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Breathing pattern and load compensatory responses in young scoliotic patients

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Breathing pattern and load compensatory responses in young scoliotic patients. M. Ramonatxo, J. Milic-Emili, C. Prefaut.
ABSTRACT: The breathing pattern and mouth occlusion pressure developed in 0.1 seconds ($P_{0.1}$) were measured at rest in sixteen young scoliotic patients in whom the blood gases were within the normal limits. The patients exhibited rapid and shallow breathing. $P_{0.1}$ was increased above normal, indicating a compensatory increase of neuromuscular inspiratory drive in the face of a stiffer respiratory system. $P_{0.1}$ (% predicted) correlated positively with the angle of scoliosis. Both duration of inspiration and inspiratory duty cycle correlated negatively with angle of scoliosis and $P_{0.1}$ (% predicted). On theoretical grounds we show that these changes in breathing pattern are beneficial, both in terms of reducing the energy cost of breathing and preventing the development of inspiratory muscle fatigue.
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Scoliosis is the most common cause of thoracic deformities in children and adolescents. It is generally accepted that scoliosis comprises a typical restrictive pattern of lung volume [1] and an increase of total respiratory system elastance (Ers), mainly reflecting increased elastance of the chest wall [2–4]. Surprisingly scoliotics, in general, exhibit a substantial reduction of inspiratory muscle strength, assessed in terms of maximum static inspiratory airway pressure (PImax) [5,6]. Moreover, Lisboa *et al.* [6] have reported a marked reduction in maximum static transdiaphragmatic pressure in patients with severe scoliosis.

In the early stages of the disease, at least in young patients, blood gases are not impaired which seems to indicate a good compensating response to scoliosis. This compensation could be due to an increase of the inspiratory neural drive, which allows them to maintain normal alveolar ventilation. Furthermore, as indicated by Bellemare and Grassino [7, 8], in the face of an increased load to breathe and respiratory muscle weakness, patients may adopt breathing patterns which allow them to breathe below the fatiguing threshold of the respiratory muscles.

In the present investigation we have made a detailed analysis of the breathing pattern together with measurements of the mouth occlusion pressure ($P_{0.1}$) in sixteen young scoliotic patients in order to clarify the strategy of breathing which they adopt in the face of increased respiratory loading.

Methods

We studied sixteen patients aged 8–23 yrs (nine females, seven males) with scoliosis (idiopathic in seven, congenital in three, and paralytic in six). All were non-smokers and had no associated cardiac or pulmonary disorders. None were receiving medical treatment at the time of the study. The mean angle of spinal curvature, as measured by the method of Cobb [9], was 81° (range: 40–175°). Their physical characteristics are given in table 1. The predicted height was calculated with the formula of Bjure *et al.* [10], which predicts the height loss by the angulation of the primary curve, except for the subject in whom the angle of scoliosis was 175°. Her predicted height was computed from the arm span [11]. The predicted height was used to compute the predicted lung volumes. The study was approved by the institutional ethics committee, and informed consent was obtained from the participants or their parents.

The subdivisions of lung volume and forced expiratory volume in one second (FEV_1) were measured with a 9 litre Spirotest III (E. Jaeger, Würzburg, Germany). The functional residual capacity (FRC) was measured by the helium dilution method. All volumes were expressed at body temperature and pressure, saturated. The predicted values used for subjects under eighteen years were those of Laval *et al.* [12] and for subjects over eighteen years those of Ceca [13]. The steady-state diffusing capacity for carbon monoxide ($DLco_{ss}$) was measured using the method of Bates *et al.* [14] with a Godart Diffusion Test (Utrecht, Holland). A Rahn-Otis sampler (Warren E. Collins, Inc., Cleveland OH) with an instrumental dead-space of about 30 ml was used to collect the end-tidal sample, in order to measure the end-tidal fraction of CO. The predicted values are from our laboratory [15]. Samples of arterial blood

Table 1. - Physical characteristics of sixteen scoliotic patients (seven males and nine females)

	Age yr	Weight kg	Height m	Predicted Height m	Angle of Scoliosis
Mean	15.4	38.5	1.46	1.53	81°
SD	3.2	10.7	0.15	0.14	31°

were drawn by capillary from the ear and immediately analysed on a Corning 168 pH/blood gas system (Corning Medical Instruments, Medfield, MA).

