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Rib Cage Asymmetry in Idiopathic Scoliosis

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Summary: Seventy-one patients attending a scoliosis clinic and 10 control subjects were studied by a stereoradiographic three-dimensional reconstruction of the spine and rib cage. The symmetry of each rib pair (at each anatomic level) was described by measurements of rib arc length, chord length, enclosed area, maximum curvature, and frontal and lateral angulations. Patients were divided into four groups: 19 with a single right thoracic curve, 15 with a single left lumbar or thoracolumbar curve, 22 with double curves, and 15 with a curve with <10° Cobb angle. In the control group and the group with minimal scoliosis, there was no statistically significant rib asymmetry. Among the patients with scoliosis, 11 of 19 patients with right single thoracic curves had rib arc lengths greater on the right side at the curve apex, and nine of 15 patients with left lumbar scoliosis had longer ribs on the left side in the corresponding region of the thoracic spine. Eleven of 22 patients with double curves had symmetrical rib lengths (within ±3%), the other 11 had ribs longer on the left. These proportions should not have occurred by chance ($p < 0.001$). The mean rib length difference in patients with single thoracic curves was 1.39% (right longer than left), in single lumbar curves it was 3.57% (left longer than right), and in double curves 3.18% (left longer than right). These differences between the groups of patients and control subjects were statistically significant ($p < 0.01$). Based on correlations between rib arc length and other measurements of rib size, there was evidence of general rib hypertrophy on the long rib side of patients having length asymmetries. **Key Words:** Scoliosis—Rib cage—Etiology—Skeletal growth.

Adolescent-onset idiopathic scoliosis is considered primarily a deformity of the spine, although it is associated with asymmetries of the entire trunk. While it is of unknown etiology, it is clearly associated with growth during the adolescent growth spurt and progresses only slowly after skeletal maturity. Because of this association with growth, a number of attempts have been made to associate the development of the deformity with growth abnormalities. Stature (12,18) and components of stature, spine length measurements, and overall height (13,20,21) have been shown to be abnormal in these patients. There is some evidence of abnormal levels of circulating growth hormones (17). The higher incidence in females may be related to differing growth patterns (5).

Since adolescent scoliosis develops during a period of rapid growth, it is possible that abnormal rates or small asymmetries of growth could develop. This study is directed at the overall hypothesis that idiopathic scoliosis could be initiated by an overgrowth or hypertrophy of one side of the thorax. Roaf (15) considered that asymmetrical growth of the vertebral bodies might cause scoliosis, although his attempts to treat it by unilateral growth

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arrest were not successful. Dangerfield et al. (3) compared 233 girls with scoliosis with an age-matched unaffected control group and found evidence of greater upper arm length on the right-hand side, more pronounced among patients with scoliosis. Normelli et al. (14) studied cadaveric specimens of the rib cage of patients with scoliosis, compared with a control group, and found a tendency toward greater rib length on the concave side of the scoliosis. Using a new method for measuring rib cage dimensions in vivo (4), our study was directed at measuring the rib cage shape of patients at the time of development of the scoliosis. Our purpose was to measure the size, shape, and orientation of the ribs in three selected groups of patients with adolescent-onset idiopathic scoliosis and to compare them with results from subjects with minimal scoliosis.

METHODS

Patient Groups

Seventy-one patients attending a scoliosis clinic and for whom clinical posteroanterior (PA) spinal radiographs were requested met the entry criteria and were studied by means of steroradiography of the thorax. A further 14 patients were excluded. Scoliosis curvatures of <10° Cobb angle were considered to be negligible. Patients included in the study had to fit into one of four subgroups:

Thoracic group: 19 patients (17 female, two male) with a single right convex thoracic curve (20–56° Cobb angle, mean 36.3°) and no curve in the lumbar region. Their mean age was 15.0 years (range 5–37 years).

