]. According to Sagi et al. [28] this might be a frequent reason for the appearance of the spondylolysis at the level of L_4–L_5. Our research seems to confirm this thesis; in the case of L_5 a highly visible outgrowth of the inferior articular processes compensates for the short durability of the chondrous structure. An excessive unbalanced load may promote the appearance of micro defects (perhaps vascular) in the vicinity of a vertebra, which might negatively influence its further development.

Our observations may also be taken into consideration with regard to the early detection of factors predisposing to vertebral column pathologies. It may be assumed that complete high-rendition visualisation will to be carried out in the next few years. Our research provides a concise description of the morphology and developmental tendencies of the foetal lumbar vertebrae, illustrated with graphic reconstructions.

CONCLUSIONS

During the period between the 11th and 23rd weeks of intra-uterine development the growth of the lumbar vertebral column and its structural elements is strictly correlated to the C-R length changes. The shape of the lumbar posterior elements undergoes a transformation which progresses according to the following scheme: the dorsal surface of each of lumbar vertebra increases its oblong size at the expense of the diagonal one. The changes progress dynamically in a descending manner until the 14th week of intra-uterine development.

REFERENCES

1. Aaronson OS, Hernaz-Schulman M, Bruner JP, Reed GW, Tulipan NB (2003) Myelomeningocele: prenatal evaluation – comparison between transabdominal US and MR imaging. Radiology, 227: 839–843.
2. Bardeen CR (1905) The development of the thoracic vertebrae in man. Am J Anat, 4: 163–174.
3. Bareggi R, Grill V, Zweyer M, Narduci P, Forabosco A (1994) A quantitative study on the spatial and temporal ossification patterns of the vertebral centra and neural arches and their relationship to the fetal age. Ann Anat, 176: 311–317.
4. Basu PS, Elsebaie H, Noordeen MH (2002) Congenital spinal deformity. A comprehensive assessment at presentation. Spine, 27: 2225–2259.
5. Birnholz JC (1986) Fetal lumbar spine: measuring axial growth with US. Radiology, 158: 805–807.
6. Blaas HG, Eik-Nes SH, Isaksen CV (2000) The detection of spina bifida before 10 gestational weeks using two- and three-dimensional ultrasound. Ultrasound Obstet Gynecol, 16: 25–29.
7. Cinotti G, De Santis P, Nofroni I, Postacchini F (2002) Stenosis of lumbar intervertebral foramen. Anatomic study of predisposing factors. Spine, 27: 232–229.
8. Czyż M, Kędzia A (2003) Preliminary metrological study of the lumbar vertebral column during the foetal period. Folia Morphol, 62: 259–262.
9. Czyż M, Kędzia A (2003) Komputerowa analiza wytrzymałościowa numerycznego modelu kręgu lędźwiowego płodu. X KK KOWBAN 2003. Proceedings of the 10th National Conference on Supporting Research Projects by Computer Techniques; 2002 October 22–24; Wrocław, Polanica Zdrój, Poland, pp. 99–104.
10. Finnel RH, Gould A, Spiegelstein O (2003) Pathobiology and genetics of neural tube defects. Epilepsia, 44: 14–23.
11. Frey L, Hauser W (2003) Epidemiology of neural tube defects. Epilepsia, 44: 1–13.
12. Isaksen CV, Eik-Nes SH, Blass HG, Torp SH, Van Der Hagen CB, Ormerod E (2000) A correlative study of

