J. Anat. (1991), **178**, pp. 21–38
With 4 figures
Printed in Great Britain

A segmental analysis of thoracic shape in chest radiographs of children. Changes related to spinal level, age, sex, side and significance for lung growth and scoliosis

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(*Accepted* 10 *April* 1991)

INTRODUCTION

The thorax, like any other part of the skeleton, displays variations in dimensions and proportions which are partly individual and also linked to age, sex and race (Williams & Warwick, 1980). The bony framework has the shape of a truncated cone. At birth the chest's bony framework is quite flexible; the chest is nearly circular in shape, and the plane of the ribs is nearly horizontal. As the child develops an erect posture, the shape of the chest changes so that the lateral dimension of the chest cavity exceeds the anteroposterior dimension and the ribs become structurally stronger (Keith, 1923; Meredith & Knott, 1937; Kendig, 1977; Burwell *et al.* 1983; Grivas, 1984).

The outstanding function of the thorax is in respiration. In addition, the ribs are the principal agents for the support of the thoracic vertebrae by virtue of their rigidity, not only as bony braces but also because of their service as instruments through which the forces exerted by the attached muscles and ligaments and the forces of intrathoracic pressures and stresses are transmitted to the vertebrae through their costovertebral articulations (Bisgard, 1934). In standing, sitting and lifting the trunk must balance on the pelvis, as it must also during walking, as the trunk moves along the vertical and lateral as well as the progressional axis (Davis, 1959; Morris *et al.* 1961; Waters & Morris, 1972; see also Newman, 1968).

The appraisal of thoracic functions in health and disorder by structural methods has included measurements of the ribcage on radiographs: (1) to estimate lung volume (Hurtado & Fray, 1933; Prime, 1971; Simon *et al.* 1972); and (2) to measure rib–vertebra angles segmentally in relation to the spinal deformity of scoliosis (Wojcik *et al.* 1990*a*, *b*; Wythers, 1990; Wythers *et al.* 1991*a*, *b*, *c*).

Most recently, the study of a new surgical treatment for progressive infantile idiopathic scoliosis suggested that the upper thorax in this disorder, like that of the normal infant, is funnel-shaped (Grivas *et al.* 1990*a*, *b*; 1991*e*). The finding was confirmed in a preliminary report of 24 preoperative children with progressive IIS compared with 233 age-matched controls (Grivas *et al.* 1990*c*; 1991*a*, *b*). In this comparison, a new method was developed to measure thoracic shape segmentally. First we report details of the thoracic ratio method used to calculate thoracic shape in the controls; then we give our findings for the entire sample of control children.

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Table 1. *Number of boys and girls by age* ($n = 412$)

Age (years)	Boys ($n = 193$)	Girls ($n = 219$)
0–0·999	13	17
1–1·999	13	18
2–2·999	11	19
3–3·999	16	21
4–4·999	11	12
5–5·999	12	13
6–6·999	10	12
7–7·999	12	10
8–8·999	8	12
9–9·999	12	11
10–10·999	15	11
11–11·999	11	13
12–12·999	11	11
13–13·999	10	8
14–14·999	9	12
15–15·999	7	17
16–16·999	3	2
17–17·999	9	0

These show that thoracic shape in the frontal plane is related to spinal level, age, sex and side with implications for (1) the adaptation of the ribcage to the upright posture and gait, (2) lung growth and (3) the causation of idiopathic scoliosis.

The rib–vertebra angle findings bilaterally from ribs 1–12 for the same sample of children are reported in separate papers (Grivas *et al.* 1991*c*, *d*).

MATERIAL AND METHODS

The subjects

Posteroanterior (PA) chest radiographs were obtained from 412 children attending the Accident and Emergency Department at the University Hospital, Nottingham, during 1989–90 (Table 1). The children selected had minimal disorders or diseases involving trauma, infections, foreign bodies, heart murmurs and mild asthma. None of the patients had a scoliosis of 5° or more. Two patients with congenital fusion of upper ribs both in a hemithorax were identified but not included in this series. Radiographs which were oblique were excluded. The chest radiographs were usually obtained in full inspiration.

Age and sex groups

The age of each subject was calculated as decimal age. The subjects were arranged into three age groups by sex in accordance with the classification of Karlberg (1989) (infancy = 0–2.999 years, boys = 37, girls = 54; childhood = 3–10.999 years, boys = 96, girls = 102; and puberty = 11–17.999 years, boys = 60, girls = 63).

Measurements on chest radiographs

Thoracic ratios

On each chest radiograph, the outline of the lateral border of the thorax is drawn (Fig. 1). Next, the midpoint of the distal end-plate at each vertebral body from T1–12 is marked. Then, at each segment, the distance from the middle of the end-plate to the outline of each of the right and left thoracic cage is measured. These distances are

