

SCOLIOSIS AND GROWTH

Patterns of Asymmetry in Normal Vertebral Growth

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This study reviews published observations of asymmetrical appearance of primary ossification centres in human fetal vertebral arches. It reports studies of vertebral asymmetry in 39 vertebral columns of infants and children including asymmetry in pedicle length and vertebral arch height, asymmetry in neurocentral fusion, and vertebral body flattening on its left anterior aspect. It relates these patterns of asymmetry to the commonly observed left thoracic scoliosis of infancy and right thoracic scoliosis of adolescents and adults. It discusses the implications of these observed asymmetries of normal vertebral growth in the aetiology of scoliosis, and the possible influences of handedness and aortic pressure in the production of these vertebral asymmetries in adolescence.

Key words: asymmetry; growth; neurocentral fusion; primary ossification; scoliosis; vertebral arch

Accepted 5.ii.83

Idiopathic scoliosis is widespread throughout the world though varying considerably in its prevalence in different races (Lonstein 1977). It is regarded as "multifactorial" in origin, but its pathogenesis remains obscure (Nachemson & Sahlstrand 1977).

Its development is related to growth, and progression of a curvature is most likely during periods of rapid growth, particularly around puberty (Burwell 1971). It may be part of a generalized growth disturbance as it is associated with plagiocephaly in infants (Burwell 1971), unequal limb lengths in adolescents (Willner 1975, Burwell & Dangerfield 1977, Taylor & Slinger 1980) and asymmetrical rib growth (Sevastikoglou et al. 1980). Some development asymmetries have been attributed to "out-of-phase" growth of corresponding bilateral elements, e.g. limb length inequality, which is more prevalent in adolescents than in adults of the same population (Taylor & Slinger 1980). Knutsson (1963) pointed out that

asymmetrical growth of the vertebral arches at the neuro-central growth plates could produce rotational deformity and lateral curvature of the vertebral column.

Any investigation of out-of-phase growth or developmental asymmetry in vertebrae requires study of vertebral arches, which arise from bilateral primary ossification centres, as opposed to vertebral bodies, which arise from single midline centres.

Primary centres appear in presacral vertebral arches in human embryos ranging from about 40 mm to 80 mm crown rump length (CRL) (Mall 1906, Teissandier 1944, Noback & Robertson 1951, Bagnall *et al.* 1977). Bilateral fusion of the arches with the centra takes place from about 3 to 7 years postnatally but in some regions of the thoracic spine it may be delayed till the 8th year or later (Knutsson 1963, Canadell & Beguiristain 1979).

In the context of *normal growth*, this study

examines the *events* of first appearance of vertebral arch primary centres and of neurocentral fusion, and vertebral arch *dimensions* before and after neurocentral fusion since asymmetry in these events and dimensions could relate to the pathogenesis of scoliosis and to the patterns of laterality of scoliotic curvatures (Knutsson 1963, Taylor 1978, 1980).

MATERIALS AND METHODS

Fetal material: Appearance of primary centres of ossification in vertebral arches.

Author's study

Twenty human fetuses in the range 38–82 mm CRL, fixed in 10 per cent formalin, were eviscerated, cleared by a modified Spalteholtz technique (Mall 1906) and stained by alizarin red, an accurate and sensitive indicator of ossifying bone (Noback & Robertson 1951).

- Each fetus was examined at low power magnification:
- to identify those fetuses in the "presacral stage" of appearance of vertebral arch ossification; i.e. presacral arch centres are present but no sacral centres are present;
 - to identify the vertebral level and side of any unilateral vertebral arch centres.

Review of the literature

Studies of vertebral ossification in human fetuses, which present detailed data on the presence of individual vertebral arch centres and identify the level and side of any unilateral centres, were reviewed. These studies with the author's material, made it possible to compute the incidence and distribution of unilateral centres in thoracic and lumbar vertebral arches (Table 1, Figure 1).