Lumbar group: 15 patients (12 female, three male) with a single left lumbar or thoracolumbar curve (11–43° Cobb angle, mean 22.5°) and no curve in the thoracic region. Their mean age was 13.7 years (range 9–17 years).

Double curve group: 22 patients (21 female, one male) with double curves (right thoracic 18–75° Cobb angle, mean 38.0°; left lumbar 15–71° Cobb angle, mean 38.3°). Their mean age was 15.3 years (range 12–27 years).

Minimal curve group: 15 patients (10 female, five male) having clinical appearance of a scoliosis but subsequently found at radiography to have no scoliosis curve with a Cobb angle of >10°. (Range of curves found 5–10° Cobb angle). Their mean age was 12.9 years (range 11–15 years).

Control group: 10 subjects without scoliosis who were radiographed. There were six cadavers (three male and three female) and four volunteers (one female and three male). The mean age was 39.5 years (range 26–54 years). Radiographs showed only minor spinal curvatures, measuring up to 8° by the Cobb method.

A strict definition was adopted for single and double curves. For a patient to be considered to have a double curve, any spinal curvature less than the major curve had to have a Cobb angle that was within 10° of that of the major curve. By using this definition, we also found that both curves in patients with double curves had similar magnitudes of lateral deviation from the spinal axis (the axis passing through T-1 and L-5) in each curve. The other patients had only minimal lateral deviation outside their single curve. Therefore, we felt that the three groupings of patients with scoliosis represented three distinct patterns of spinal shape.

Among the patients with thoracic scoliosis (thoracic and double curve groups), 5 patients had the curve apex at T-7, 22 at T-8, 8 at T-9, and 6 at T-10.

Stereoradiography

Rib cage geometry was measured by a stereoradiographic technique (4). First, four radioopaque skin markers (2-mm steel balls) were taped over the sternal notch, the ziphisternum, and the angles of the tenth ribs to locate the positions of the sternum and costal cartilages. The subject then stood facing the x-ray cassette, and the clinical PA exposure was made with the x-ray tube directly behind the subject. Then the tube was raised and angled downward at 20°, the film cassette was changed, and a second stereo pair exposure was made. A low-dose x-ray technique with high-speed films and screens was used, and the x-ray entry dose for the additional stereo pair film was about half of the annual whole-body background dose.

The midline of each rib image was marked and digitized, along with images of the skin markers and six landmarks on each vertebra. Positions of the vertebral landmarks and skin markers were calculated by standard photogrammetric methods. An iterative computer program was then used to calculate three-dimensional coordinates of digitized points on the ribs. The rib cage reconstruction (Fig. 1) was completed by extrapolating the costal cartilage shape between the ends of the imaged parts of the ribs to points on the sternum, whose position was estimated from the skin markers applied to pal-