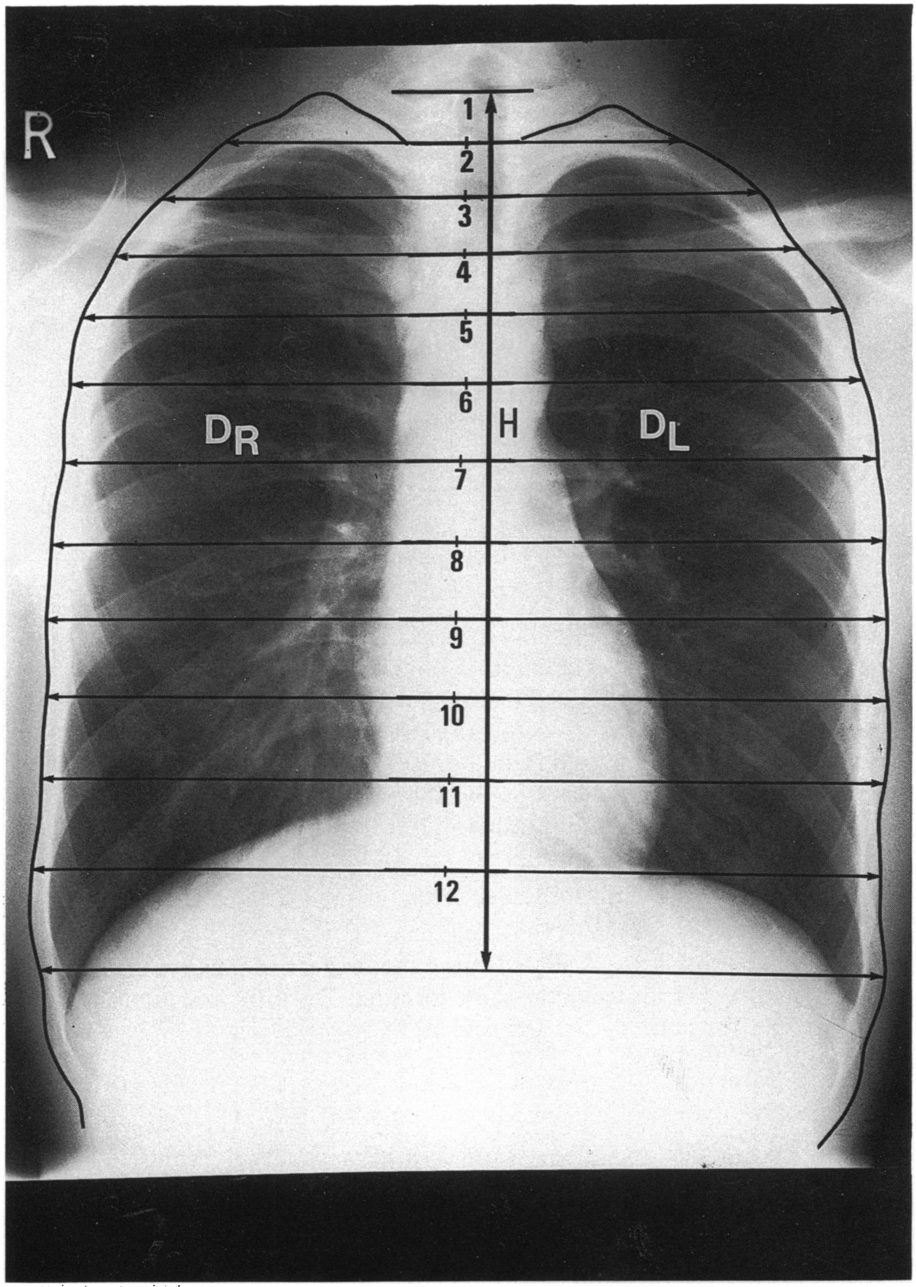

Fig. 1. Chest radiograph to show the method of measurement for calculation of thoracic ratios. D_R (D_L) = distance measured from midpoint of the distal end-plate of each vertebral body (T1–12) to the outline of the lateral border of the right (left) thoracic cage. H, distance from T1–12 (see text).

standardised by dividing by the measured T1–12 distance. They are termed segmental right and left thoracic ratios (TRs). Ratios are also calculated segmentally for the total width of the chest (right plus left measured lengths).

Table 2. *Reliability study for thoracic ratio method: intra and interobserver error study* (95 % *confidence limits*)

Hemithorax...	Thoracic spinal level	Right Observer error*		Left Observer error*	
		Intra	Inter	Intra	Inter
	1	0·0126	0·0272	0·0181	0·0219
	2	0·0058	0·0140	0·0207	0·0391
	3	0·0095	0·0170	0·0181	0·0301
	4	0·0111	0·0253	0·0133	0·0293
	5	0·0168	0·0264	0·0180	0·0246
	6	0·0124	0·0311	0·0051	0·0277
	7	0·0053	0·0354	0·0083	0·0235
	8	0·0065	0·0360	0·0071	0·0251
	9	0·0046	0·0385	0·0240	0·0325
	10	0·0064	0·0356	0·0177	0·0211
	11	0·0062	0·0293	0·0235	0·0166
	12	0·0066	0·0358	0·0239	0·0262

*95 % confidence limits.

Reliability study for thoracic ratios

The chest radiographs of 10 children, 5 boys and 5 girls, aged within the range of the study population, were obtained from the Agia Sofia Paediatric Hospital, Athens. Segmental thoracic ratios (TRs) were calculated twice (TBG) for the right and left hemithoraces from T1–12 on each radiograph. The difference for each pair (right and left) of TRs was then calculated. Finally, the intraobserver error was calculated as 95 % confidence limits using the formula:

$$\text{Intraobserver error:} = \frac{\text{SD}}{\sqrt{2}} \times 2$$

The interobserver error was calculated using the first set of TBG readings and those of an orthopaedic registrar, using the same formula. The intra and interobserver error findings for TRs for each of the left and right spinal levels (T1–12) are shown in Table 2.

Statistical analysis

Statistical techniques included Mann–Whitney, Kruskal–Wallis, Pearson and Spearman correlation coefficients, ANOVA, t test for asymmetry, and tests for skewness and kurtosis including the one-sample Kolmogorov–Smirnov test.

RESULTS

Thoracic ratios (*TRs*)

Figure 2 shows the thoracic ratios by level for left and right hemithorax for each of the boys and girls in the 3 age groups (infancy, childhood and puberty, Tables 3–5).

TR changes with spinal rib level

Figure 2 shows that for each age group in boys and girls, the TRs increase from T1 to about T10–11 (Tables 3–5).

