Idiopathic Scoliosis

MECHANICAL PROPERTIES OF THE RESPIRATORY SYSTEM AND THE VENTILATORY RESPONSE TO CARBON DIOXIDE

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ABSTRACT The aims were to examine the effects of scoliosis (angle), and age on lung volumes, elastic properties of the respiratory system, and the ventilatory response to CO_2. The mean age of the 55 patients was 25.4±SEM 2.5 yr, and the mean angle was 80±SEM 4.2.

The mean±SEM percent predicted lung volumes were vital capacity (VC), 60.5±2.7; total lung capacity (TLC), 70.2±2.6; functional residual capacity (FRC), 79.3±3.2; and residual volume (RV), 99.7±5.2. The correlation coefficients between the angle of scoliosis and each of the following were significant: TLC (−0.548), percent predicted TLC (−0.547), VC (−0.485), percent predicted VC (−0.523), FRC (−0.533), percent predicted FRC (−0.338), RV (−0.438), and percent predicted RV (−0.318). The mean compliance of the total respiratory system (C_{rs}) was 0.049 liter/cm H_2O±SEM 0.004, and the mean compliance of the chest wall (C_{cw}) was 0.080 liter/cm H_2O±SEM 0.012. The C_{rs} and C_{cw} were inversely proportional to the angle (r − 0.620 and −0.721) and directly proportional to the height and the weight.

The mean $\Delta\dot{V}/\Delta P_{CO_2}$ was 1.32 liter/min per mm Hg (SEM 0.171), and the mean $\Delta V_T/\Delta P_{CO_2}$ was 28.9 ml/mm Hg (SEM 3.64). The correlation coefficients between $\Delta\dot{V}/\Delta P_{CO_2}$ and the following were height, 0.499; VC, 0.792; TLC, 0.632; and C_{rs}, 0.520; and between the $\Delta V_T/\Delta P_{CO_2}$ and the following were height, 0.500; VC, 0.878; TLC, 0.802; and C_{rs}, 0.590.

We conclude that body size and the deformity were the determinants of the lung volumes and the mechanical properties of the respiratory system, and that these variables were the major factors in both the magnitude and pattern of the ventilatory response to CO_2. The correlations between age and the mechanical properties of the respiratory system, $\Delta\dot{V}/\Delta P_{CO_2}$, and $\Delta V_T/\Delta P_{CO_2}$, were not significant, but the correlation coefficients between age and several of the derivatives of $\Delta\dot{V}/\Delta P_{CO_2}$ and $\Delta V_T/\Delta P_{CO_2}$ were significant.

INTRODUCTION

Idiopathic scoliosis is the most common type of structural scoliosis, and the lateral curvature associated with rib cage deformity is due to rotation of the vertebrae (1). According to the age of onset of the curvature, idiopathic scoliosis is classified into three groups, and these are infantile, childhood, and adolescent. Adolescent scoliosis, the most frequent, usually occurs in females, and the convexity is to the right (2). The characteristic feature of the rib cage deformity, which may be extreme, is prominence of the posterior angles of the ribs on the side of the convexity; and when severe, this may simulate kyphosis. Anteriorly, these ribs are flattened. The posterior angles of the ribs on the side of the concavity are flattened, and anteriorly they are prominent. Although it was thought that after cessation of vertebral growth, there was little progression of the angle of scoliosis (3), Collis and Ponseti (4) observed an increase of 15° or more in 38% of patients who were observed for 25 yr and not treated surgically.

Respiratory function abnormalities in scoliosis are common, and when severe, lead to respiratory failure. It may be postulated that the mechanical abnormalities, which are the basic functional changes, are the result of several mechanisms. These mechanisms, and their effects, include abnormal elastic properties of the respiratory system as a result of vertebral and rib cage deformity, and abnormal configurational changes

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TABLE I
Age, Height, Body Weight, and Angle of Scoliosis in 55 Patients

	Age	Height	Weight	Angle of scoliosis
	yr	*cm*	*kg*	°
Mean	25.4	155	46	80.0
SEM	2.5	1.83	1.45	4.2
Range	9–72	117–180	18–66	35–130

of the rib cage during breathing (5); impaired development of the rib cage and lung during growth (6); accelerated degenerative age changes (7); and impairment of the force developed by the inspiratory muscles as a result of the abnormal shape of the rib cage.

Although the mechanical abnormalities of the respiratory system are the basic functional changes in scoliosis, there are few studies on the mechanical properties of the respiratory system; and none has analyzed the relationship between the angle of scoliosis and the abnormal elastic properties of the respiratory system. The compliance of the total respiratory system (C_{rs})[1] was reduced in five patients with severe scoliosis studied by Bergofsky, Turino, and Fishman (8), but in three of the five patients, the compliance of the lung was reduced. By contrast, in a group of adults the range of slopes of the pressure-volume curves of the total respiratory system and its components were wide (9), and in children the C_{rs} was normal (7). Both of these papers lacked data on the angle of scoliosis and statistical analyses of the effects of deformity. The C_{rs} was reduced in one adult patient with respiratory failure (7), and Caro and Dubois postulated that rigidity of the rib cage was the result of accelerated degenerative changes with age.

Although Bergofsky et al. (8) and associates in subsequent papers (10, 11) have argued that the increased work of breathing due to the reduced compliance of the respiratory system impairs the ventilatory response to CO_2, the ventilatory responses to CO_2 were low only in their patients with chronic hypercapnia. Because acclimization of the cerebrospinal fluid to hypercapnia reduces the ventilatory response to CO_2, because the range of slope in normals is wide,

[1] *Abbreviations used in this paper:* C_{cw}, compliance of the chest wall; C_{rs}, compliance of the total respiratory system; $C_l$dyn, dynamic compliance of the lung; $C_l$stat, static compliance of the lung; FEV_1, forced expiratory volume in 1 s; FRC, functional residual capacity; Pa_{CO_2}, partial pressure of CO_2 in arterial blood; $P_{st}(L)$, static transpulmonary pressure; RV, residual volume; TLC, total lung capacity; $\dot{V}$, resting ventilation; $\Delta\dot{V}/\Delta P_{CO_2}$, slope of the ventilatory response to CO_2, $\dot{V}_{O_2}$, oxygen consumption; V_T, resting tidal volume; $\Delta V_T/\Delta P_{CO_2}$, slope of the tidal volume response to CO_2; VC, vital capacity.