The breathing pattern and $P_{0.1}$ were studied at rest in the sitting position. Subjects breathed through a mouthpiece and a No. 2 Fleisch pneumotachograph (A. Fleisch, Lausanne, Switzerland) connected to a two-way valve, which separated the inspiratory and expiratory lines. The flow signal was electronically integrated to obtain tidal volume. Mouth occlusions were performed with a silent, electromagnetically operated valve, which was closed during expiration and opened automatically about 150 ms after the onset of the occluded inspiration. Since closure was silent, the subjects were unable to anticipate which breath was going to be occluded. Mouth pressure was measured using a Validyne transducer and model CD 15 carrier demodulator (Validyne Corp., Northbridge, CA). All signals were recorded on a Gould ES-1000 electrostatic recorder (Gould Inc., Cleveland OH) using a paper speed of 100 $mm \cdot s^{-1}$. Subjects were asked to breathe room air for about five minutes to get used to the circuit. Afterwards, ten occlusions were made in each subject at the rate of one per minute. The inspiratory (T_I), expiratory (T_E), total cycle time (T_T), tidal volume (V_T), and mean inspiratory flow (V_T/T_I) were measured from two breaths prior to each occluded breath. The results given for each patient are the mean values of all measurements.

The predicted values used for $P_{0.1}$ were those of GAULTIER *et al.* [16], while those for minute ventilation ($\dot{V}_E$) and breathing pattern (T_I, T_E, etc.) were taken from JAMMES *et al.* [17]. Unless otherwise specified, predictions were made according to age. In this connection, it should be noted that both V_T/T_I and T_I/T_T are essentially independent of age, over the age span of the present patients (8–23 yrs), while T_I, T_E, T_T and V_T tend to increase progressively between 8 and 21 yrs [16, 17]. By contrast, $P_{0.1}$ reaches the adult value at an age of about 14 yrs, higher values being observed at younger ages [16].

Regression analysis was carried out using the least-squares method.

Results

Lung function and blood gas data (table 2)

The patients as a group exhibited the restrictive pattern of lung volumes previously described [1], namely a reduction of vital capacity (VC), total lung capacity (TLC) and FRC associated with an increase of the RV/TLC ratio. In six of the patients, however, VC, TLC and FRC were within normal limits. In two of the six the angle of scoliosis was greater than 70° (77 and 88°, respectively).

Although it is often assumed that lung function abnormality becomes detectable only when the Cobb spinal angle exceeds 70° [1], three of our patients exhibited a restrictive pattern with lower angles (55, 60 and 60°, respectively). A significant negative correlation was found between the angle of scoliosis and the percent predicted VC ($r = -0.64$; $p < 0.01$) and TLC ($r = -0.62$; $p < 0.02$). No significant correlation was found between either percent predicted RV or FRC and the angle of scoliosis, while the RV/TLC ratio correlated positively with the angle of scoliosis ($r = 0.58$; $p < 0.02$). The FEV_1/VC ratio was within the normal limits in fourteen patients, but slightly reduced in two (63 and 68%, respectively).

The arterial oxygen tension (Pa_{O_2}) and carbon dioxide tension (Pa_{CO_2}) were within the normal limits in all patients, while the steady-state diffusing capacity for CO, expressed as a fraction of minute ventilation, was slightly reduced in two patients (77 and 78% of predicted normal, respectively).

Ventilatory variables and mouth occlusion pressure (table 3)

The mean minute ventilation ($\dot{V}_E$) was within the normal limits according to age but was associated with a high frequency (*f*) and a low V_T. The latter, expressed as % of predicted normal, correlated significantly with the angle of scoliosis ($r = -0.72$; $p < 0.01$) while $\dot{V}_E$ and *f*, both expressed as % of predicted, did not. A normal $\dot{V}_E$ associated with rapid and shallow breathing should imply a lower alveolar ventilation, which was not the case in our patients. However, when $\dot{V}_E$ was normalized for body weight ($\dot{V}_E$/BW), it averaged 157% of predicted normal [17].