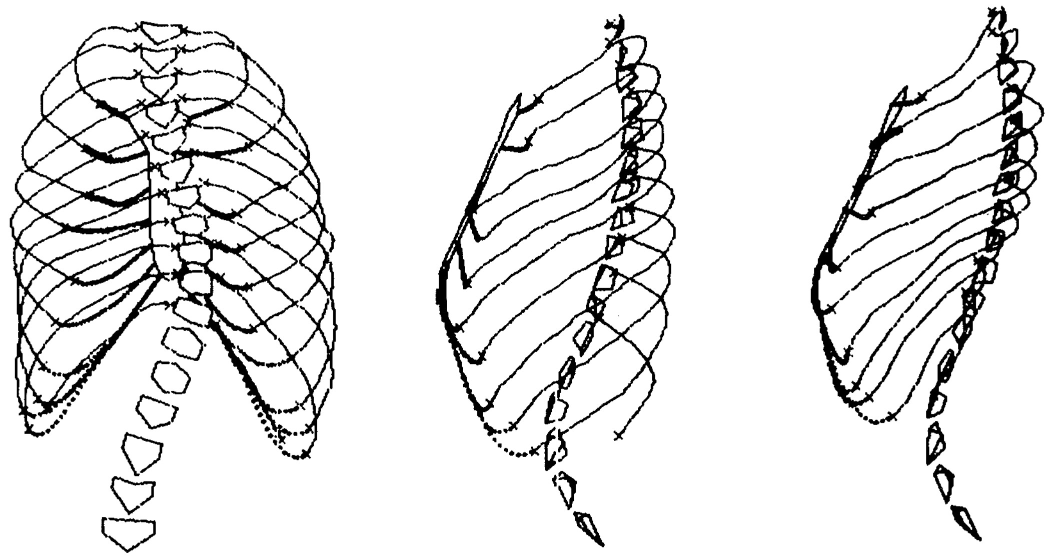

FIG. 1. Example of reconstruction of the rib cage, made from stereoradiographs of a 14-year-old patient with a 40° Cobb right thoracic scoliosis. The ends of the bony parts of each rib are indicated by an "x." Both hemithorax projections are viewed from the left.

pated landmarks. Measurements of four cadaveric sterna were used to establish the relationship of each costal cartilage to the sternal landmarks. The precision of the rib reconstruction was found to be ±1 mm (SE), based on repeated marking and digitizing of one rib cage. Accuracies of ±2% for descriptive measurements (linear measurements), ±4% for curvature, and ±1.5° for angulation measures were determined based on measurements of a flat disk of known shape (4).

Description of Rib Shape

Rib geometry was described by shape and orientation measurements (Fig. 2). Rib arc length was calculated as the sum of distances between measured points on the rib. The anterior endpoints were extrapolated from sternal markers, as described above, and the posterior endpoints were extrapolated from the vertebral landmarks, based on morphologic measurements of thoracic vertebrae. Measurements of the bony part of the rib were calculated with respect to a "best-fit plane" of the bony part since it was found that the rib midlines lay close to a flat plane. The best-fit plane was calculated by least-squares linear regression. Maximum distances of points from the best-fit plane were typically 5 mm, and the maximum observed distance was 20 mm. The shape measurements were the rib arc length (the sum of the length of the bony part of the rib and of the costal cartilage), the chord length (the straight-line distance between costovertebral junction and costochondral junction), the enclosed area (bounded by the rib and costal cartilage and the chord), and the maximum rib curvature (which occurred in the posterior half of the rib). Because curvature is the second derivative of the shape measurements and hence is very prone to measurement error, a measure of maximum rib curvature was obtained by fitting a parabola to the posterior part of

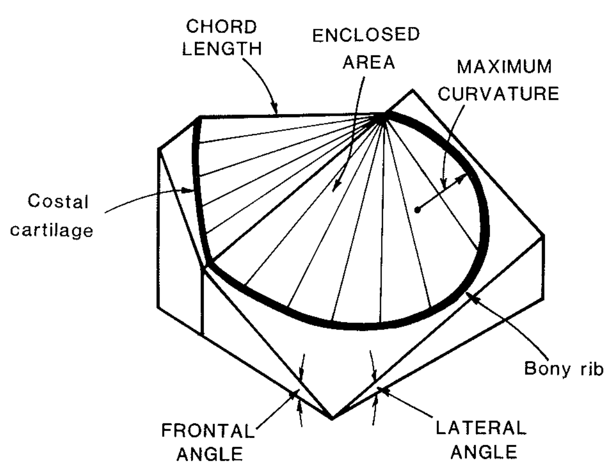

FIG. 2. Shape and orientation measures of rib and costal cartilage shape, shown diagrammatically by reference to the "best-fit plane" of the bony part of the rib.