prenatal ultrasound and post-mortem findings in fetus and infants with an abnormal karyotype. Ultrasound Obstet Gynecol, 16: 37–45.
13. Jeffrey JE, Campbell DM, Golden MH, Smith FW, Porter RW (2003) Antenatal factors in the development of the lumbar vertebral canal. Spine, 28: 1418–1423.
14. Jenis LG, An HS (2000) Spine update. Lumbar foraminal stenosis. Spine, 25: 389–394.
15. Keeling JW, Hansen B, Kjaer I (1997) Pattern of malformations in the axial skeleton in human trisomy 21 fetuses. Am J Med Genet, 68: 466–471.
16. Kędzia A, Czyż M (2003) Ossification process and lumbar spine morphology in the prenatal period. Med Sci Monit, 9: 343–350.
17. McLain RF, Yerby SA, Moseley TA (2002) Comparative morphometry of L4 vertebrae. Comparison of large animal models for the human lumbar spine. Spine, 27: E200–E206.
18. McMaster MJ (1998) Congenital scoliosis caused by a unilateral failure of vertebral segmentation with a contralateral hemivertebra. Spine, 23: 998–1005.
19. McMaster MJ, Singh H (2001) The surgical management of congenital kyphosis and kyphoscoliosis. Spine, 26: 2146–2155.
20. Nolting D, Hansen BF, Keeling JW, Kjaer I (2002) Histological examinations of bone and cartilage in the axial skeleton of human triploidy fetuses. APMIS, 110: 186–192.
21. Nolting D, Hansen BF, Keeling JW, Reintoft I, Kjaer I (2000) Prenatal malformed lumbar vertebral corpora in trisomies 21, 18, and 13, evaluated radiographically and histologically. APMIS, 108: 422–428.
22. O'Rahilly R, Muller F, Meyer DB (1980) The human vetebral column at the embryonic period proper. 1. The column as a whole. J Anat, 131: 565–575.
23. Panattoni GL, Todros T (1989) Fetal motor activity and spine development. Panminerva Med, 31: 183–186.
24. Panjabi MM, Goel V, Oxland T, Takata K, Duranceau J, Krag M, Price M (1992) Human lumbar vertebrae. Quantitative three-dimensional anatomy. Spine, 17: 299–306.
25. Papp T, Porter RW, Craig CE, Aspden RM, Campbell DM (1997) Significant antenatal factors in the development of lumbar spinal stenosis. Spine, 22: 1805–1810.
26. Parent S, Labelle H, Skalli W, Latimer B, de Guise J (2002) Morphometric analysis of anatomic scoliotic specimens. Spine, 27: 2305–2311.
27. Rouse GA, Filly RA, Toomey F, Grube GL (1990) Short--limb skleletal dysplasias: evaluation of the fetal spine with sonography and radiography. Radiology, 174: 177–180.
28. Sagi HC, Jarvis JG, Uhthoff HK (1998) Histomorphic analysis of the development of the pars interarticularis and its association with isthmic spondylosis. Spine, 23: 1635–1640.
29. Schild RL, Wallny T, Fimmers R, Hansmann M (2000) The size of the fetal thoracolumbar spine: a three-dimensional ultrasound study. Ultrasound Obstet Gynecol, 16: 468–472.
30. Scoles PV, Linton AE, Latimer B, Levy ME, Digiovanni BF (1988) Vertebral body and posterior element morphology: the normal spine in middle life. Spine, 13: 1082–1086.
31. Unsinn KM, Geley T, Freund MC, Gassner I (2000) US of the spinal cord in newborns: spectrum of normal findings, variants, congenital anomalies and acquired diseases. RadioGraphics, 20: 923–938.
32. Ursu TR, Porter RW, Navaratnam V (1996) Development of the lumbar and sacral vertebral canal in utero. Spine, 21: 2705–2708.
33. Wagenvoort AM, Bekker MN, Go AT, Vandenbussche FP, Van Buchem MA, Valk J, Van Vugt JM (2000) Ultrafast scan magnetic resonance in prenatal diagnosis. Fetal Diagn Ther, 15: 364–372.
34. Wallny TA, Schild RL, Fimmers R, Wagner UA, Hansmann ME, Schmitt O (1999) The fetal spinal canal — a three-dimensional study. Ultrasound Med & Biol, 25: 1329–1333.
35. Wild A, Jager M, Werner A, Eulert J, Krauspe R (2001) Treatment of congenital spondyloptosis in an 18-month--old patient with a 10-year follow-up. Spine, 26: 502–505.
36. Zaretsky MV, McIntire DD, Twickler DM (2003) Feasibility of the fetal anatomic and maternal pelvic survey by magnetic resonance imaging at term. Am J Obstet Gynecol, 189: 997–1001.