Table 2. - Lung function and blood gas data of sixteen scoliotic patients

	VC	TLC % predicted	FRC	RV/TLC %	FEV_1/VC %	Pa_{O_2} mmHg	Pa_{CO_2} mmHg	$DL_{COss}/\dot{V}_E$ % predicted
Mean	68.1	82.5	88.3	35.0	85.0	92	37	93.5
SD	30.6	31.2	39.4	13.8	9.9	8	3	14.7

Definition of abbreviations: VC: vital capacity; TLC: total lung capacity; FRC: functional residual capacity; FEV_1: forced expiratory volume in one second; $DL_{COss}/\dot{V}_E$: steady state diffusing capacity for CO divided by minute ventilation.

Table 3. - Ventilatory variables and mouth occlusion pressure in sixteen scoliotic patients

	$\dot{V}$E $l\cdot\text{min}^{-1}$	VT l	f min^{-1}	TI s	TI/TT	VT/TI $l\cdot\text{s}^{-1}$	$P_{0.1}$ $\text{cmH}_2\text{0}$
Mean	10.97	0.48	24.3	1.18	0.43	0.42	2.79
SD	2.76	0.12	7.6	0.37	0.04	0.11	1.13
				% predicted*			
Mean	90	70	131	81	95	102	170
SD	29	14	41	24	4	27	69

Definition of abbreviations: $\dot{V}$E: minute ventilation; VT: tidal volume; f: respiratory frequency; TI: inspiratory duration; TI/TT: ratio of inspiratory to total cycle duration; VT/TI: mean inspiratory flow; $P_{0.1}$: mouth occlusion pressure developed in 0.1 sec. *Predictions made according to age.

Since the metabolic rate is related to body weight this probably explains the normal arterial blood gases. Interestingly, although both the average values of VT/TI and TI/TT were within the normal limits, the latter correlated negatively with the angle of scoliosis (fig. 1A) and positively with the VC (% predicted) (fig. 1B). Furthermore, TI (% predicted) also correlated negatively with the angle of scoliosis ($r=-0.57$; $p<0.05$).

The mean value of $P_{0.1}$ was higher than predicted normal and correlated positively with the angle of scoliosis (% predicted) (fig. 2A) and negatively with VC (% predicted) (fig. 2B). A negative correlation was found between TI (% predicted) and $P_{0.1}$ (% predicted) (fig. 3) and between TI/TT and $P_{0.1}$ (% predicted) ($r=-0.72$; $p<0.01$). However, no significant correlation was found other than TE or TE (% predicted) and the following parameters: angle of scoliosis, VC (% predicted) or $P_{0.1}$ (% predicted). This seems to imply that the reduction in TI/TT was due mainly to a proportionally greater decrease in TI. The tidal volume (% predicted) decreased significantly with $P_{0.1}$ (% predicted) (fig. 4). By contrast, f (% predicted) did not correlate significantly with $P_{0.1}$ (% predicted).

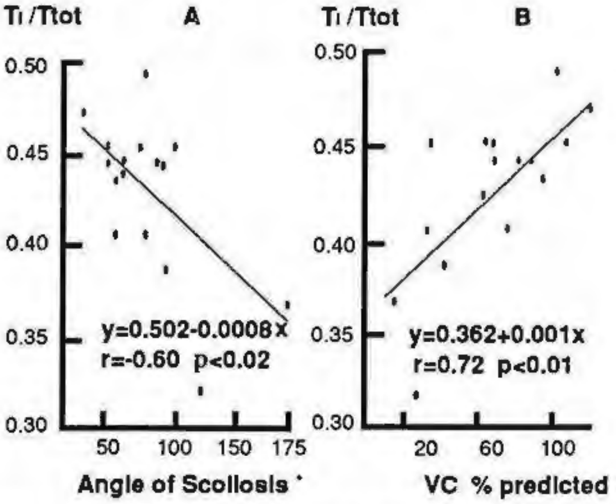

Fig. 1. Relationship between ratio of inspiratory to total cycle duration (TI/TT) and A: angle of scoliosis; B: vital capacity (VC) expressed as percent of predicted normal. Results in sixteen scoliotic patients.