TABLE 1. *Averages (SD) of rib asymmetry measures in the five groups of subjects studied*[a]

Group	Arc length (%)	Enclosed area (%)	Maximum curvature (%)	Chord length (%)	Frontal angle (°)	Lateral angle (°)
Thoracic	1.39	6.00[b]	30.04[b]	4.72[b]	13.74[b]	−7.86[b]
(n = 19)	(4.68)	(8.37)	(21.71)	(2.97)	(7.10)	(6.42)
Lumbar	−3.57[b]	−5.54[b]	2.89	0.73	2.29	1.03
(n = 15)	(3.08)	(5.21)	(15.04)	(1.39)	(7.45)	(5.21)
Double	−3.18[b]	−3.24	22.48[b]	2.62[b]	8.68[b]	−5.96[b]
(n = 22)	(3.80)	(6.81)	(19.38)	(3.34)	(6.14)	(7.76)
Minimal	−1.97	−2.27	6.42	0.25	2.72	−2.92
(n = 15)	(4.51)	(7.71)	(14.14)	(1.51)	(8.36)	(7.06)
Control	−0.97	−1.58	5.23	−0.13	2.04	−1.66
(n = 10)	(4.83)	(8.75)	(14.27)	(1.64)	(6.19)	(3.69)

[a] The values for each subject were averaged from measurements obtained at the four levels T-7 through T-10.
[a] Highly significant difference between groups ($p < 0.01$, analysis of variance) on all parameters.
[b] Significantly different from zero ($p < 0.05$, t test).

each rib and the maximum curvature of this parabola was used for the measurement of rib curvature. The measurements of rib orientation were the angle made by the best-fit plane of the bony part of the rib to the horizontal as viewed from the front ("frontal angle") and the angle as viewed from the side ("lateral angle"). The sign conventions were such that frontal angle was positive with the rib angled downward anteriorly; the lateral angle was positive with the rib angled downward laterally.

Symmetry Measurements

Symmetry of the ribs was measured at each anatomic level by subtracting the value obtained for the left rib from that of the right rib and then expressing the difference as a percentage of the average for the two sides. For the angular measures of rib orientation, the symmetry was expressed as a simple difference in degrees.

To characterize the rib cage symmetry of each subject, the value of each asymmetry measure for the levels T2-11 was averaged (measurements at T-1 and T-12 were not considered reliable, for technical reasons). Also, the mean rib asymmetry for the levels T7-10 was calculated for each patient. These four levels were selected because they were the levels at which the apices of the thoracic curves occurred.

Statistical Analyses

In patients with thoracic curves (groups 1 and 3), correlation analyses were performed to determine whether rib asymmetry measures were related to spinal lateral deviation from the spinal axis. These were intrasubject correlations between local measures taken at each anatomic level. Analyses of variance were used to determine whether rib asymmetry measures were different in the five different groups of subjects. The frequency of subjects having longer ribs on the left side, those having longer ribs on the right side, and those with no significant difference was compared by the chi-square test. For this purpose, 3% of rib length asymmetry (averaged over the four levels T7-10) was used as the threshold of significant rib length difference. This threshold was based on estimates of the precision of the measurement technique. Correlation analyses were performed to describe associations between different measures of rib asymmetry, the magnitude of the scoliosis (Cobb angle), and the age of the patient. These were intersubject correlations of global or regional measurements of each patient.

RESULTS

Among patients with single curve thoracic scoliosis, there was asymmetry of all rib measurements

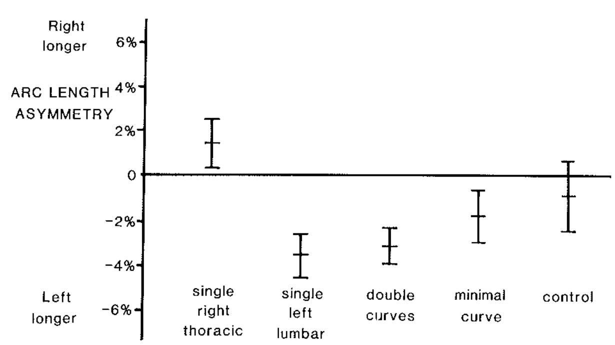

FIG. 3. Mean and SEM for each group of subjects of rib arc length asymmetry (calculated for each patient as the percentage difference, right-left, mean of the four levels T-7 through T-10).