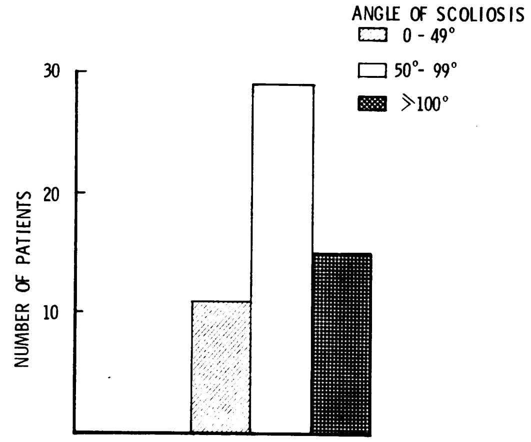

FIGURE 1 The distribution of the angle of scoliosis, calculated by the method of Cobb (12), among 55 patients with idiopathic scoliosis.

and because the numerical data are insufficient to demonstrate functional relationships, their hypothesis could not be confirmed by their data.

The aims of this investigation were to measure the elastic properties of the respiratory system and the ventilatory response to CO_2 in a large group of patients with idiopathic scoliosis, and to analyze the contributions of age and scoliosis to the functional abnormalities.

METHODS

Patients. 55 patients with idiopathic scoliosis, aged 9–72 yr (17 male, 38 female), who were in their usual state of health were studied. The age, angle of scoliosis, and anthropometric data are summarized in Table I and Fig. 1, and the individual data are in Table I (Appendix).[2] The angle of scoliosis was measured by the method of Cobb (12). In the majority of patients the curve was thoracic, and most had adolescent scoliosis (Fig. 2). The patients were asymptomatic except for dyspnea in some patients, and a history of cardiac failure in seven patients. Four patients also had chronic obstructive pulmonary disease, and the criterion of diagnosis was a forced expiratory volume in 1 s/vital capacity (FEV_1/VC) of less than 70%. The data from these patients were not included in the general statistical analyses, but were used to illustrate the effects of obstructive lung disease on the lung volumes in scoliosis.

Measurements. The functional residual capacity (FRC) was measured by the closed-circuit, constant-volume, helium dilution method. Other subdivisions of the lung volumes and the FEV_1 were measured on a 9-liter Godart spirometer (Godart NV., De Bilt, Holland). The predicted normal values for subjects over 15 yr were those of Needham, Rogan, and McDonald (13); and for subjects 15 yr and under, Helliesen, Cook, Friedlander, and Agathon (14).

[2] See NAPS document 02566 for three pages of Appendix Tables I and II. Order from ASIS/NAPS, c/o Microfiche Publications, 305 East 46th Street, New York 10017. Remit with order for each NAPS document number $1.50 for microfiche or $5.00 for photocopies. Make checks payable to Microfiche Publications.

The C_{rs} was measured by the positive pressure breathing method (15, 16). The corrected volume changes above FRC were plotted against the corresponding end-expiratory pressures at the mouth. The slope of the line (C_{rs}) was linear over the range of end-expiratory mouth pressures encountered (0–12 cm H_2O). The individual variation on repeated measurement was 5–10% of the C_{rs}. The static compliance of the lung ($C_l$stat) was measured by a method similar to that of Stead, Fry, and Ebert (17). The esophageal pressure was measured with a thin latex balloon, 10 cm long and 3.5 cm in circumference, surrounding a catheter of 1.2 mm ID. The balloon was positioned in the lower third of the esophagus and during measurements contained a constant volume of air in the range of 0.2–0.4 ml. Transpulmonary pressure was obtained by subtracting the pressure at the mouth from the esophageal pressure with a Sanborn 267B differential pressure transducer (Hewlett-Packard Co., Waltham Div., Waltham, Mass.). Airflow was measured with a Lilly-type pneumotachograph, and volume was obtained by electronic integration of the flow signal (Godart integrator). The airflow at the mouth was interrupted by a solenoid interrupter valve of variable duration and frequency of interruption. The duration of interruption was 0.6–0.8 s, which allowed airway pressure to plateau and the transpulmonary pressure to be estimated in the presence of cardiac oscillations. The frequency of interruptions was designed to provide 6–10 interruptions over the VC. The subject performed several maximal inspirations before the pressure-volume curves of the lung were measured. The pressure-volume curves of the lung and total respiratory system were graphed, and the pressure-volume curve of the chest wall was obtained by subtracting the static transpulmonary pressure (P_{st}[L]) from the pressure at corresponding lung volumes of the pressure-volume curve of the total respiratory system. The variation of the $C_l$stat on repeated measurements in the majority of patients was less than 10%, but was larger in some patients when the cardiac oscillations in the transpulmonary pressure were large. The dynamic compliance of the lung ($C_l$dyn) was measured during normal tidal breathing (18). For each patient the mean of 20–30 breaths was calculated. The data were recording on a Hewlett-Packard polygraph (Hewlett-Packard Co., Palo Alto, Calif.).

The ventilatory response to CO_2 was measured by the modified rebreathing method of Read and Leigh (19, 20). Ventilation during rebreathing was recorded on the kymograph of a Godart twin bell spirometer from the bag and bottle system into which the patient breathed. The P_{CO_2} and the P_{O_2} in the gas at the lips were continuously measured by a respiratory mass spectrometer,[3] or the CO_2 was measured with a Godart Capnograph. The initial gas mixture was 7% CO_2, 50% O_2, and 43% N_2. After the first 0.5 min, ventilation and average tidal volumes were calculated for each 0.5-min interval during the 4 min rebreathing. For each patient the ventilatory and tidal volume responses to CO_2 were expressed as the slope, and the position of their respective linear regression equations was based on least squares analysis for bivariate data (21). The rebreathing tests were performed on each patient in duplicate, and the regression analyses were based on the data from both tests.

The steady-state gas exchange data reported elsewhere (22)[4] was used to normalize the slope of the ventilatory and tidal volume response to CO_2 for the wide range of ventilation, tidal volume, and metabolic rate.

[3] MS4 Metropolitan Vickers Co., Ltd., U. K.