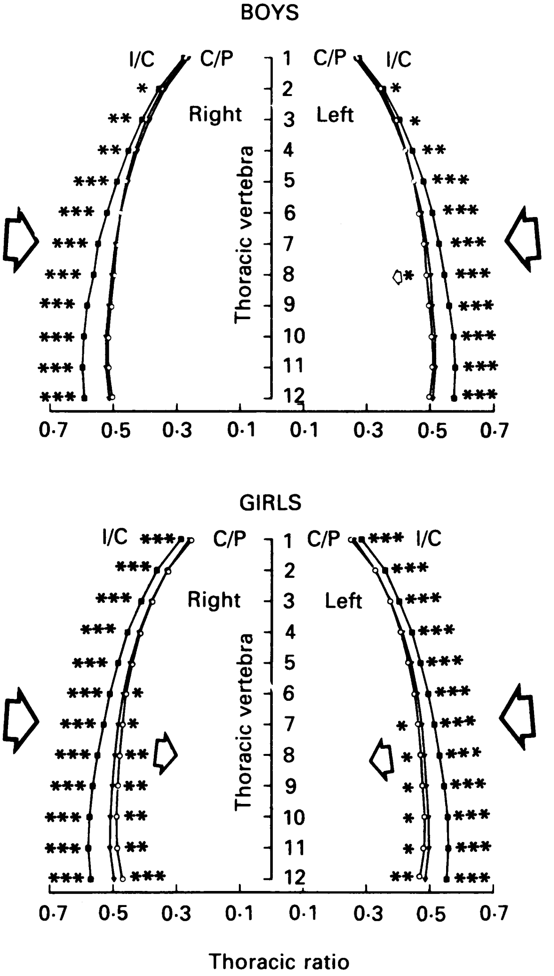

Fig. 2. Thoracic ratios for control boys and girls plotted by age group (infancy, childhood and puberty; see text). I/C, infancy/childhood; C/P, childhood/puberty. ■, infancy; ▼, childhood; ○, puberty. * $0{\cdot}01 < P < 0{\cdot}05$; ** $0{\cdot}001 < P < 0{\cdot}01$; *** $P < 0{\cdot}001$.

TR changes with age

Between infancy and childhood in both boys and girls there is a statistically very highly significant reduction in TRs which is least evident in the upper part of the chest in boys (Fig. 2; Tables 3–5). The percentage diminution of TRs is greater in girls than boys at T1–4 (average diminution, boys 4·9% left, 5·2% right; girls 7·7% left, 8·6% right). At T5 and below the percentage diminution is similar (average diminution, boys 8·7% left, 10·3% right; girls 9·2% left, 10·3% right).

Between childhood and puberty, the boys show little or no change in thoracic ratios. In contrast, the girls show a further relative narrowing of the lower chest below T5 (T7–12, 3·3% average diminution), but little or no change in the upper part of the chest (T1–6, 1·3% average diminution).

TRs and sex differences

In infancy, there are no significant differences in TRs between boys and girls (Tables 3–5).

Table 3. *Thoracic ratios (left) according to spinal level, age group and sex*

		Boys				Girls				
Spinal level	Age group	Mean	*P* I/C C/P	±1SD	*P*¹ for age	Mean	*P* I/C C/P	±1SD	*P*¹ for age	*P*² boys/ girls
1	I	0·276	ns	0·037		0·285	***	0·042		ns
	C	0·262		0·037	ns	0·260		0·034	***	ns
	P	0·271	ns	0·038		0·252	ns	0·035		**
2	I	0·352	*	0·037		0·359	***	0·045		ns
	C	0·336		0·037	*	0·329		0·038	***	ns
	P	0·345	ns	0·034		0·329	ns	0·035		**
3	I	0·404	*	0·038		0·404	***	0·045		ns
	C	0·384		0·039	*	0·377		0·042	***	ns
	P	0·391	ns	0·037		0·376	ns	0·036		**
4	I	0·444	**	0·037		0·444	***	0·051		ns
	C	0·422		0·036	*	0·414		0·039	***	ns
	P	0·423	ns	0·031		0·410	ns	0·035		*
5	I	0·479	***	0·035		0·471	***	0·049		ns
	C	0·449		0·038	***	0·442		0·041	***	ns
	P	0·448	ns	0·030		0·434	ns	0·037		**
6	I	0·507	***	0·038		0·495	***	0·054		ns
	C	0·473		0·037	***	0·461		0·040	***	*
	P	0·467	ns	0·032		0·453	ns	0·037		**
7	I	0·528	***	0·035		0·514	***	0·051		ns
	C	0·489		0·037	***	0·475		0·040	***	*
	P	0·482	ns	0·033		0·464	*	0·040		**
8	I	0·545	***	0·038		0·530	***	0·051		ns
	C	0·502		0·040	***	0·483		0·041	***	**
	P	0·489	*	0·034		0·472	*	0·041		**
9	I	0·560	***	0·042		0·545	***	0·049		ns
	C	0·507		0·042	***	0·489		0·042	***	**
	P	0·499	ns	0·037		0·477	*	0·043		**
10	I	0·574	***	0·045		0·556	***	0·045		ns
	C	0·516		0·043	***	0·496		0·045	***	**
	P	0·507	ns	0·045		0·484	*	0·045		**
11	I	0·579	***	0·051		0·558	***	0·044		ns
	C	0·517		0·044	***	0·497		0·044	***	ns
	P	0·511	ns	0·042		0·483	*	0·049		ns
12	I	0·575	***	0·057		0·553	***	0·047		ns
	C	0·509		0·046	***	0·486		0·047	***	ns
	P	0·499	ns	0·046		0·468	**	0·052		ns

I, infancy; C, childhood; P, puberty; ¹, Kruskal–Wallis test; ², Mann–Whitney test; ns, not significant; * $0·01 < P < 0·05$; ** $0·001 < P < 0·01$; *** $P < 0·001$. *P* for I/C and C/P = infancy compared with childhood, and childhood compared with puberty, respectively.

In childhood, there are no sex differences for TRs at T1–5 in the left hemithorax (Table 4) and at T1–9 in the right hemithorax (Table 4). The sex differences for left TRs are at T6 to T10. The findings show that the TRs are lower in girls than in boys and particularly for the left hemithorax; i.e. the lower, particularly left, chest of girls is narrower than that of boys (see below, TR asymmetry).

In puberty, the girls' TRs are significantly lower than those for the boys at most levels (left T1–10, right T1–12; Tables 3–5). Again, these findings imply that from 11 years of age the girls' thoracic cage is narrower relative to spinal length than that of the boys at most levels (Table 5).