Discussion

Lung function

Our patients exhibited a restrictive pattern which correlated with the angle of scoliosis. This is in agreement with previous observations [3, 10, 18]. According to BERGOFSKY [1], abnormal lung function becomes detectable only when the angle of scoliosis exceeds 70°. However, we found abnormally low values of TLC, FRC and VC in four patients in whom the angle of scoliosis was less than 70°. This is in line with the results of COOPER *et al.* [19] who studied 108 adolescents with mild to moderate idiopathic scoliosis (range of angle of scoliosis: 35–55°), and found that 38% had a TLC below 2 SD of the predicted value. They attributed this to decreased inspiratory muscle strength, probably reflecting defective mechanical coupling between inspiratory muscles and chest wall. A restrictive pattern was also found by SMYTH *et al.* [20] in six out of 44 adolescents with mild idiopathic scoliosis (spinal curvature less than 30°). They also found a correlation between Pimax (% predicted) and VC (% predicted), and concluded that the force developed by the inspiratory muscles is an important determinant of abnormal lung function. Although the nature of this abnormality is not fully understood, most of the available evidence indicates that in scoliotic patients the respiratory muscle strength is reduced, the more so the greater the angle of scoliosis [5, 20]. The reduced muscle strength, however, can not entirely explain the restrictive pattern observed in some patients with mild to moderate scoliosis (angle less than 70°) because, as shown by the present results and those of COOPER *et al.* [19], some of these patients also exhibit an abnormally low FRC. This should probably be imputed to abnormal mechanical properties of the chest wall. Thus, in some scoliotic patients, abnormal respiratory mechanics can be present at spinal angles of less than 70°.

In spite of spirographic modifications, blood gases

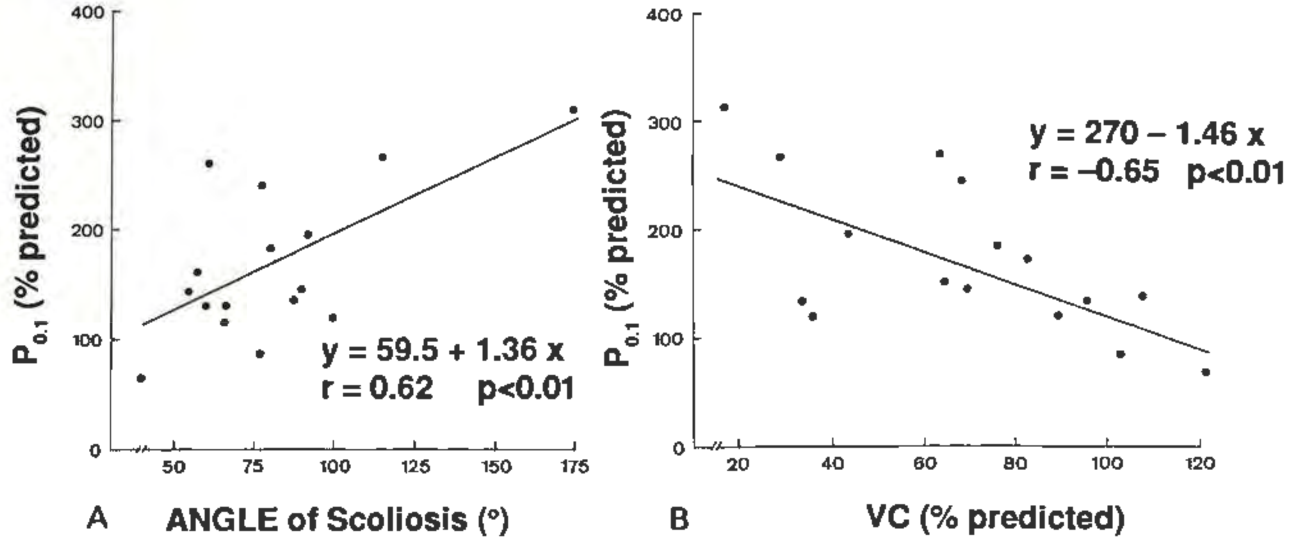

Fig. 2. Relationship between mouth occlusion pressure ($P_{0.1}$), expressed as percent of predicted normal and A: angle of scoliosis; B: vital capacity (VC) expressed as percent of predicted normal. Results in sixteen scoliotic patients.