[4] Kafer, E. R. 1975. Idiopathic scoliosis. Gas exchange and the effect of age on arterial blood gases. *J. Clin. Invest.* Submitted for publication.

FIGURE 2 The age of onset of deformity and sex distribution in 55 patients with idiopathic scoliosis.

RESULTS

Physical characteristics. The correlation coefficients between the angle of scoliosis, and the height and the weight were, respectively, −0.506 ($P < 0.001$) and −0.371 ($P = 0.001–0.010$). In 11 of the 27 patients 18 yr or younger, the body weight was at or below the third percentile (23). The correlation coefficients between the age and the variables height, weight, and angle were not significant.

Lung volumes. In the majority of patients both the VC and the total lung capacity (TLC) were less than the predicted lung volume, and the mean ±SEM percent predicted VC (60.5±2.7%) was significantly less than the mean percent predicted TLC (70.2±2.6%) (Table II and Fig. 3).[2] The TLC, percent predicted TLC, VC, and percent predicted VC were inversely proportional to the angle of scoliosis (Table III). The mean percent predicted FRC was 79.3 (SEM 3.2) and was significantly less than the mean percent predicted RV (99.7±5.2 SEM) (Table II, Fig. 4). The FRC, percent predicted FRC, residual volume (RV), and the percent predicted RV were all inversely proportional to the angle of the scoliosis (Table III). The quantitative relationships between the angle and the percent predicted lung volumes indicate that for a 100° angle, the precent reduction in TLC and its subdivisions was between 29 and 37%. The range of reduction of lung volume for a 100° angle was 0.5–2.1 liters (Table III).

Scoliosis and chronic obstructive pulmonary disease. Although the VC was reduced in all the patients with obstructive pulmonary disease and scoliosis, there was a diverse pattern of change in the other subdivisions of the lung volumes (Figs. 3 and 4). In two patients the RV was elevated, and in one the FRC was also increased. The TLC was normal in two and reduced in one patient. The FEV_1 range in the four patients was 0.6–1.3 liters.

TABLE II
Lung Volumes and C_{rs} in Patients with Scoliosis

	TLC	TLC	VC	VC	FRC	FRC	RV	RV	C_{rs}
	liter	*% predicted*	*liter*	*% predicted*	*liter*	*% predicted*	*liter*	*% predicted*	*liter/cm H_2O*
Mean	3.08	70.2‡	1.94	60.5‡	1.75	79.3§	1.13	99.7§	0.049
SEM	0.17	2.6	0.13	2.7	0.09	3.2	0.05	5.2	0.004
Number of patients	44	44	51	51	45	45	44	44	42

‡ Significance of difference $P = 0.010 - 0.025$.
§ Significance of difference $P = 0.001 - 0.005$.

Mechanical properties of the respiratory system. The mean C_{rs} was 0.049 liter/cm H_2O (SEM 0.004) (Table II).[2] The C_{rs} was directly proportional to height ($r = 0.663$) and to weight ($r = 0.508$), and was inversely proportional to the angle (Fig. 5*a*). The C_{rs} was unrelated to the age of the patients.

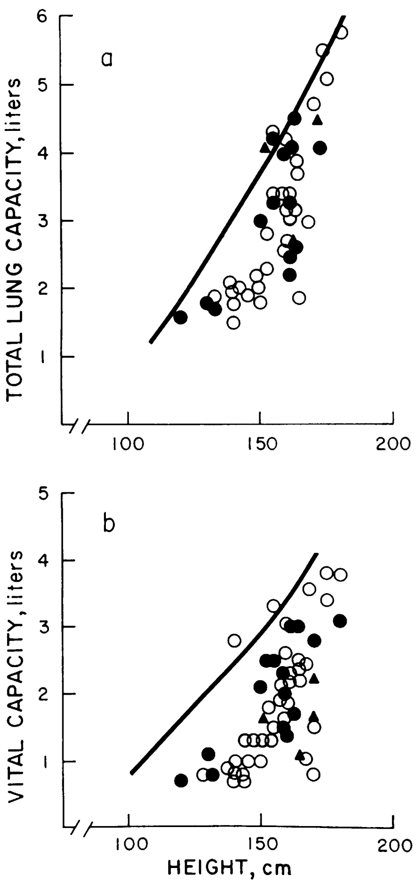

FIGURE 3 The relationship between the patients' height and TLC (upper panel), and VC (lower panel). ○, patients over 15 yr; ●, patients 15 yr and under; ▲, patients with scoliosis and obstructive pulmonary disease. The continuous line is the predicted TLC (upper panel) and predicted VC (lower panel) for patients 15 yr and under (14).

The compliance of the chest wall (C_{cw}) was measured in 24 patients whose age (mean±SEM) was 20.1±2.2 yr (range 9–52 yr) and angle was 88.9±6.2 SEM (range 38–150). These mean values are similar to those of the total group. The mean C_{cw} was 0.080 liter/cm H_2O (SEM 0.012); and was directly proportional to the height ($r = 0.777$), and to the weight ($r = 0.671$). The C_{cw} was inversely proportional to the angle, and the correlation coefficient was -0.721 (Fig. 5*b*). The correlation coefficient between age and C_{cw} was not statistically significant ($r = -0.165$, $P > 0.05$).

The VC was directly proportional to the C_{rs} (Fig. 6*a*) and to the C_{cw} (Fig. 6*b*). The correlation coefficients were 0.798 and 0.854, respectively. The relationship between the VC and the C_{rs} was similar to that observed by Naimark and Cherniack (24), and Johnson and Mead (25) in normals by the positive pressure breathing method. The relationship in the patients with scoliosis was $C_{rs} = 0.023\ VC + 0.004$.

The mean $C_l$dyn, measured in 25 patients, was 0.105 liter/cm H_2O (SEM 0.010), and the mean $C_l$stat was 0.177 liter/cm H_2O (SEM 0.011). These mean values were not significantly different (paired *t* test).

Ventilatory response to CO_2. The ventilatory response to CO_2 was measured in 24 patients whose mean age was 26.0±3.7 SEM years (range 9–72 yr), whose mean angle was 88.0±6.7 (SEM), and whose mean SEM Pa_{CO_2} was 42.3±1.26. In six patients the Pa_{CO_2} was 45 mm Hg or more; the values were 46, 46, 56, 53, 50, and 53 (Patients 6, 31, 42, 44, 45, and 47).[2] The data analyses exclude the patients who also had chronic obstructive lung disease.