Table 4. *Thoracic ratios (right) according to spinal level, age group and sex*

		Boys				Girls				
Spinal level	Age group	Mean	P I/C C/P	±1SD	P^1 *for age*	Mean	P I/C C/P	±1SD	P^1 for age	P^2 boys/girls
1	I	0·270	ns	0·042		0·287	***	0·039		ns
	C	0·262		0·037	ns	0·260		0·033	***	ns
	P	0·270	ns	0·040		0·252	ns	0·035		**
2	I	0·356	*	0·049		0·363	***	0·045		ns
	C	0·336		0·038	ns	0·330		0·038	***	ns
	P	0·345	ns	0·037		0·330	ns	0·037		*
3	I	0·409	**	0·044		0·413	***	0·043		ns
	C	0·385		0·039	*	0·381		0·041	***	ns
	P	0·395	ns	0·035		0·379	ns	0·038		*
4	I	0·452	**	0·046		0·456	***	0·044		ns
	C	0·424		0·036	**	0·419		0·042	***	ns
	P	0·432	ns	0·033		0·416	ns	0·039		**
5	I	0·488	***	0·044		0·485	***	0·042		ns
	C	0·453		0·036	***	0·447		0·042	***	ns
	P	0·458	ns	0·032		0·440	ns	0·039		**
6	I	0·519	***	0·046		0·511	***	0·042		ns
	C	0·476		0·036	***	0·468		0·041	***	ns
	P	0·477	ns	0·032		0·460	*	0·039		**
7	I	0·547	***	0·048		0·530	***	0·044		ns
	C	0·492		0·036	***	0·484		0·042	***	ns
	P	0·488	ns	0·033		0·470	*	0·041		**
8	I	0·561	***	0·051		0·549	***	0·045		ns
	C	0·504		0·040	***	0·494		0·041	***	ns
	P	0·497	ns	0·036		0·479	**	0·041		**
9	I	0·582	***	0·057		0·564	***	0·047		ns
	C	0·513		0·042	***	0·502		0·042	***	ns
	P	0·507	ns	0·040		0·485	**	0·043		**
10	I	0·592	***	0·059		0·574	***	0·048		ns
	C	0·522		0·044	***	0·508		0·044	***	*
	P	0·516	ns	0·042		0·489	**	0·046		***
11	I	0·579	***	0·064		0·578	***	0·049		ns
	C	0·522		0·045	***	0·510		0·046	***	ns
	P	0·516	ns	0·041		0·487	**	0·047		***
12	I	0·591	***	0·068		0·570	***	0·050		ns
	C	0·512		0·049	***	0·497		0·048	***	*
	P	0·503	ns	0·046		0·471	***	0·050		***

I, infancy; C, childhood; P, puberty; [1], Kruskal–Wallis test; [2], Mann–Whitney test; ns, not significant; * $0·01 < P < 0·05$; ** $0·001 < P < 0·01$; *** $P < 0·001$.

Right TRs and left TRs plotted against age

Tables 6 and 7 show the TRs analysed against age for the left and right hemithorax respectively. The findings show statistically significant sex differences at T5–12. These findings support the conclusion that the thoracic cage of girls is narrower (relative to spinal length) than that of boys and particularly in the lower half of the chest (T5–12).

TR asymmetry

Table 8 shows TR differences (TRDs, left minus right) by level for each of the boys and girls in the three age groups. The mean TR differences that are statistically significantly different for asymmetry are all negative, implying larger right than left thoracic ratios.

The findings show, in infant boys, a significant TR asymmetry from T3–12; and in

Table 5. *Thoracic ratios (left plus right) according to spinal level, age group and sex*

		Boys				Girls				
Spinal level	Age group	Mean	*P* I/C C/P	±1 SD	*P*^{1} *for age*	Mean	*P* I/C C/P	±1 SD	*P*^{1} for age	*P*^{2} boys/girls
1	I	0·554	ns	0·077		0·572	***	0·080		ns
	C	0·524		0·074	ns	0·521		0·067	***	ns
	P	0·541	ns	0·078		0·504	ns	0·069		**
2	I	0·708	*	0·084		0·722	***	0·089		ns
	C	0·672		0·075	ns	0·659		0·076	***	ns
	P	0·690	ns	0·070		0·659	ns	0·071		*
3	I	0·813	**	0·081		0·817	***	0·086		ns
	C	0·768		0·077	*	0·758		0·082	***	ns
	P	0·786	ns	0·068		0·755	ns	0·073		**
4	I	0·896	**	0·082		0·899	***	0·091		ns
	C	0·846		0·071	**	0·834		0·079	***	ns
	P	0·855	ns	0·061		0·826	ns	0·071		**
5	I	0·967	***	0·077		0·957	***	0·087		ns
	C	0·903		0·072	***	0·890		0·081	***	ns
	P	0·906	ns	0·059		0·874	ns	0·073		**
6	I	1·026	***	0·080		1·007	***	0·088		ns
	C	0·948		0·071	***	0·929		0·079	***	*
	P	0·943	ns	0·062		0·913	ns	0·074		**
7	I	1·075	***	0·078		1·044	***	0·084		ns
	C	0·981		0·071	***	0·959		0·079	***	*
	P	0·970	ns	0·064		0·935	*	0·078		***
8	I	1·107	***	0·085		1·079	***	0·084		ns
	C	1·006		0·076	***	0·977		0·078	***	*
	P	0·986	ns	0·066		0·951	*	0·079		**
9	I	1·142	***	0·093		1·109	***	0·085		ns
	C	1·020		0·081	***	0·991		0·080	***	*
	P	1·006	ns	0·074		0·962	*	0·083		***
10	I	1·165	***	0·100		1·130	***	0·082		ns
	C	1·038		0·084	***	1·004		0·085	***	**
	P	1·023	ns	0·079		0·974	*	0·087		***
11	I	1·176	***	0·111		1·136	***	0·082		ns
	C	1·039		0·085	***	1·007		0·085	***	*
	P	1·027	ns	0·080		0·970	**	0·092		***
12	I	1·165	***	1·121		1·123	***	0·086		ns
	C	1·021		0·090	***	0·983		0·090	***	**
	P	1·002	ns	0·088		0·938	**	0·098		***

I, infancy; C, childhood; P, puberty; ^{1}, Kruskal–Wallis test; ^{2}, Mann–Whitney test; ns, not significant; * $0·01 < P < 0·05$; ** $0·001 < P < 0·01$; *** $P < 0·001$.

infant girls significant TR asymmetry from each of T3–6 and T9–10. In childhood, the boys show TR asymmetry present at T5 and T9–10, and the girls at T3–12. In puberty, the boys show TR asymmetry at T4–10 and the girls at T4–9. Little or no age effect in TR asymmetry is found. A sex difference in TR asymmetry is detectable only in childhood and only at three levels (T6–8, each about 1 % asymmetry). The findings show that the right TRs at T6–8 are greater in girls than in boys by about 0·5–1 %.