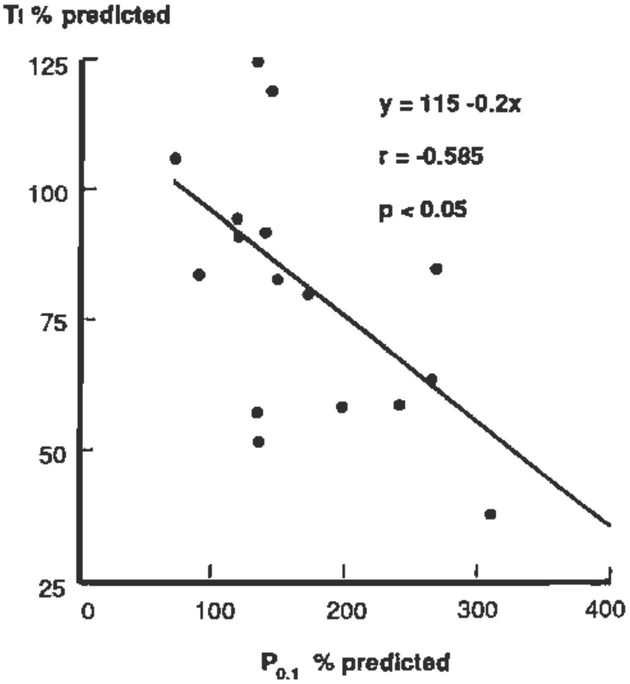

Fig. 3. Relationship between Ti and $P_{0.1}$, both expressed as percent of predicted normal, in sixteen scoliotic patients.

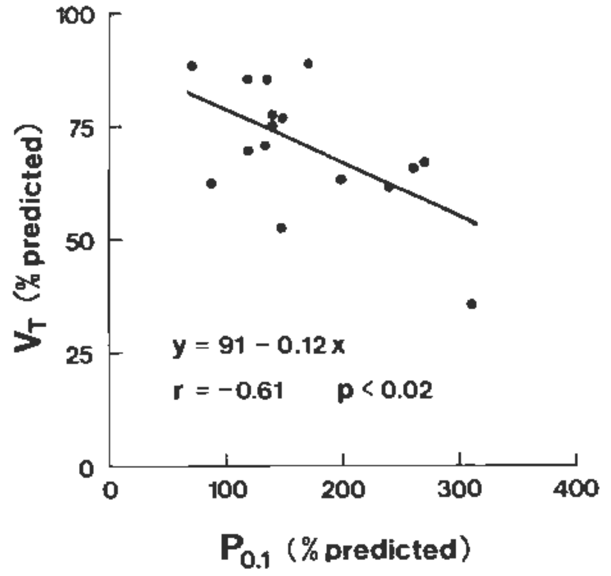

Fig. 4. Relationship between tidal volume (VT) and $P_{0.1}$, both expressed as percent of predicted normal, in sixteen scoliotic patients.

were normal, in line with the results of KAFER [21]. In accordance with OLGIATI *et al.* [22], we found normal diffusing capacity for CO in almost all patients.

Mouth occlusion pressure

Several studies performed in scoliotics show an increase of Ers which correlates with the degree of spinal curvature [2, 3]. This implies a greater elastic load to breathe with increased angle of scoliosis. The observation that all of our patients had normal blood gases implies load-compensation. In fact, $P_{0.1}$ in our patients was higher than predicted normal, the increase being proportional to the angle of scoliosis and the restriction. According to the regression equation in figure 2A, for angles of scoliosis from 100–150°, the average $P_{0.1}$ should be about 230% of predicted normal. According to KAFER [3], over the same spinal angle span, Ers increases to about 260% of normal. Thus, it appears that the neuromuscular inspiratory drive, as reflected by $P_{0.1}$, increased in virtually direct proportion to the increase in Ers such as to maintain an adequate alveolar ventilation. This is also true in patients with pulmonary fibrosis in whom the arterial blood gases are, in general, also within the normal limits [23]. This indicates that in patients with scoliosis and pulmonary fibrosis the increase in $P_{0.1}$ is unlikely to be due to a change in chemical stimulus to breathe. Whether the increase in $P_{0.1}$ reflects automatic (reflex) or behavioural responses [24] is not known. The same is also true in terms of the abnormalities in breathing pattern.