The mean $\Delta\dot{V}/\Delta P_{CO_2}$ was 1.32 liter/min per mm Hg, SEM 0.171,[2] and the mean $\Delta V_T/\Delta P_{CO_2}$ was 28.9 ml/mm Hg, SEM 3.64.[2] The mean $\Delta\dot{V}/\Delta P_{CO_2}$ in 12 subjects 18 yr or over was 1.26±SEM 0.25, and this was compared to the mean values in normals, whose ventilatory response to CO_2 was measured by the same method (19, 26). The mean $\Delta\dot{V}/\Delta P_{CO_2}$ in patients with scoliosis (18 yr or over), was significantly less than Kronenberg and Drage's young series, mean $\Delta\dot{V}/\Delta P_{CO_2}$ 3.36±SEM 0.48, P = 0.001 − 0.01; Kronenberg and Drage's total series, mean 2.70±SEM

Table III
Regression Equations and Correlation Coefficients of the Relationships between the Angle of Scoliosis, and the Lung Volumes and the Percent Predicted Lung Volumes in Patients with Scoliosis

Dependent variable Y	Number of patients	Independent variable X	Regression equation and SD slope	Significance of slope > 0	Correlation coefficient
				P	r
TLC	44	Angle	$y = 4.76 - 0.021x \pm 0.005$	<0.001	−0.548
TLC, % *predicted*	44		$y = 96.20 - 0.321x \pm 0.076$	<0.001	−0.547
VC	51	Angle	$y = 3.12 - 0.015x \pm 0.005$	<0.001	−0.485
VC, % *predicted*	51		$y = 87.60 - 0.338x \pm 0.079$	<0.001	−0.523
FRC	45	Angle	$y = 2.64 - 0.011x \pm 0.003$	<0.001	−0.533
FRC, % *predicted*	45		$y = 102.50 - 0.286x \pm 0.104$	0.005 − 0.010	−0.338
RV	44	Angle	$y = 1.55 - 0.005x \pm 0.002$	0.010 − 0.020	−0.438
RV, % *predicted*	44		$y = 129.60 - 0.369x \pm 0.170$	0.025 − 0.050	−0.318

0.31, $P = 0.001 - 0.01$ (26) and Read's group, 2.65±SEM 0.28, $P = 0.01 - 0.001$ (19). The differences between Read's group, and Kronenberg and Drage's young and total groups were not significant.

The correlation coefficients between the $\Delta\dot{V}/\Delta P_{CO_2}$ and the following were significant: VC, 0.792 ($P < 0.001$) (Fig. 7*a*); TLC, 0.632 ($P < 0.001$); C_{rs}, 0.520 ($P < 0.001 - 0.01$), and also between the $\Delta\dot{V}/\Delta P_{CO_2}$ and the anthropometric data, resting ventilation, and oxygen consumption (Table IV). The correlation coefficient between the $\Delta\dot{V}/\Delta P_{CO_2}$ and the angle was not significant. The relationship between the $\Delta\dot{V}/\Delta P_{CO_2}$ and the VC for the total group ($n = 24$) was $\Delta\dot{V}/\Delta P_{CO_2} = 0.796\text{VC} - 0.003$, $r = 0.792$ (Fig. 7*a*), and was similar to the relationships in subjects of 18 yr or over ($n = 12$), and under 18 yr ($n = 12$). In the subjects over 18 yr, $\Delta\dot{V}/\Delta P_{CO_2} = 0.889\text{VC} - 0.225$, $r = 0.892$ ($P < 0.001$); and in subjects under 18 yr $\Delta\dot{V}/\Delta P_{CO_2} = 0.695\text{VC} + 0.231$, $r = 0.689$ ($P = 0.01 - 0.05$).

The correlation coefficients between the $\Delta V_T/\Delta P_{CO_2}$ and the following were significant: VC, 0.878 ($P < 0.001$) (Fig. 7*b*), TLC, 0.802 ($P < 0.001$); C_{rs}, 0.590 ($P = 0.001 - 0.01$); resting tidal volume, 0.783 ($P < 0.001$); height, 0.500 ($P = 0.01 - 0.05$); weight, 0.448 ($P = 0.025 - 0.05$), and angle, −0.468 ($P = 0.01 - 0.05$). The relationship between the $\Delta V_T/\Delta P_{CO_2}$ and the VC for the total group ($n = 24$), $\Delta V_T/\Delta P_{CO_2} = 18.82\text{VC} - 2.43$, $r = 0.878$, was similar in the subjects 18 yr or older ($n = 12$) and under 18 yr ($n = 12$). In the subjects 18 yr or older, the $\Delta V_T/\Delta P_{CO_2} = 20.77\text{VC} - 6.857$, $r = 0.934$ ($P < 0.001$); and for subjects under 18 yr, $\Delta V_T/\Delta P_{CO_2} = 16.69\text{ VC} + 2.265$, $r = 0.818$ ($P = 0.001 - 0.01$).

Neither of the slopes, $\Delta\dot{V}/\Delta P_{CO_2}$ or $\Delta V_T/\Delta P_{CO_2}$, nor the positions of the response curves were related to the P_{CO_2}, plasma bicarbonate, or the pH.

The effect of age on the ventilatory response to CO_2 was explored by the examining of the correlations between the slopes ($\Delta\dot{V}/\Delta P_{CO_2}$, $\Delta V_T/\Delta P_{CO_2}$) and age for the total group, angle 80° or greater and 18 yr or older (Tables V and VI). The correlation between $\Delta V_T/\Delta P_{CO_2}$ and age for subjects with scoliosis of 80° or greater was of marginal statistical significance. Therefore, in order to normalize for the wide range of body size (BSA or height), metabolism ($\dot{V}_{O_2}$), resting ventilation ($\dot{V}$), or tidal volume (V_T), the $\Delta\dot{V}/\Delta P_{CO_2}$ and $\Delta V_T/\Delta P_{CO_2}$ were expressed as ratios of the variables obtained during the steady-state gas exchange study (22).[4] For the subjects 18 yr or older, the correlation coefficients between age and $\Delta\dot{V}/\Delta P_{CO_2}/\dot{V}_{O_2}$ and $\Delta\dot{V}/\Delta P_{CO_2}/\dot{V}$ were significant, and these derivatives for the whole group were of marginal statistical significance (Table V). The correlation coefficients between age and the $\Delta V_T/\Delta P_{CO_2}/\text{ht}$ and $\Delta V_T/\Delta P_{CO_2}/V_T$ in subjects with scoliosis of 80° or greater were significant (Table VI).