TABLE 2. *Nos. of patients having rib length asymmetry in the T7-10 region, broken down by patient group*[a]

Rib asymmetry	Thoracic curve	Lumbar curve	Double curves	Minimal curve	Control
Left > right	4	9	11	5	2
Same (±3%)	4	6	11	10	6
Right > left	11	0	0	0	2

[a] $p = 0.001$, chi-square test.

in the region T7-10 except arc length difference when compared with symmetrical cases. The significant differences were between 4.72 and 30.04% (Table 1). In the group with lumbar scoliosis only, arc length (mean on right side 3.57% greater than mean on left side) and enclosed area (mean on right side 5.54% greater than on left side) were found to be significantly ($p < 0.05$) different from symmetry. Patients with double curves were asymmetric in all measurements except rib enclosed area, and the general pattern of rib asymmetry in these patients was similar to that seen in the patients with single thoracic curves; except that while the patients with single thoracic scoliosis had longer ribs on average on the right side, those with lumbar curves and double curves had longer ribs on the left side (Fig. 3). Eleven of 19 patients with single thoracic curves had longer ribs on the right; nine of 15 patients with single lumbar curves had longer ribs on the left (Table 2). The chi-square test indicated that these results should not have occurred by chance ($p < 0.001$). Analysis of variance indicated significant differences ($p < 0.05$) between the five groups studied in all asymmetry measurements (Table 1). A very similar trend was seen in the measurements averaged over the region T2-11, except that the single thoracic curve group had a smaller mean rib length asymmetry (0.2%) when averaged over T2-11 than in the region T7-10 (1.39% asymmetry), which implies that this asymmetry tended to be localized to the curve apex region.

When the average values (left and right sides) of the rib measurements were examined to determine whether the overall rib cage size or shape was different between the patient groups, no significant differences were found among the four clinical groups, except that the "control" group of older subjects consistently had larger ribs as measured by rib length, area, and chord length (Table 3).

Intrasubject correlation studies showed that in many patients in the two groups with thoracic scoliosis, the degree of rib asymmetry was related to the lateral deviation (in the frontal plane) of the corresponding vertebra. There was a statistically significant intrasubject correlation ($r > 0.55$, $p < 0.05$) in 33 of the 41 patients in these groups for the asymmetry of maximum curvature and frontal angle, 20 of 41 for lateral angle, and 21 of 41 for chord length. In the case of rib arc length asymmetry, there was no consistent correlation with vertebra deviation. An example of correlations in one patient is shown in Fig. 4.

When the global measurements (intersubject correlations) were examined, we found that there was no correlation between Cobb angle and the magnitude of rib arc length asymmetry (Fig. 5). However,

TABLE 3. *Averages (SD) of rib measurements in the five groups of subjects*[a]

Group	Arc length (mm)	Enclosed area (mm^2)	Maximum curvature (mm^{-1})	Chord length (mm)	Frontal angle (°)	Lateral angle (°)
Thoracic	395.0	19,881	0.0209	134.1	25.70	39.43
(n = 19)	(39.5)	(4,043)	(0.004)	(22.0)	(8.28)	(6.08)
Lumbar	402.5	20,979	0.0224	144.0	23.41	40.40
(n = 15)	(32.3)	(3,128)	(0.004)	(12.85)	(7.92)	(5.33)
Double	401.0	20,030	0.0201	127.2	25.13	41.21
(n = 22)	(27.1)	(2,665)	(0.003)	(16.46)	(6.24)	(5.41)
Minimal	391.9	19,986	0.0227	141.8	19.21	42.29
(n = 15)	(27.3)	(2,775)	(0.004)	(17.8)	(7.54)	(5.88)
Control	452.7	27,467	0.0210	174.6	19.07	39.41
(n = 10)	(48.8)	(5,306)	(0.002)	(16.30)	(5.77)	(6.80)

[a] The values for each subject were averaged from right and left sides and from measures obtained at the four levels T-7 through T-10. No significant differences between the four groups of patients were found.