Breathing pattern

The breathing pattern of our patients was characterized by a decrease of T_I, V_T and T_I/T_T proportional to the angle of scoliosis and the restriction. This is in line with the results of SMYTH *et al.* [25] in adolescents with mild asymptomatic scoliosis (thoracic curvature $<35°$). They found reduced tidal volume responses, whereas frequency responses were either normal or increased during ventilatory responses to progressive hypercapnia, hypoxia or exercise. In other words, 'stress tests' induced the same breathing pattern in mild asymptomatic scoliosis as did spontaneous breathing in our population with more severe scoliosis. Such a breathing pattern is consistent with minimization of the inspiratory mechanical power ($\dot{W}_I$) [26]. Recent studies, however, indicate that the energy cost of breathing is probably more closely related to the mean pressure developed by the inspiratory muscles over the breathing cycle ($\bar{P}_I$) than to $\dot{W}_I$) [27, 28], confirming an earlier report by MCGREGOR and BECKLAKE [29]. Accordingly, it seems of interest to consider to what extent the breathing pattern adopted by scoliotic patients minimized $\bar{P}_I$.

Based on the assumption that inspiratory driving pressure varies sinusoidally with time and using steady-state solutions, OTIS *et al.* [26] were able to predict the optimal frequency of breathing at which a given alveolar ventilation should be performed most economically in terms of $\dot{W}_I$. Making the same assumptions, MEAD [30] extended this analysis in terms of minimum $\bar{P}_I$. There are several objections to both of these analyses [31], a fundamental one being that, by definition, a sinusoidal solution implies that T_I/T_T has a fixed value of 0.5. This is clearly not the case in both normal humans and patients in whom T_I/T_T is known to deviate at times quite markedly from a value of 0.5 [32]. Furthermore, BELLEMARE and GRASSINO [7, 8] have demonstrated the importance of T_I/T_T in terms of inspiratory muscle fatigue. The basic message of their investigation and others [33, 34] is that inspiratory muscle fatigue should occur when the $\bar{P}_I/P_{I\max}$ ratio exceeds a critical value of 0.15–0.20. This critical value has been termed 'fatiguing threshold' [7]. Since $P_{I\max}$ is reduced in scoliotic patients, it follows that during tidal breathing they should be closer to the 'fatiguing threshold' than normal individuals. In addition, their $\bar{P}_I$ should increase because of increased Ers. Neglecting the resistive pressure losses, which in these patients should be relatively small, and assuming that the inspiratory driving pressure increases linearly with time, $\bar{P}_I$ is given by [23]:

$$\bar{P}_I = 0.5 \cdot \mathrm{Ers} \cdot V_T \cdot T_I/T_T \qquad (1)$$

where $0.5 \cdot \mathrm{Ers} \cdot V_T$ is the mean pressure developed during inspiration. Since V_T can be partitioned into the deadspace (V_D) and alveolar (V_A) components, and the alveolar ventilation ($\dot{V}_A$) is equal to V_A/T_T, Equation (1) can be rewritten:

$$\bar{P}_I = 0.5 \cdot \mathrm{Ers} \cdot T_I(\dot{V}_A + V_D/T_T) \qquad (2)$$

Since $60/T_T$ is equivalent to *f*, equation (2) can be rewritten:

$$\bar{P}_I = 0.5 \cdot \mathrm{Ers} \cdot T_I(\dot{V}_A + V_D \cdot f) \qquad (3)$$