Postnatal material

From the large collection of human material at the Smithsonian Institute, Washington, DC, 39 infant and juvenile skeletons (35 Eskimo and 4 white North American) were obtained. In younger specimens the vertebral arches were separate from the centra. Older vertebrae were included if neurocentral fusion lines were visible. The approximate age of each skeleton, at the time of death, was derived from femoral length measurement (Dale-Stewart 1979). The vertebrae measured are grouped by age and region of the vertebral column in Table 2. The two principal age-groups, 0–6 years and 7–13 years, are chosen because neurocentral fusion has occurred in most vertebrae by the age of 7 years.

Table 1. Appearance of unilateral primary centres in presacral vertebral arches of fetuses

Author	No. of fetuses in range 33–93 mm CRL	No. of fetuses in presacral stage of ossification*	No. of unilateral centres	
			L	R
Mall	16	10	3	1
Teissandier	53	37	2	5
Noback & Robertson	56	28	—	14
Bagnall				
et al.	35	34	7	33
Taylor	20	13	2	5
Total	180	122	14	58

* Presacral arch centres present, but no sacral centres.

Inspection and measurement. Inspection for bilateral asymmetry revealed:

- Asymmetry in "pedicle length".
- Asymmetry in vertebral arch height.
- a) Asymmetry of the planes of the neurocentral joints.

VERTEBRAL ARCH ASYMMETRY AT 3 STAGES OF DEVELOPMENT

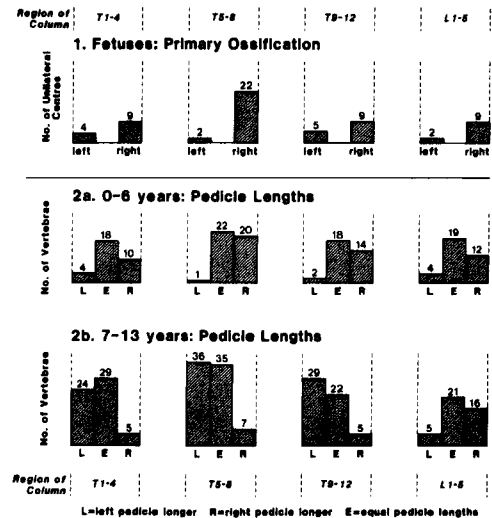


Figure 1. Note the correspondence of asymmetry in fetal ossification and infant pedicle lengths, and the reversal of asymmetry (thoracic levels) following neurocentral fusion.

Table 2. Postnatal material: number of vertebrae measured

Age range years	No. of vertebral columns	No. of vertebrae*				
		T1-4	T5-8	T9-12	L1-5	
0- 4	9	17	37	44	40	37
5- 6	8					
7- 8	9	22	67	80	65	61
9-11	10					
12-13	3					
Total	39	104	124	105	98	

* Most columns were incomplete.

b) Asymmetry in the extent of neurocentral fusion.
4. Anterior left flattening of some vertebral bodies.

These asymmetries appeared to show some consistency in relation to side. In addition some random tropism was seen. No vertebral body "wedging" was found.

To allow accurate measurement of asymmetries, all vertebrae were photographed, mounted in small groups on plasticine with their superior surfaces as nearly as possible normal to the plane of light from the Pentax macro lens. The Pentax K100 camera was mounted on a copypod directly above the vertebrae. Prints were made at low magnification ranging from $\times 2.5$ actual vertebral size for infant material to $\times 1$ for the oldest specimens.

1. "Pedicle length" was measured to the nearest 0.1 mm using Vernier calipers, from the vertebral arch margin at the centre of the neurocentral joint to the upper margin of the superior articular facet at its centre (thoracic vertebrae) or at its posterior margin (lumbar vertebrae).

Data recorded from 378 out of 431 vertebrae photographed, i.e. where there was no damage preventing accurate measurement, no distortion due to inaccurate mounting and neurocentral fusion lines were visible on both sides. Differences of 5 per cent or more between right and left are recorded R>L or L>R and lesser differences are recorded as "equal" (E) in Figure 1.

2. Vertebral arch heights were measured in 14 columns, where inspection suggested asymmetry in the "same direction" (e.g. R>L) in two or more adjacent vertebrae. Isolated examples of asymmetry in arch height were disregarded. Right and left heights were measured from the tip of each superior articular process to the lower margin of the lamina vertically below. Arch height asymmetry was compared to any pedicle length asymmetry in the same vertebrae to see if there was any correlation.