DISCUSSION

The method of thoracic ratios we report here as a means of expressing chest shape and relative size has not previously been reported.

Table 6. *Thoracic ratios (left) for boys and girls by spinal level and age*

Spinal level	Sex	Linear regression equation ($y = a+bx$)		Correlation coefficient	Significance of r	P^1 boys/girls
		a	b	r		
1	Boys	0·265	0·0002	0·035	ns	ns
	Girls	0·280	−0·002	−0·290	***	
2	Boys	0·341	0·00003	−0·004	ns	ns
	Girls	0·350	−0·001	−0·226	***	
3	Boys	0·392	−0·0002	−0·035	ns	ns
	Girls	0·396	−0·001	−0·210	**	
4	Boys	0·435	−0·001	−0·154	*	ns
	Girls	0·436	−0·002	−0·245	***	
5	Boys	0·470	−0·002	−0·263	***	*
	Girls	0·466	−0·002	−0·290	***	
6	Boys	0·499	−0·002	−0·352	***	**
	Girls	0·489	−0·003	−0·324	***	
7	Boys	0·520	−0·003	−0·414	***	***
	Girls	0·508	−0·003	−0·378	***	
8	Boys	0·540	−0·004	−0·480	***	***
	Girls	0·522	−0·004	−0·423	***	
9	Boys	0·551	−0·004	−0·485	***	***
	Girls	0·535	−0·005	−0·473	***	
10	Boys	0·563	−0·005	−0·482	***	***
	Girls	0·545	−0·005	−0·488	***	
11	Boys	0·566	−0·005	−0·472	***	***
	Girls	0·549	−0·006	−0·508	***	
12	Boys	0·563	−0·006	−0·495	***	***
	Girls	0·544	−0·006	−0·542	***	

[1] ANOVA for sex corrected for age; ns, not significant; * $0·01 < P < 0·05$; ** $0·001 < P < 0·01$; *** $P < 0·001$.

Table 7. *Thoracic ratios (right) for boys and girls by spinal level and age*

Spinal level	Sex	Linear regression equation ($y = a+bx$)		Correlation coefficient	Significance for r	P^1 boys/girls
		a	b	r		
1	Boys	0·267	0·00004	0·006	ns	ns
	Girls	0·282	−0·002	−0·320	***	
2	Boys	0·344	−0·0001	−0·015	ns	ns
	Girls	0·352	−0·002	−0·222	***	
3	Boys	0·395	−0·0002	−0·028	ns	ns
	Girls	0·403	−0·002	−0·232	***	
4	Boys	0·438	−0·0008	−0·103	ns	ns
	Girls	0·446	−0·003	−0·280	***	
5	Boys	0·475	−0·002	−0·208	**	*
	Girls	0·478	−0·003	−0·342	***	
6	Boys	0·505	−0·003	−0·313	***	*
	Girls	0·502	−0·004	−0·383	***	
7	Boys	0·531	−0·004	−0·421	***	**
	Girls	0·523	−0·004	−0·441	***	
8	Boys	0·548	−0·004	−0·462	***	**
	Girls	0·540	−0·005	−0·493	***	
9	Boys	0·565	−0·005	−0·480	***	**
	Girls	0·554	−0·006	−0·527	***	
10	Boys	0·576	−0·005	−0·484	***	***
	Girls	0·564	−0·006	−0·547	***	
11	Boys	0·580	−0·006	−0·492	***	***
	Girls	0·565	−0·007	−0·567	***	
12	Boys	0·575	−0·006	−0·512	***	***
	Girls	0·562	−0·007	−0·590	***	

[1] ANOVA for sex corrected for age; ns, not significant; * $0·01 < P < 0·05$; ** $0·001 < P < 0·01$; *** $P < 0·001$.

Table 8. *Thoracic ratio differences (TRDs, left minus right) according to spinal level, age group and sex*

		Boys					Girls					
Spinal level	Age group	Mean		±1SD	*P* for asymmetry	P^1 for age	Mean		±1SD	*P* for asymmetry	P^1 for age	P^2 boys/girls
1	I	−0·002	ns	0·012	ns		−0·002	ns	0·009	ns		ns
	C	0·000		0·009	ns	ns	0·000		0·009	ns	ns	ns
	P	0·001	ns	0·007	ns		0·000	ns	0·008	ns		ns
2	I	−0·004	ns	0·019	ns		−0·003	ns	0·012	ns		ns
	C	−0·001		0·011	ns	ns	−0·001		0·010	ns	ns	ns
	P	0·000	ns	0·013	ns		−0·002	ns	0·014	ns		ns
3	I	−0·005	ns	0·017	*		−0·009	*	0·019	**		ns
	C	−0·001		0·012	ns	ns	−0·003		0·013	*	ns	ns
	P	−0·004	ns	0·015	ns		−0·003	ns	0·020	ns		ns
4	I	−0·008	ns	0·020	*		−0·012	ns	0·026	**		ns
	C	−0·002		0·015	ns	ns	−0·005		0·018	*	ns	ns
	P	−0·008	ns	0·017	***		−0·006	ns	0·020	*		ns
5	I	−0·010	ns	0·022	*		−0·014	ns	0·029	***		ns
	C	−0·004		0·017	*	ns	−0·005		0·019	**	ns	ns
	P	−0·010	*	0·018	***		−0·006	ns	0·022	*		ns
6	I	−0·012	ns	0·025	**		−0·016	ns	0·039	**		ns
	C	−0·003		0·019	ns	ns	−0·008		0·018	***	ns	*
	P	−0·010	*	0·018	***		−0·007	ns	0·019	**		ns
7	I	−0·019	*	0·032	***		−0·016	ns	0·046	ns		ns
	C	−0·003		0·020	ns	ns	−0·009		0·021	***	ns	*
	P	−0·007	ns	0·020	*		−0·006	ns	0·020	*		ns
8	I	−0·016	ns	0·032	**		−0·020	ns	0·046	ns		ns
	C	−0·002		0·024	ns	ns	−0·011		0·023	**	ns	*
	P	−0·009	ns	0·022	**		−0·007	ns	0·023	*		ns
9	I	−0·022	*	0·036	***		−0·019	ns	0·046	*		ns
	C	−0·005		0·023	*	ns	−0·014		0·027	***	ns	ns
	P	−0·008	ns	0·023	**		−0·008	ns	0·023	*		ns
10	I	−0·018	ns	0·036	**		−0·019	ns	0·046	*		ns
	C	−0·005		0·025	*	ns	−0·012		0·028	**	ns	ns
	P	−0·009	ns	0·025	**		−0·005	ns	0·025	ns		ns
11	I	−0·019	ns	0·035	**		−0·020	ns	0·046	ns		ns
	C	−0·005		0·027	ns	ns	−0·013		0·029	**	*	ns
	P	−0·005	ns	0·025	ns		−0·004	*	0·027	ns		ns
12	I	−0·016	ns	0·033	**		−0·017	ns	0·044	ns		ns
	C	−0·004		0·029	ns	ns	−0·010		0·031	**	ns	ns
	P	−0·004	ns	0·027	ns		−0·003	ns	0·029	ns		ns