Equation (2) indicates that, for constant Ers and V_D, a given $\dot{V}_A$ can be achieved with a progressively lower $\bar{P}_I$ as T_I and/or T_I/T_T are decreased. This is tantamount to saying that under the same constraints, a given $\dot{V}_A$ involves less $\bar{P}_I$ as T_I and/or *f* decrease (equation 3). Clearly, in normal individuals the breathing pattern during eupnoeic breathing does not conform to these optimization criteria, as both T_I and T_I/T_T are relatively large. This probably reflects the fact that the oxygen cost of breathing is normally rather small [26], and hence the requirement for optimization is not stringent. By contrast, in scoliotics there may be the need to reduce $\bar{P}_I$ both because the inspiratory efforts must be stronger in order to defend $\dot{V}_A$ in the face of increased Ers, and in view of decreased $P_{I\max}$. In fact, in our patients both T_I and T_I/T_T decreased significantly with increasing $P_{0.1}$ and angle of scoliosis (fig. 1A). The considerable sparing of $\bar{P}_I$ that can be achieved by decreased T_I is illustrated in figure 5, which depicts the relationship

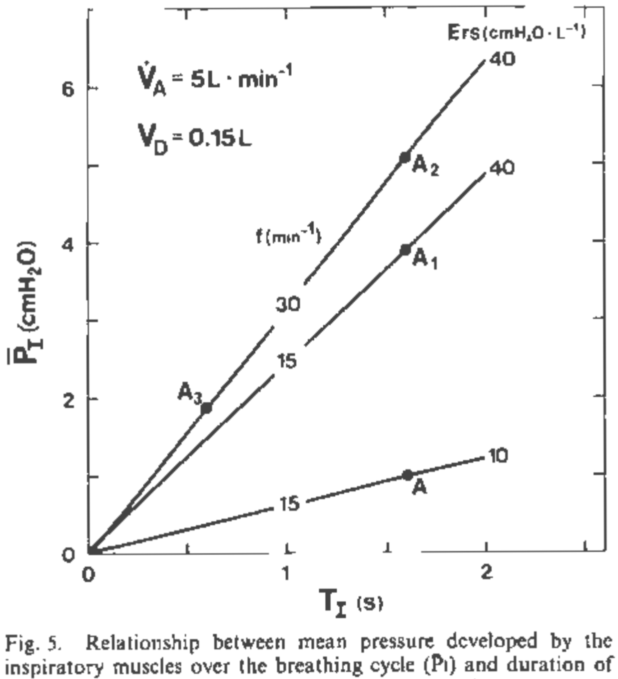

Fig. 5. Relationship between mean pressure developed by the inspiratory muscles over the breathing cycle ($\bar{P}_I$) and duration of inspiration (T_I). The curves were computed according to equation (3) for constant alveolar ventilation ($\dot{V}_A$) and dead space (V_D) and different values of total respiratory system elastance (Ers) and breathing frequency (*f*). Note that at constant *f* (and hence $1/T_T$) the inspiratory duty cycle (T_I/T_T) decreases progressively with decreasing T_I. For further explanations see text.

between $\bar{P}$I and TI computed according to equation (3) for constant $\dot{V}$A (5 $l \cdot \text{min}^{-1}$) and VD (0.15 l), and different values of Ers and f. The lower curve in figure 5 shows the relationship pertaining to normal adult Ers (10 $\text{cmH}_2\text{O} \cdot l^{-1}$) and f (15 breaths per min) while the middle and upper curves were computed for an Ers value of 40 $\text{cmH}_2\text{O} \cdot l^{-1}$, such as observed in patients with severe scoliosis [3], and f values of 15 and 30 breaths per min, the latter reflecting the tachypnoea which is encountered in scoliotic patients (table 3). Point A in figure 5 represents the approximate values of $\bar{P}$I and TI for normal adults at rest; point A_1 indicates the corresponding values expected at the same f (15 min^{-1}) but increased Ers to 40 $\text{cmH}_2\text{O} \cdot l^{-1}$; point A_2 pertains to the latter Ers value but increased f (30 min^{-1}). It can be seen that $\bar{P}$I for point A_2 is about 5 times greater than for point A, amounting to about 5 $\text{cmH}_2\text{0}$. Since the 'fatiguing threshold' ($\bar{P}$I/PImax) amounts to 0.15–0.20 [7], this implies that a PImax greater than 25–33 cmH_2O would be required in order for the hypothetical patient depicted by point A_2 to avoid inspiratory muscle fatigue. PImax values of this order or lower have been reported for patients with severe scoliosis [6]. Such patients, however, exhibit shorter TI which can be as low as 0.6 s. As indicated by point A_3 in figure 5 this implies a considerable reduction in $\bar{P}$I, and hence inspiratory muscle fatigue can be readily avoided in spite of the decreased PImax.