DISCUSSION

The effects of scoliosis on body size and lung volumes. The relationships between size, structure, and function are one of the fundamental problems in scoliosis. There are no satisfactory methods of predicting normal values for size, volume, or function. The recognition of the effects of scoliosis on height led Zorab, Prime, Harrison, and Harrison (27, 28) to predict height from tibial length (29, 30); however, they subsequently concluded that the relationship between tibial length and height was not sufficiently accurate for predicting lung volumes (31). Hepper, Black, and Fowler (32) assumed that the same relationship exists in scoliosis between arm span and theoretical height as in normals between arm span and height, and predicted the lung volumes in scoliosis from the arm span. They calculated that in scoliosis the mean underestimation of predicted VC and TLC based on height was 20%. Bjure, Grimby, and Nachemson (33) predicted the theoretical height from the angle and length of spine. Both these methods assume a normal relationship between theoretical

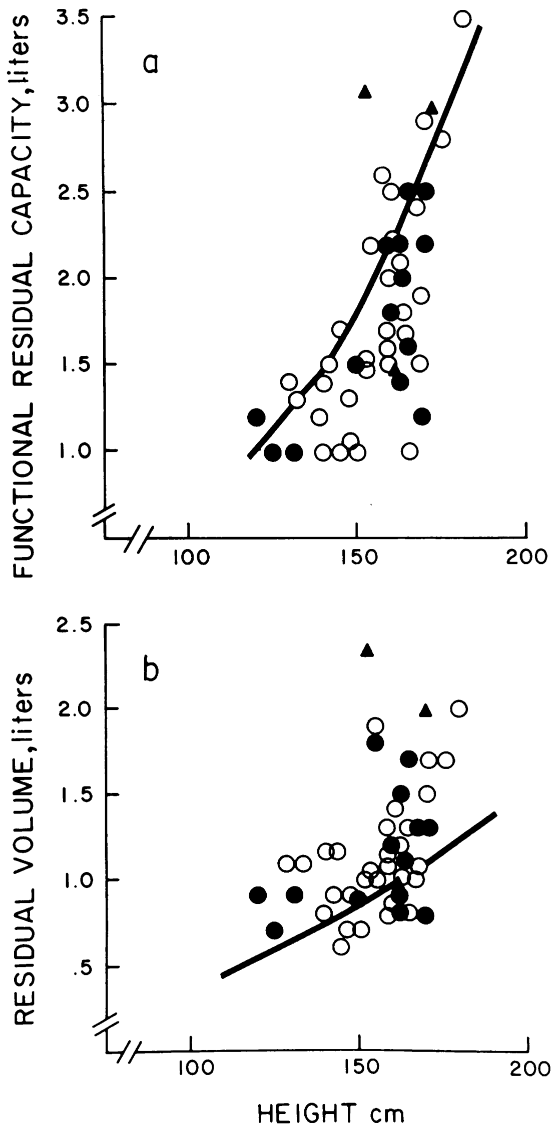

FIGURE 4 The relationship between the patients' height and FRC (upper panel) and RV (lower panel). The symbols are as in Fig. 3. The continuous line is the predicted FRC (upper panel) and predicted residual volume (lower panel) for patients 15 yr and under (14).

height and the biological factors that determine thoracic volume and ventilatory function. Our study has demonstrated a significant negative correlation between the angle and both the height and the weight; and 41% of the subjects of 18 yr or younger had body weights at or below the third percentile for their age. Therefore we postulate that because body size is a major biological determinant of the functional capacity of the respiratory system, the impairment of body growth by scoliosis contributes to decreased functional capacity of the respiratory system. Therefore also, the validity of predicting theoretical height from other body dimensions for the purposes of predicting lung volumes is questioned.

We have demonstrated an inverse relationship between the angle and the VC, percent predicted VC, the TLC, and the precent predicted TLC (Table III). These results are qualitatively similar to earlier observations that the greatest reductions in VC and TLC were seen when the angle was large (34–36). The apparent different effects of scoliosis on the FRC previously observed (7, 8) have been resolved by this study, in which both the FRC and the percent predicted FRC were inversely related to the angle. It is reasoned that these differences were probably due to differences in the severity of scoliosis. It has also been shown in this study that although the range of values of percent predicted RV was wide (Fig. 4), there was an inverse relationship between the angle and the RV and the percent predicted RV. It will, however, be noted that while the intercepts on the *y* axis for the percent predicted TLC, VC, and FRC were between 87.6 and 102.5, the intercept for the percent predicted RV was 129.6 (Table III). It is postulated that several mechanisms are responsible for the inverse relationships

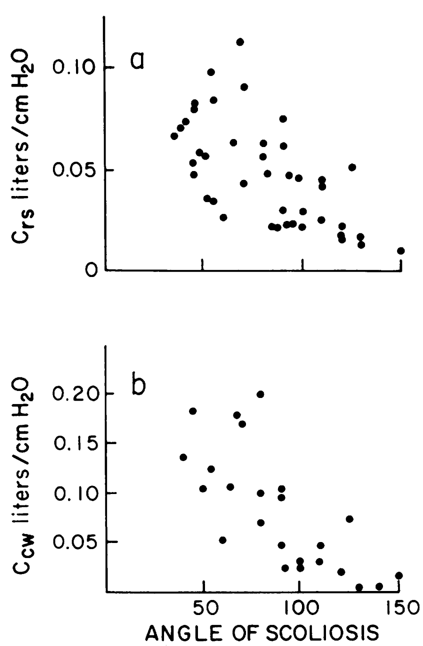

FIGURE 5 *a*. The relationship between the compliance of the total respiratory system (C_{rs}, liter/cm H_2O) and the angle of scoliosis in 42 patients with idiopathic scoliosis; the correlation coefficient was −0.620, and C_{rs} = 0.092 − 0.0005 angle of scoliosis (SD = 0.0001). *b*. The relationship between the compliance of the chest wall (C_{cw}, liter/cm H_2O) and the angle of scoliosis in 24 patients with idiopathic scoliosis: the correlation coefficient was −0.721, and C_{cw} = 0.211 − 0.0015 angle of scoliosis (SD slope = 0.0003).