I, infancy; C, childhood; P, puberty; [1], Kruskal–Wallis test; [2], Mann–Whitney test; ns, not significant; * $0·01 < P < 0·05$; ** $0·001 < P < 0·01$; *** $P < 0·001$.

The ICP model of growth

An important feature of our analysis of thoracic ratios in children from 0 to 17 years is the use of the ICP model of Karlberg (1985, 1989). This model breaks down growth mathematically into three additive and partly superimposed components – infancy, childhood and puberty. These components strongly reflect the different hormonal phases of the growth process. As a result, the model provides an improved instrument for detecting and understanding growth failure. It has already been considered in relation to Perthes' disease (Burwell *et al.* 1986) and applied to slipped upper femoral epiphysis (Hägglund *et al.* 1987) and adolescent idiopathic scoliosis (Hägglund *et al.* 1990).

The thoracic ratio method

The thoracic ratio method expresses the width of the left and right hemithoraces segmentally in relation to the distance from T1 to T12. It does not express rib length directly but the values are dependent on rib lengths as measured on AP projections of the chest radiographs. Oblique radiographs were excluded from the series. Subjects with minimal lateral spinal curves (4° or less) were included; such curves could influence the findings, but the effect is likely to be small.

Three major factors which determine the TRs are evidently (1) rib length, (2) thoracic spinal length, and (3) the obliquity of the ribs measured as rib–vertebra angles (Grivas *et al.* 1991 *d*). Another factor, likely to exert a lesser influence on the different segmental pattern between boys and girls, is the lower position of the female ribcage compared with males; the manubrium sterni is at a lower level (T3) in females than in males (T2) (Williams & Warwick, 1980). In a subsequent paper we account for the higher position of the male thoracic cage by neuromuscular factors which favour the more cranial musculature acting longitudinally in the trunk (Grivas *et al.* 1991 *d*).

Relation to spinal level and age

Figure 2 shows the shape of the thorax in the frontal (AP) plane as thoracic ratios. Three features are worthy of comment. First, the broadening of the chest from T1–10/11; second, between infancy and childhood, the chest narrows relative to spinal length from above downwards. Third, between childhood and adolescence in girls (but not in boys) there is a further narrowing of the chest in its lower half (T6–12). Above T6 between childhood and puberty there is no detectable change in the relative width of the chest in either boys or girls.

Drooping of the shoulders, sternum and ribs during growth and early adult life

In passing from infancy to adult life, a progressive drooping of the shoulders takes place; both outer and inner ends of the clavicle descend, but the descent is greatest at the outer ends. In this connection, Keith (1923) wrote: 'The falling of the shoulders is not an isolated occurrence, but part of a process in which the whole thoracic region participates. This drooping or ptosis, which may be recognisable by the end of childhood, becomes evident by the end of the third decade. The sternal ends of the ribs and the sternum itself come to take up a respiratory position at a level of one or more vertebrae lower down than in childhood. The level of the domes of the diaphragm descends, the oesophagus becomes elongated, the lateral segments of the ribs more oblique in position, the angles formed by the ribs with their cartilages more oblique. With the descent of the ribs the back-to-front diameter of the thorax is necessarily diminished.'

The relative narrowing of the chest during growth: lung growth, rib growth, rib–vertebra angles and scoliosis

The narrowing in the frontal plane of the thorax relative to its length occurs when the chest is broadening in its transverse dimension relative to its AP dimension (Fig. 3; Meredith & Knott, 1937; Burwell *et al.* 1983; Grivas, 1984).

In attempting to interpret the age and sex-related changes in chest width (thoracic ratios), consideration is needed of (1) lung growth, (2) rib growth and (3) rib–vertebra angles.

Lung growth

Keith (1923) concluded that the evolution of the upright posture gave an enhanced respiratory importance to the upper thorax; in particular, the roots of the lungs are attached to the pericardium which is fixed to the diaphragm. Hence diaphragmatic movements are essential for the proper aeration of the apical part of man's lungs.

The postnatal growth and development of the lung is reviewed by Thurlbeck (1975). Hieronymi (1961) observed that the lung changed shape as it grew, and that it grew

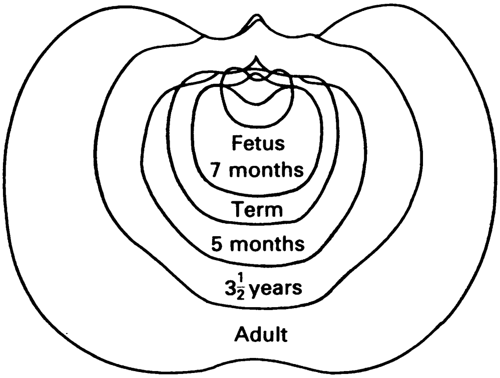

Fig. 3. Diagram to show the changes in shape of the thorax during growth. (Reproduced with permission from Vernon E. Krahl: Anatomy of the mammalian lung. In *Handbook of Physiology, Section 3*: *Respiration*, vol. 1 (ed. W. O. Fenn & H. Rahn. Baltimore: Williams & Wilkins, 1964, p. 229).

more in height than it does in width. Simon *et al.* (1972), using chest radiographs, found that lung width and length in boys increase in a fairly linear relationship with age from 5 to 19 years. In contrast, in girls during the later stages of growth, lung width increases proportionately less than lung length. Simon *et al.* concluded that further data are needed before they could be certain that this was not a sampling error.