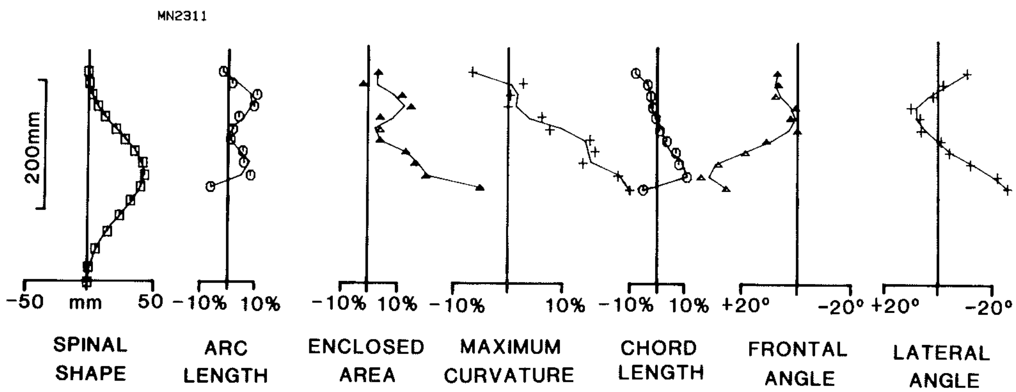

FIG. 4. Graphs showing the back view of the spine of one patient and the symmetry of rib measurements as a function of position in the spine. Symmetry measures were obtained by subtracting the measurement of the left rib from the corresponding measurement of the right rib. Many measures show a correlation with vertebral lateral deviation. (From the same patient as in Fig. 1. Note that this patient did not have radiographically visible ribs at T-12.)

in thoracic curves the magnitude of scoliosis (Cobb angle) correlated with the asymmetry of maximum curvature ($r = 0.31$), of frontal angulation ($r = 0.59$) and of lateral angulation ($r = 0.36$) (Table 4). There were strong correlations between most of the components of rib asymmetry in this group of patients. The high correlation between rib arc length asymmetry and rib area asymmetry ($r = 0.96$) suggests that there may be a general hypertrophy of the ribs in these patients.

DISCUSSION

There are several other reports of musculoskeletal abnormalities in patients with scoliosis, including abnormal growth (5,7,13,20,21) and length asymmetry of multifidus muscle slips, with a pattern that suggested that it was a primary abnormality (6). The only previous measurements of rib length asymmetry were reported in a small series of cadavers by Normelli et al. (14). Animal models involving rib resection (2,8,16,19) demonstrate the feasibility of rib length asymmetry as a cause of scoliosis, as does the clinical occurrence of scoliosis after rib resection (10). The rib cage apparently has a mechanical role in the development of scoliosis. Asymmetric angles of ribs were found to be predictive of progression in patients with infantile scoliosis (11), whereas a mechanical model of the thorax demonstrated the "stiffening" role of the rib cage (1).

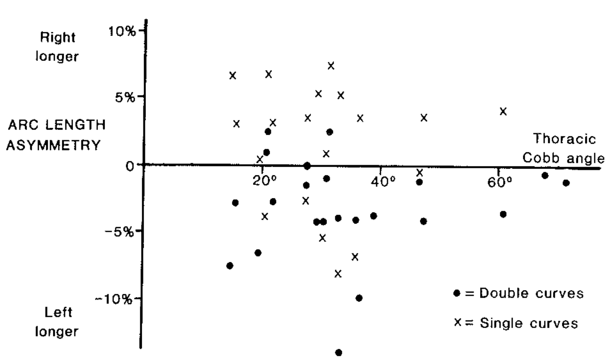

FIG. 5. Scatterplot showing absence of correlation between rib arc length asymmetry and Cobb angle in the single right thoracic curves of 19 patients and in the thoracic curves of 22 patients with double curves.