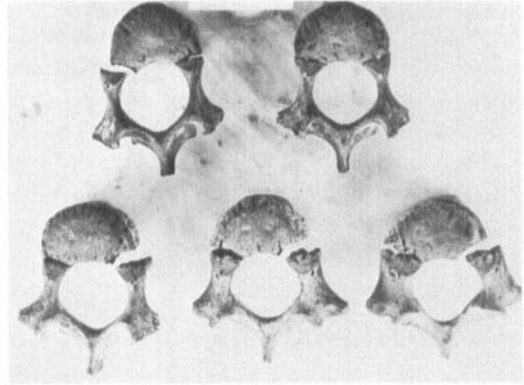


Figure 2. Asymmetry in neurocentral fusion in lumbar vertebrae (child aged 5 years).

3. Asymmetry. (a) Asymmetry in the planes of neurocentral fusion was demonstrated by a difference in the angles formed by the fusion lines when projected to the "mid-sagittal line" of the vertebra. The side with the smaller angle is termed "more sagittally oriented".

(b) Asymmetry of the timing or extent of neurocentral fusion:

Type 1: fused on one side; unfused on the other (Figure 2);

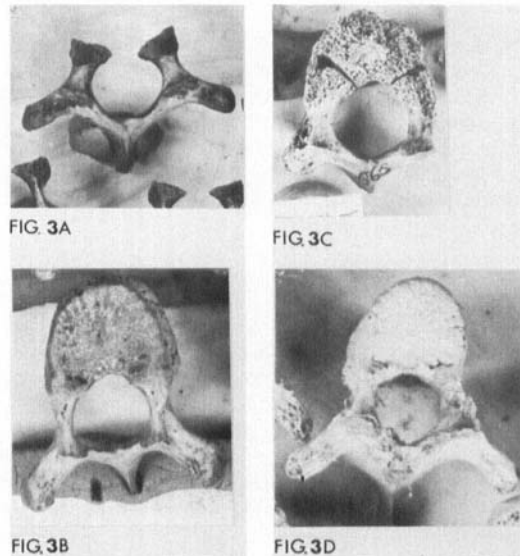


Figure 3. a) thoracic vertebral arch - age 5½ years. b) 9th thoracic vertebra - aged 8 years. c) 9th thoracic vertebra - aged 11 years. d) 5th thoracic vertebra - aged 11 years.

Table 3. Numbers of vertebrae showing asymmetry in neurocentral fusion

Vertebral level	More advanced on left			More advanced on right		
	Type 1	Type 2	Total	Type 1	Type 2	Total
	T1-6	—	2	2	—	6
T8-L1	—	2	2	1	7	8
L2-5	10	2	12	—	—	0

Type 2: fused on both sides with unequal extent of fusion (Figure 3b).

The number of cases of asymmetry was noted according to vertebral level (Table 3).

Vertebral body flattening on the left anterior aspect is recorded as the percentage of vertebrae, at each vertebral level, showing such flattening, as judged by inspection.

RESULTS

Asymmetrical appearance of primary centres of ossification

Figure 1 and Table 1 show the number and distribution of unilateral centres in five studies including the author's study. Thirty-one per cent of 122 fetuses showed one or more unilateral centres. Of unilateral centres, 58/72 are on the right side. This is a highly significant departure from the expected random distribution. In the mid thoracic region, 22/24 of unilateral centres are on the right side. Many unilateral centres occur in two or more successive vertebral arches on the same side: there are 10 examples of two successive centres, three of three successive centres and one of five successive centres. Most of these involve the T5-10 region on the right side.

Postnatal growth

1. *Pedicle lengths.* Pedicle lengths on right and left are unequal by 5 per cent or more in about half the vertebrae measured in both age groups but the distribution of the asymmetry differs

dramatically comparing two age groups (Figure 1).