The plot of segmental thoracic ratios by age groups (Fig. 2) is one way of expressing the proportional changes of thoracic viscera, mainly the heart and lungs and principally the lungs during growth. As Figure 2 shows, the relative narrowing of the girls' lower thorax between childhood and puberty is consistent with the proportionate change in the girl's lung in the later stages of growth reported by Simon *et al.* (1972).

Rib growth

Thoracic ratios do not provide any direct measurement of rib growth. An indirect indication of rib growth is provided by data obtained longitudinally from chest radiographs to estimate lung growth (Simon *et al.* 1972). The centile charts for lung width and length were unusual in that the girls never exceeded the boys (like centile charts for head size and foot length).

Direct measurements of rib growth in the living subject are now attainable using a stereoradiographic 3-dimensional reconstruction using x-radiation (Stokes *et al.* 1989).

Rib–vertebra angles (*RVAs*)

In a subsequent paper we report the pattern of RVAs in the same sample of children and how these vary with rib-level, age and sex (Grivas *et al.* 1991*d*). Briefly, (1) the RVAs droop increasingly from above downwards; (2) with increasing age the upper RVAs increase, particularly in boys; and (3) the lower RVAs droop, particularly in girls.

The narrowing of the chest relative to its length during growth is associated with elevating upper RVAs (above 90°) and drooping lower RVAs (below 90°). The latter may contribute to the relative chest narrowing in its lower part between infancy and childhood in both boys and girls.

In the period between childhood and puberty, the boys show no further relative narrowing of the chest. In contrast, the girls' lower chest (T6–12) narrows further

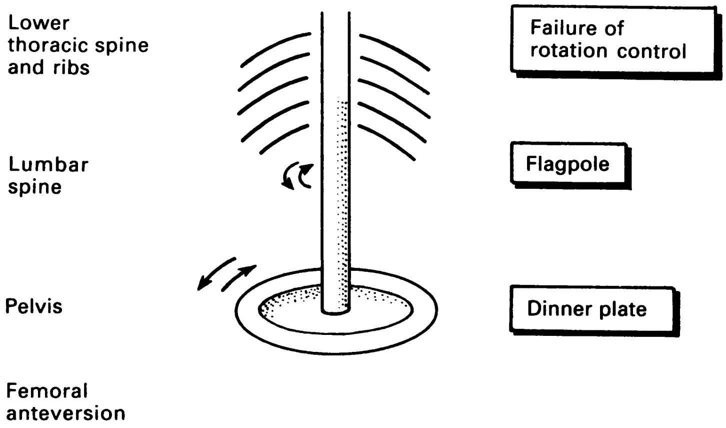

Fig. 4. General aetiological theory for adolescent idiopathic scoliosis ('Dinner Plate'-'Flagpole' concept). (Reproduced with permission from Burwell *et al.* 1988.)

relative to its spinal length; but there is no further RVA drooping between childhood and puberty to account for this chest narrowing. Hence it is suggested that in girls (but not in boys) rib growth in the lower half of the chest is impaired relative to spinal growth. This conclusion may have relevance to a recent theory of aetiology for adolescent idiopathic scoliosis.

Aetiological theory for scoliosis (*Fig.* 4)

Briefly, the theory states that adolescent idiopathic scoliosis results from a breakdown of rotation control in the spine due to the opposing action of two mechanisms, namely: (1) a pelvic rotation-inducing system, (involving gait, femoral anteversion and the pelvis = 'Dinner Plate') with rotation transmitted to the lumbar and thoracic spine ('Flagpole') and counteracted by (2) a spinal rotation-defending system, involving discs, ligaments, ribs, sagittal spinal shape and neuromuscular mechanisms.

This general aetiological theory has been developed in the light of subsequent data, including those for the ribcage reported here and elsewhere (Grivas *et al.* 1991*c*, *d*). The theory now includes an age-related defect (possibly developmental delay) affecting certain spinal cord segments. The muscular effects, through asymmetric trunk muscle action, weaken the spinal rotation-defending system during movements and particularly gait causing RVA drooping and asymmetry. The alteration in the rib levers leads to a cyclical failure of rotation control in the trunk causing the 3-dimensional mechanical alteration of the spine, termed scoliosis. In the immature human spine under load, this alteration (torsion) produces asymmetric loading of vertebral growth-plates; the resulting growth asymmetry of the vertebral bodies potentiates the torsional deformity to cause progressive idiopathic scoliosis (Burwell *et al.* 1991*a*, *b*, *c*; Burwell and Dangerfield, 1992).

The physiological basis of the general aetiological theory will now be used to explain some of our thoracic ratio findings.

Relative narrowing of the chest during growth: a hypothesis involving pelvic and thoracic inertia in gait

The relative diminution of TRs particularly of the lower thorax with increasing age in boys and girls may be a mechanism to reduce the rotational inertia created in the thorax from the rotating thoracolumbar spine and pelvis in gait (Gregersen & Lucas, 1967; Sutherland *et al.* 1980; Cole *et al.* 1990). Such a mechanism would conserve energy. It will be recalled that inertia (I) equals Σmr^2, (where Σ = sum, m = mass and r = radius). Hence, a relative diminution of thoracic width would produce a much greater reduction of rotational inertia, because inertia is a function of the square of the distance. In evolutionary terms, the chest narrowing is consistent with an adaptation of the human ribcage to bipedal gait.

This hypothesis suggests that RVA drooping, as a mechanism to narrow the chest for mechanical reasons (energy conservation), can go so far; below a certain RVA droop, rotation control of the spine would be compromised. To avoid this situation in girls, rib growth is impaired in order to narrow the lower thorax further between childhood and puberty to lessen the rotational inertial burden (Grivas *et al.* 1991*d*). On this view, the girl's lung bears the imprint of this mechanism in its proportionate change in the late stages of growth (Simon *et al.* 1972).