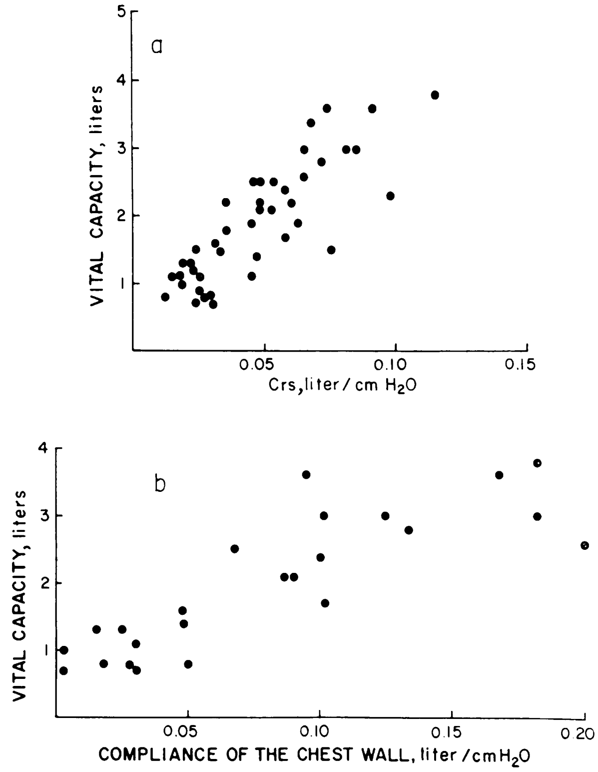

FIGURE 6 *a.* The relationship between the C_{rs} and the VC in 42 patients with idiopathic scoliosis: the correlation coefficient was 0.798. *b.* The relationship between the C_{cw} and the vital capacity in 24 patients with idiopathic scoliosis: the correlation coefficient was 0.854.

TABLE IV

The Relationships between the Slope of the Ventilatory Response to Carbon Dioxide (Dependent Variable) and Anthropometric Data, Resting Ventilation, and Oxygen Consumption in 24 Patients

Independent variable x	Correlation coefficient r	Significance P	Regression equation
Weight, *kg*	0.385	>0.05*	$y = 0.029x + 0.053$
Height, *cm*	0.499	0.01 − 0.05	$y = 0.030x - 3.130$
BSA, m^2	0.445	0.01 − 0.05	$y = 1.583x - 0.844$
Ventilation, BTPS *liter/min*	0.410	0.01 − 0.05	$y = 0.233x - 0.096$
Oxygen consumption, STPD, *liter/min*	0.397	0.05*	$y = 8.869x - 0.328$

* One-tailed test of significance; *P*, 0.025 − 0.05.

between angle and lung volumes; they include impairment of body and thoracic cage development and the effects of rib cage and vertebral deformity on the elastic properties of the respiratory system and on respiratory muscle force.

Elastic properties of the respiratory system. This study has also demonstrated an inverse relationship between the angle and both C_{rs} and C_{cw} (Fig. 5*a* and 5*b*). Therefore, although the elastic properties of the respiratory system were a function of body size, they were also dependent on the magnitude of the deformity. The mechanism of this relationship is, however, unknown. It may be argued that this relationship is due to the effect of scoliosis on the development of the thorax, abnormalities in the elastic properties of the chest wall due to the vertebral and rib cage deformity, and a relatively greater contribution of the diaphragm to deformation of the thorax during breathing than in normal humans (5). Although it was postulated (7) that in scoliosis there is an accelerated stiffening of the rib cage with age, this was not confirmed by either the C_{rs} or C_{cw} data. The C_{rs} analysis was based on the data of 42 patients and was representative of the entire age range. However, although the mean age of the patients in whom the C_{cw} was measured was similar to the total group, C_{cw} data was available on only two patients over 40 yr of age. Therefore, if the effect of age on C_{cw} was nonlinear and increased with age, then this may be the cause of the failure to demonstrate age-dependent changes in the C_{cw}.

As has been observed in normal and obese subjects, there was a direct relationship between the vital capacity, and the C_{rs} and also the C_{cw} (24, 25, 37) (Fig. 6*a* and 6*b*). The similarity between the relationship observed in normals (24, 25), and that in idiopathic

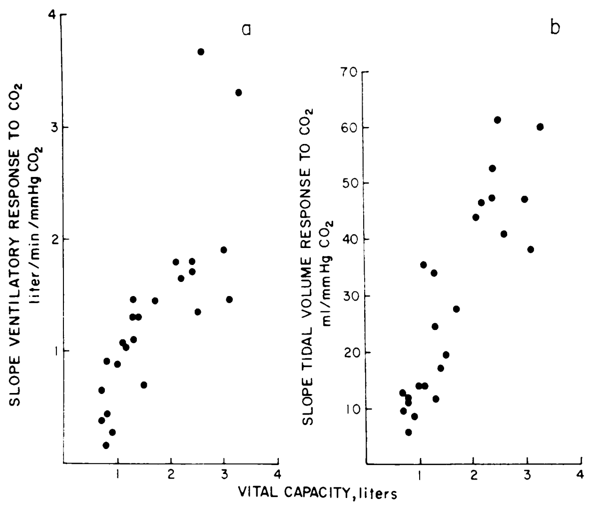

FIGURE 7 *a.* The relationship between the slope of the ventilatory response to carbon dioxide (liter/min/mm Hg) and the VC in 24 patients with idiopathic scoliosis: the correlation coefficient was 0.792, and the regression equation was $\Delta\dot{V}/\Delta P_{CO_2} = 0.796$ VC $- 0.003$ (SD slope = 0.131). *b.* The relationship between the slope of the tidal volume response to carbon dioxide (ml/mm Hg) and the VC in 24 patients with idiopathic scoliosis: the correlation coefficient was 0.878, and the regression equation was $\Delta V_T/\Delta P_{CO_2} = 18.82$ VC $- 2.43$ (SD slope = 2.18).