The rib length asymmetries of patients with single lumbar curves were generally in the opposite direction of those with single thoracic curves. Most of the patients with double curves had longer ribs in the left side, so in this respect they were similar to the lumbar curve group. Both the minimal curve group and the control group generally had left ribs longer than right, suggesting that the "normal" rib lengths are slightly asymmetric. The patients with single right thoracic curves differed more from these groups than they did from the symmetric case.

Patients with curves differing from the common idiopathic curve patterns of either right thoracic scoliosis or left lumbar scoliosis or both were excluded from this study. However, we believe that our three groups had distinct and different overall patterns of deformity because of the strict criteria adopted for the single curve groups. Possible relationships of the finding that rib length asymmetries differed in different curve groupings to mechanisms

TABLE 4. *Correlations between measures of rib asymmetry (mean of T-7 through T-10), Cobb angle, and age in 41 patients with right thoracic scoliosis (single and double curves)*[a]

	Cobb angle	Arc length	Enclosed area	Maximum curvature	Chord length	Frontal angle	Lateral angle
Arc length	(NS)	—	—	—	—	—	—
Enclosed area	(NS)	0.96 (0.00)	—	—	—	—	—
Maximum curvature	0.31 (0.02)	0.46 (0.00)	0.53 (0.00)	—	—	—	—
Chord length	(NS)	0.27 (0.05)	0.37 (0.01)	0.35 (0.01)	—	—	—
Frontal angle	0.58 (0.00)	0.32 (0.02)	0.40 (0.01)	0.47 (0.00)	(NS)	—	—
Lateral angle	−0.36 (0.01)	−0.51 (0.00)	−0.54 (0.00)	−0.39 (0.01)	(NS)	0.38 (0.01)	—
Age	(NS)	(NS)	(NS)	(NS)	(NS)	(NS)	(NS)

[a] Statistical probabilities are in parentheses.
NS, not significant ($p < 0.05$).

of the development of scoliosis are not clear. Right thoracic curves were associated with longer ribs on the convex side. If asymmetric growth could initiate scoliosis, then this finding is surprising, since greater growth might be expected to cause deviation to the opposite side. Also, if the ribs take a mechanical role in such a mechanism, then their absence in the lumbar region would leave the causes of lumbar scoliosis unexplained.

In this study it was difficult to obtain a good control group for comparisons with patients for ethical reasons. The control group was older than the patients, and patients in the minimal curve group had been radiographed on suspicion of scoliosis, so some of these patients may proceed to develop progressive scoliosis. Lonstein and Carlson (9) identified risk factors for progression of scoliosis, including young age, unfused iliac apophysis, larger curve, and double curve pattern. The patients in the minimal curve group did not appear to have a high probability of progression, based on these criteria.

Since these rib cage asymmetries were dependent on the location and number of curves, these findings raise the question of whether the rib changes were secondary to the scoliosis or whether they were its cause. Secondary remodeling of the ribs caused by lateral forces from the spine was expected to cause an asymmetry of rib curvature rather than hypertrophy of the thorax. Thus, it appears unlikely that the findings of rib arc length asymmetry were secondary to the spinal deformity. Also, since rib arc length asymmetry did not correlate with lateral deviation within each spine or with the thoracic Cobb angle, this suggests that the spinal deformity was not the cause of the rib length asymmetry. The high correlations between the various measures of asymmetry of rib size support the idea of a general rib hypertrophy in these patients. However, this cross-sectional correlational study cannot determine the causal relationship definitely, but forms the basis for a longitudinal study that may resolve this question.

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