Relation to sex—more slender female thorax and caudocranial rib development?

In the adult female, thoracic capacity is less, absolutely and proportionately (Williams & Warwick, 1980).

Our findings given in Tables 3–5 show that in infancy there are no sex differences for TRs at any level from T1–12. In childhood, the sex differences for TRs are present in the lower thorax and are more extensive on the left (T6–10) than on the right (T10–12).

At puberty the sex differences for TRs are present at most spinal levels, and are equally evident in right and left hemithorax (T1–10). The greater slenderness of the female thorax is consistent with the greater slenderness of the female vertebrae compared with the male (Glasbey, 1983; Schultz *et al.* 1984). We have suggested already that TR diminution reduces rotational inertia of the thorax during gait; there is a greater need for such a reduction in girls because of the greater rotational inertia generated by their larger pelves (see Burwell *et al.* 1988, 1989, 1991*a*, *b*; Burwell & Dangerfield, 1992).

Comparing these pubertal findings with those of childhood, it is seen that hemithoracic development revealed by sex differences for TRs is caudocranial (Tables 3–5).

Relation to side—developmental laterality?

TR asymmetry (TRD) is evident below T2 and more in puberty than childhood. Table 8 shows that the mean TR differences which are statistically significant for asymmetry are all negative, implying larger right than left thoracic ratios. This finding is in accordance with the larger size of the right half of the thorax (Gaupp, 1909) and the right lung being larger than the left lung by about 10–20% (Williams & Warwick, 1980). Del Bigio (1989) has suggested that the larger right lung predisposes a chest to develop a right thoracic idiopathic scoliosis, a hypothesis which does not account for left thoracic idiopathic scoliosis.

Our findings show sexual dimorphisms for thoracic asymmetry. Girls in childhood have TRDs at T6–8 which are significantly different from boys by about 0·5–1% (Table 8). In the left hemithorax below T5 in childhood, TRs are significantly smaller in girls than in boys (T6–10, Table 3). No such sex differences are found on the right during childhood (Table 4). At puberty, sex differences for TRs are found at all levels on right and left except T11–12. Hence it seems that developmentally the left lower hemithorax is ahead of the right in childhood (developmental laterality). In connection with adult limb bones, laterality is shown by the favouring of the left clavicle, the right upper limb bones and the left lower limb bones (Schultz, 1937).

Relation to idiopathic scoliosis

Elsewhere we show that the funnel-shaped upper thoracic shape of infantile idiopathic scoliosis is like that of each of (1) a normal human fetus; (2) asphyxiating thoracic dysplasia (Jeune's disease; Smith, 1978); and (3) a normal adult rabbit (Grivas *et al.* 1991*a*, *b*). In adult humans (and gibbons) the thorax is barrel-shaped when viewed from the front, while in the large apes it has a definite funnel-shaped appearance (see Aiello & Dean, 1990). Our findings suggest that there are different velocities of postnatal growth in the upper and lower ribs of the human.

In our series of chest radiographs, 2 young children had congenital rib fusions of an upper hemithorax (hemifunneling) each of which was associated with a scoliosis curve, convex to the side of the rib defect and below the last level of the rib fusions (Grivas *et al.* 1990*d*); these children were not included in this analysis.

No data are yet available for thoracic ratios in adolescent idiopathic scoliosis.

SUMMARY

Thoracic ratios (TRs) were measured segmentally (T1–12) in the chest radiographs of 412 children aged 0–17 years attending hospital with minimal disorder or diseases (boys 193, girls 219). A new method for measuring TRs was used which calculates the width of the left hemithorax, the right hemithorax and the total thorax relative to T1–T12 distance. The data were analysed in 3 age groups – infancy, childhood and puberty, after the classification of Karlberg (1989). The findings are as follows.

1. The chest broadens from T1 to about T10–11.
2. Between infancy and childhood, relative to its length the chest narrows from above downwards and particularly in the lower chest (T5–12 average diminution, boys 9·5%, girls 9·8%). In the upper chest, the narrowing is more marked in girls than boys (T1–4 average diminution, boys 5·1%, girls 8·2%).
3. Between childhood and puberty, the girl's but not the boy's chest narrows further in its lower half (below T6 average diminution 3·3%). At T6 and above there is no detectable change in the relative width of the chest in either boys or girls.
4. The relative narrowing of the chest during growth appears to result from several mechanisms: (1) elevation of upper rib–vertebra angles (above 90°); (2) drooping of lower rib–vertebra angles (below 90°); and (3) linear rib growth being impaired relative to thoracic spinal growth in the lower ribcage (T6–12) of girls between childhood and puberty (Grivas *et al.* 1991*d*).
5. The hypothesis is suggested that the relative narrowing of the lower chest with increasing age reduces the rotational inertia of the thorax in gait. There is a greater need for such reduction in girls because of the greater rotational inertia generated by the mass of their larger pelves. This hypothesis provides a mechanical explanation for the proportionate change in the girl's lung in the later stages of growth (Simon *et al.* 1972).
6. Developmentally, the left hemithorax is ahead of the right hemithorax in childhood.
7. Thoracic asymmetry favouring the right chest is found, and more so in puberty than childhood which is connected with the larger size of the thorax and lung in the adult.
8. The evidence suggests that hemithoracic development is caudocranial; this is consistent with an adaptation of the human ribcage to control spinal rotation and counterrotation when bipedal gait was acquired in evolution.
9. In progressive infantile idiopathic scoliosis, the upper chest is funnel-shaped. It

differs from the shape of the appropriate controls derived from the present study (Grivas *et al.* 1991*a*, *b*).

10. Congenital rib fusions of an upper hemithorax (hemifunnelling) can be associated with a scoliosis curve below the last level of the rib fusions and convex to the side of the rib defects (Grivas *et al.* 1990*c*).

The authors are indebted to Action Research for the Crippled Child for financial support, Dr J. C. G. Pearson, Senior Lecturer, Department of Community Medicine and Epidemiology, for statistical advice, Dr N. Tsoutsaios for contributing to the reliability study, and Mrs A. Bexon and Mrs C. Taylor for manuscript preparation.

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