In the 0-6 year age group the right pedicle is longer in 56/67 of all vertebrae showing pedicle length asymmetry, but the left pedicle is the longer in 36/43 of those thoracic vertebrae showing asymmetry in the 7-13 year age-group. In both age groups the distribution of asymmetry represents a highly significant departure from a random asymmetry. Lumbar vertebrae are the only ones measured which do not reverse the "direction" of asymmetry at 7 years.

2. *Vertebral arch height.* Generally, longer pedicles correspond to lesser arch heights, i.e. the arch height is greater on the side opposite the longer pedicle. This correlation of "opposite asymmetries" involves two or more adjacent vertebrae in each of 10 columns from the 7-13 years group. Vertebrae from T4 to L1, particularly in the region T6 to T9, are involved. In seven columns longer left pedicles correlate with higher right arches and in three columns longer right pedicles correlate with higher left arches.

3. *Neurocentral fusion.* In this material, neurocentral fusion takes place at 4 years in the lumbar region and is complete between 7 and 8 years in the midthoracic region. Fusion lines remain visible until 11 years and occasionally till 13 years.

a. *Plane of fusion:* In most columns showing planar asymmetry, in both younger and older groups, the more sagittally oriented neurocentral joints correspond to the side of the longer pedicles in small groups of adjacent vertebrae. Correspondence between longer pedicles and more sagittally oriented joints is most consistent in mid and lower thoracic vertebrae.

b. *Extent of fusion:* Examples of type 1 or type 2 asymmetry are seen in 20/32 skeletons in the 4-11 year range. Five columns show asymmetrical fusion in two or more lumbar vertebrae. The region T2-7 is least often involved (Table 3). L1 is grouped with lower thoracic vertebrae as it resembles them, having fusion more advanced on the right than on the left when there is asymmetry (Figure 2).

4. *Anterior left vertebral body flattening.* No

flattening was seen in the 0–6 year age-group. In the 7–13 year group, flattening was found in vertebrae in the range T4 to L3, varying from 5 per cent of T4, L2 and L3 vertebrae to 28 per cent of vertebrae in the T7 to L1 regions (Figure 3d).

DISCUSSION

A slight thoracic scoliosis, usually convex to the right, is a normal feature of the adult vertebral column. Farkas (1941) and Taylor (1978) describe it as convex to the right in the mid or lower thoracic region. Its presence is attributed to aortic pressure or to right handedness, but the curve is not present at birth and its direction is not consistently related to handedness or consistently directed away from the side of aortic pressure. Most attention has been given to asymmetry in vertebral bodies with scant attention to asymmetry in vertebral arches (Miles 1944).

School screening surveys show that a high proportion of the adolescent population have mild scoliotic curves of a similar nature to those described as physiological in adults (Lonstein 1977, Taylor & Slinger 1980). In addition, progressive scoliosis in adolescents whether idiopathic or associated with muscle paralysis, tends to have the major curve convex to the right in the thoracic region (Moe & Kettleson 1970). The *constancy* of this common pattern of right thoracic scoliosis suggests that some *common factor of normal growth* determines the direction and situation of the curve. On the other hand, scoliosis in infants is usually convex to the left in the thoracic region and frequently resolves spontaneously, and may occasionally reverse its direction by adolescence in the same individuals (Bjerkreim 1977, Taylor 1980).

These well recognized patterns of scoliotic curvature in infancy and adolescence, correlate well with the patterns of asymmetry and "out of phase" growth observed in the current study. The appearance of right neural arch centres before the corresponding left centres, most frequently in the mid-thoracic region, constitutes good evidence that the right mid-thoracic arches are more mature than their left counterparts. This differ-

ence in maturity varies from one to five centres "in advance" on the right. In the time taken for five centres to appear, the fetus would be expected to increase in length by about 20 per cent (Noback & Robertson 1951). The observation that right mid-thoracic pedicles are most frequently longer than corresponding left pedicles in infants and young children suggests that this difference in maturity persists postnatally. Correlation of asymmetry in pedicle length with asymmetry in the plane of neurocentral joints provides supportive evidence for the real nature of these small changes. Both asymmetries tend to give the appearance of vertebral bodies rotated towards the left side.