The tidal volume also decreased with increasing $P_{0.1}$ (fig. 4). This merely reflects the fact that with normal VT/TI (as was essentially the case in most of our subjects), a decrease of TI necessarily implies a lower VT. In this connection it should be noted that another mechanism is available to reduce $\bar{P}$I in the face of increased Ers, namely expiratory muscle activity. In this way the burden to breathe can be shared between the inspiratory and the expiratory muscles. That patients with severe scoliosis can use this option is indicated by the results of LISBOA *et al.* [6]. In eight out of nine scoliotic patients they observed a positive deflection in gastric pressure during resting expiration, which is indicative of contraction of abdominal muscles [35].

The above considerations also apply to patients with increased Ers due to pulmonary fibrosis, who also exhibit rapid and shallow breathing associated with a decrease of TI and increase in $P_{0.1}$ [23]. Furthermore, although their VD/VT ratio is reduced, mainly as a result of decreased VT as in scoliotic patients, they are still able to maintain normal blood gases, as did our scoliotic patients. By contrast, in patients with chronic obstructive pulmonary disease (COPD) who invariably exhibit an increased VD, the rapid and shallow breathing pattern can lead to hypercapnia [36]. Apart from the increased VD, this may partly reflect the fact that the mechanical time constant of the respiratory system is invariably increased in COPD patients, and this implies that with a short TI a very high neuromuscular inspiratory drive is needed to ensure an adequate alveolar ventilation [37–38]. By contrast, in patients with scoliosis and pulmonary fibrosis, the time constant is reduced and hence a short TI has a smaller adverse effect in terms of generation of adequate alveolar ventilation [39].

In conclusion, in the present investigation we have shown on theoretical grounds that defence of $\dot{V}$A in the face of elastic loading can be achieved with substantial reduction in $\bar{P}$I by decreasing TI, and that scoliotic patients use this strategy of breathing. This should decrease the energy cost of breathing as well as prevent inspiratory muscle fatigue by decreasing the $\bar{P}$I/PImax ratio. In our theoretical analysis (equations 1–3) we have neglected resistive pressure losses and other factors which may affect $\bar{P}$I [31]. Furthermore, we have assumed that the inspiratory driving pressure increases linearly with time, which is probably not entirely the case in humans [31]. The effect of altered breathing pattern on gaseous exchange (specifically VD) has not been taken into account [40]. Nevertheless our analysis provides a useful kernel for future refinements. It is unlikely, however, that further refinements will alter the basic message of the present analysis.

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RÉSUMÉ: Le régime ventilatoire et la pression d'occlusion buccale ($P_{0.1}$) ont été mesurés, au repos, chez 16 jeunes patients scoliotiques dont les gaz du sang étaient dans les limites de la normale. Leur régime ventilatoire est caractérisé par un faible volume courant et une fréquence respiratoire élevée. La pression d'occlusion est supérieure à la normale, indiquant une augmentation de la commande centrale inspiratoire face à l'augmentation de l'élastance du système respiratoire. Exprimée par rapport à la valeur théorique, la pression d'occlusion est correlée positivement avec l'angle de la scoliose. Le temps inspiratoire (Ti) et le rapport du temps inspiratoire au temps total du cycle respiratoire (Ti/Ttot) sont corrélés négativement à la fois avec l'angle de la scoliose et la $P_{0.1}$. Nous montrons par une approche théorique que ces modifications de régime ventilatoire sont bénéfiques à la fois pour réduire le coût énergétique de la respiration et pour prévenir l'apparition de la fatigue des muscles inspiratoires.