TABLE V

The Relationships between Age (Independent Variable) and the Slope of the Ventilatory Response to CO_2 ($\Delta\dot{V}/\Delta P_{CO_2}$), and Its Derivatives

Group	Number of subjects	Dependent variable*		Correlation coefficient		Regression equation
		y	Mean	r	P	
$\Delta\dot{V}/\Delta P_{CO_2}$	24	$\Delta\dot{V}/\Delta P_{CO_2}$	1.32	−0.240	>0.05	$y = 1.615 - 0.011x$
		$\Delta\dot{V}/\Delta P_{CO_2}$/BSA	0.943	−0.330	>0.05	$y = 1.207 - 0.010x$
		$\Delta\dot{V}/\Delta P_{CO_2}/\dot{V}_{O_2}$	7.030	−0.397	>0.05‡	$y = 9.356 - 0.090x$
		$\Delta\dot{V}/\Delta P_{CO_2}/\dot{V}$	0.213	−0.365	>0.05‡	$y = 0.282 - 0.003x$
Angle ⩾ 80°	18	$\Delta\dot{V}/\Delta P_{CO_2}$	1.32	−0.207	>0.05	$y = 1.599 - 0.010x$
		$\Delta\dot{V}/\Delta P_{CO_2}$/BSA	0.961	−0.326	>0.05	$y = 1.255 - 0.011x$
		$\Delta\dot{V}/\Delta P_{CO_2}/\dot{V}_{O_2}$	6.801	−0.365	>0.05	$y = 9.065 - 0.081x$
		$\Delta\dot{V}/\Delta P_{CO_2}/\dot{V}$	0.208	−0.333	>0.05	$y = 0.278 - 0.0025x$
Age ⩾ 18 yr	12	$\Delta\dot{V}/\Delta P_{CO_2}$	1.26	−0.413	>0.05	$y = 2.018 - 0.020x$
		$\Delta\dot{V}/\Delta P_{CO_2}$/BSA	0.873	−0.480	>0.05	$y = 1.476 - 0.016x$
		$\Delta\dot{V}/\Delta P_{CO_2}/\dot{V}_{O_2}$	6.536	−0.628	0.01 − 0.05	$y = 12.275 - 0.150x$
		$\Delta\dot{V}/\Delta P_{CO_2}/\dot{V}$	0.197	−0.615	0.01 − 0.05	$y = 0.363 - 0.0043x$

* $\Delta\dot{V}/\Delta P_{CO_2}$, liter·min^{-1} mm Hg CO_2^{-1}; BSA, m^2; $\dot{V}_{O_2}$, resting oxygen consumption, liter·min^{-1}, STPD; $\dot{V}$, resting ventilation, liter·min^{-1}, BTPS.

‡ One-tailed test of significance, $P = 0.025 - 0.05$.

scoliosis is of great interest. In normal subjects the maximal inspiratory position is determined by the balance of the elastic forces of the lung and chest wall, and the inspiratory muscle force (38). The relationships demonstrated in this study are consistent with increased elastic forces due to the deformity being the major determinants of the maximal inspiratory position; however, the impairment of the inspiratory muscle force cannot be excluded. In young normals the RV is determined by the balance of the expiratory muscle force and the elastic forces of the rib cage (39). In the patients with scoliosis, all percent predicted RV's over 120 (8 subjects, range 130–189%) were in subjects less than 20 yr, and the angle was usually severe. This is also consistent with the increased elastic forces due to the deformity acting as the major factor in determining the RV; however, further data are required to test the role of expiratory muscle force.

Ventilatory responses to CO_2. In normals the range of slope of the ventilatory response to CO_2 is wide (19, 40–43), and no significant relationship has been demonstrable between the slope and body size (19, 40, 41). However, racial differences have been observed (44, 45), and the effects of both genetic and environ-

TABLE VI

The Relationships between the Age (Independent Variable) and the Slope of the Tidal Volume Response to CO_2 ($\Delta V_T/\Delta P_{CO_2}$) and Its Derivatives

Group	Number of subjects	Dependent variable*		Correlation coefficient		Regression equation
		y	Mean	r	P	
$\Delta V_T/\Delta P_{CO_2}$	24	$\Delta V_T/\Delta P_{CO_2}$	28.93	−0.192	>0.05	$y = 33.90 - 0.191x$
		$\Delta V_T/\Delta P_{CO_2}$/ht	188.6	−0.238	>0.05	$y = 227 - 1.475x$
		$\Delta V_T/\Delta P_{CO_2}/V_T$	81.0	−0.293	>0.05	$y = 97.84 - 0.648x$
Angle ⩾ 80°	18	$\Delta V_T/\Delta P_{CO_2}$	26.54	−0.439	>0.05‡	$y = 39.20 - 0.498x$
		$\Delta V_T/\Delta P_{CO_2}$/ht	178.1	−0.484	0.01 − 0.05	$y = 267 - 3.517x$
		$\Delta V_T/\Delta P_{CO_2}/V_T$	76.7	−0.472	0.025 − 0.05	$y = 107 - 1.206x$
Age ⩾18 yr	12	$\Delta V_T/\Delta P_{CO_2}$	27.9	−0.292	>0.05	$y = 39.83 - 0.311x$
		$\Delta V_T/\Delta P_{CO_2}$/ht	179.2	−0.331	>0.05	$y = 263 - 2.181x$
		$\Delta V_T/\Delta P_{CO_2}/V_T$	76.8	−0.419	>0.05	$y = 115 - 0.981x$

* $\Delta V_T/\Delta P_{CO_2}$ = ml·mm Hg CO_2^{-1}; height (ht); m; tidal volume at rest (V_T), liters.

‡ One-tailed test of significance, $P = 0.025 - 0.05$.

mental factors postulated (46). Patrick and Howard (47) postulated that the slope of the ventilatory response to CO_2 was less in females than in males; however, this was not confirmed by the result of their statistical analysis. No significant difference based on sex was observed in the slopes of the ventilatory response to CO_2 in patients with scoliosis.