The greater frequency of unilateral centres on the right from T5 to T8 suggest the possibility that differences in oxygenation of blood in fetal aortic arch and ductus arteriosus, with spiralling of flow, may facilitate earlier appearance of the right mid thoracic vertebral arch centres. However, this could not account for the greater frequency of right unilateral centres at all levels (Figure 1).

The most surprising finding of the current study is the reversal of thoracic pedicle length asymmetry at about the time of neurocentral closure. In the 7–13 year age group, the left pedicles are longer than the right pedicles in 49 per cent of mid and lower thoracic vertebrae. In this older group, three forms of bilateral asymmetry correlate well: pedicle length ($L > R$), neurocentral joint planes (left more nearly sagittal) and arch heights ($R > L$). These asymmetries would tend to produce thoracic vertebral body "rotation" to the right side and when lumbar vertebral body "rotation" is in the opposite direction, a right thoracic scoliosis would also result. These postnatal developmental asymmetries are described in Eskimo skeletons where the prevalence of scoliosis is not known. A preliminary survey of European juvenile vertebral columns shows a broadly similar pattern (Taylor 1983).

Asymmetry in neurocentral fusion is most obvious in lumbar vertebrae, being opposite in direction in L1 (right before left) compared to L2-5 (left before right) (Figure 2). Thoracic vertebrae resemble L1 in their pattern of asymmetrical fusion but the asymmetry is less obvious (Fig-

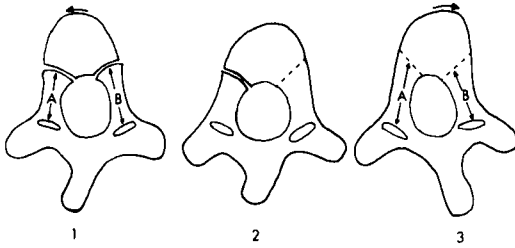


Figure 4. Reversal of "physiological scoliosis": unequal lengths produce vertebral body rotation away from the longer pedicle.

ure 3b). These asymmetries may reflect earlier closure on one side, with continuation of growth in the opposite side, which could account for the reversal of the original pedicle length asymmetry and direction of vertebral body "rotation" (Figure 4).

Vertebral body flattening on those surfaces in contact with the descending aorta, is absent in the 0–6 year group, and its prevalence increases from 30 per cent of vertebrae in the 7–13 year age-group, to 40–70 per cent of adult vertebrae (Dale-Stewart 1952). This suggests a progressive effect of aortic pressure on appositional bone growth, increasing with growth to maturity. The asymmetrical pulsatile pressure of the aorta may also affect neural arch growth by transmitted pressure. The transmitted force would have a rotational moment to the right anterior to the spinal canal. The vertebral levels showing vertebral body flattening correspond to those showing the most dramatic reversal of arch asymmetry.

There is some relation between the side of convexity of a thoracic scoliosis, the side of the longer upper limb, and handedness (Burwell & Dangerfield 1977, Taylor & Slinger 1980). Haderspeck & Schulz (1981) have shown that imbalance of lateral bending muscle forces may increase existing scoliotic curves and it is possible that greater muscle development on the side of the dominant limb influences spinal posture in adolescents.

The aetiology of progressive idiopathic scoliosis is complex. The familial nature of the condition is well established (Wynne-Davies 1968), the genetic influence probably being polygenic (Cziezel *et al.* 1981). Sex differences in

prevalence, possibly due to differences in vertebral body shape and muscle support (Taylor & Slinger 1980) are probably also genetically mediated.

This study shows that normal growth factors underlie the observed patterns of curvature in infants and in adolescents with idiopathic and other forms of scoliosis. In particular, out of phase appearance of neural arch centres and asymmetrical fusion of neurocentral joints are associated with asymmetry in pedicle length tending to produce vertebral body rotation with thoracic scoliosis which is usually convex to the left in infants and convex to the right in adolescents. Different "degrees" of asymmetry may well be under genetic control and may relate in part to asymmetry of oxygenation in the intercostal arteries arising from the fetal descending aorta and to the pressures exerted on bony vertebrae by the asymmetrically disposed descending aorta.

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