Comparison of the mean $\Delta\dot{V}/\Delta P_{CO_2}$ in patients with scoliosis who were 18 yr or older with normals of comparable age confirmed that in scoliosis the slope was significantly less than in normals. Several mechanisms may contribute to the reduction in $\Delta\dot{V}/\Delta P_{CO_2}$ in scoliosis, and they include the increased mechanical load to breathing as a result of the increased elastic forces, decreased ventilatory capacity associated with the reduced body size and metabolism, and reduced sensitivity of the chemoreceptors and/or the central respiratory control system to afferents from chemical and nonchemical stimuli.

The data have shown that the relationships between both the $\Delta\dot{V}/\Delta P_{CO_2}$ and $\Delta V_T/\Delta P_{CO_2}$, and the body size, resting ventilation, tidal volume, metabolism, and the lung volumes and elastic forces are complex. High, statistically significant direct relationships were demonstrable between both the $\Delta\dot{V}/\Delta P_{CO_2}$, and $\Delta V_T/\Delta P_{CO_2}$ and the VC for the total group, patients 18 yr or over, and patients under 18 yr. These relationships are consistent with the mechanical properties of the respiratory system, as expressed by the VC as one of the major determinants of both the magnitude and the pattern of the ventilatory response to CO_2 in scoliosis. Nevertheless, it must be recognized that body size, as a determinant of both ventilatory capacity and metabolism, contributes to the magnitude of the ventilatory response to CO_2. Measurement of the contribution of these factors is difficult because of the absence of data in humans of wide range of body size and metabolic rate, and the effects of scoliosis itself on body size.

The relationship between the mechanical properties of the respiratory system and the magnitude and pattern of the ventilatory response to CO_2 demonstrable in patients with idiopathic scoliosis contrasts with the effects of experimental elastic loading of respiratory system on the ventilatory response to CO_2 (48, 49). Neither chest strapping (48) nor application of an elastic load to the airway (49) changed the slope of the ventilatory response to CO_2. Due to the ventilatory pattern of small tidal volumes and high respiratory frequency, ventilation was achieved without a significant increase in inspiratory muscle force or work. Resistance loading, however, resulted in a decrease in the slope of the ventilatory response to CO_2 that was proportional to the added load (50, 51). As a result of the decrease in ventilation, the calculated inspiratory work in response to CO_2 stimulus remained constant. The effects of scoliosis on the ventilatory response to CO_2 are similar to the effects of external resistance loading; however, the comparison does not provide evidence of the mechanism or neural pathways responsible for the adjustment of both the magnitude and the pattern of the ventilatory responses to CO_2 in scoliosis.

Kronenberg and Drage (26) demonstrated an age-dependent decrease in the slope of the ventilatory response to CO_2. Analysis of Alexander's data (40, 41, 52) also confirmed an age-dependent decrease in the slope, $\Delta\dot{V}/\Delta P_{CO_2} = 2.289 - 0.023$ yr, $r - 0.429$ ($P = 0.01 - 0.05$). An age-dependent decrease in the $\Delta\dot{V}/\Delta P_{CO_2}$ when normalized for the resting ventilation or oxygen consumption was most clearly defined in the patients with scoliosis who were 18 yr or older. A similar relationship between age and the $\Delta V_T/\Delta P_{CO_2}$ normalized for patient height or resting tidal volume was demonstrable in patients whose scoliosis was 80° or more. The mechanism of these age-dependent changes is not simply explained. It may be argued that a change in slope of ventilatory or tidal volume response to CO_2 is due to one or more of the following mechanisms: decrease in the sensitivity of the chemoreceptors and/or a decrease in the sensitivity of the medullary respiratory centers to afferent information; changes in the efferent pathways and/or muscle function which result in a decrease in inspiratory muscle force in response to the output of the respiratory centers; and an increase in the inspiratory mechanical load. Blood gas studies during steady gas exchange at rest in patients with idiopathic scoliosis have shown an age-dependent increase in Pa_{CO_2} (22).[4] These data have also shown an age-dependent increase in V_D/V_T. Therefore, it may be argued that the age-dependent increase in Pa_{CO_2} is due to the deterioration in ventilation-blood flow maldistribution with age, and that the age-dependent decrease in the ventilatory response to CO_2 provides a synergistic mechanism for the increase in Pa_{CO_2} by impairing the compensatory increase in ventilation in response to ventilation-blood flow maldistribution. However, because chronic hypercapnia due to acclimization of the cerebrospinal fluid depresses the ventilatory response to CO_2, it is not possible to define whether chronic hypercapnia is a cause or an effect of the decrease in the ventilatory response to CO_2 with age.

The study has demonstrated the following features of respiratory function abnormalities in idiopathic scoliosis: First, statistical relationships between the severity of scoliosis, as expressed by the angle of scoliosis, and the body size, lung volumes, percent predicted lung volumes, and the elastic properties of the respiratory system. Second, statistical relationships between the body size and the mechanical properties of the respiratory system, as expressed by the lung volumes and the elastic forces, and both the slope and the pattern of the ventilatory response to CO_2. Third, some confirmatory evidence of an age-dependent decrease in the slope of both the ventilatory and tidal volume response to CO_2 has been identified in scoliosis, as has been observed in normals. This age-dependent decrease in the ventilatory response to CO_2 may impair the ventilatory compensation for ventilation-blood flow maldistribution, and may therefore be synergistic in the age-dependent increase in Pa_{CO_2}. Fourth, the above statistical relationships demonstrable in idiopathic scoliosis were absent in paralytic scoliosis due to poliomyelitis (53).

The investigation has, however, also identified unresolved problems of the functional abnormalities in scoliosis. These include the effects of scoliosis on respiratory muscle function, possible accelerated degenerative changes in the mechanical properties of the lungs and increased rigidity of the rib cage in the elderly, and the mechanism of the adjustment of the magnitude and pattern of the ventilatory response to CO_2. Finally, whilst in recent years both surgical and nonsurgical methods of correction of scoliosis have been developed, there has been little evidence that they result in either an immediate or long-term improvement in function or longevity. The development of effective surgical and nonsurgical methods of correction requires the application of quantitative functional studies for evaluation. This study has indicated some of the measurements that may prove useful in the evaluation of management.

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