Human rib cage distortability

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Chihara, Koji, Chris M. Kenyon, and Peter T. Macklem. Human rib cage distortability. J. Appl. Physiol. 81(1): 437–447, 1996.—In five normal men, we divided the rib cage into lung-apposed [pulmonary rib cage (RCp)] and diaphragm-apposed [abdominal rib cage (RCab)] compartments and calculated their absolute cross-sectional areas (Arc,p and Arc,ab) by anteroposterior and lateral dimensions measured by magnetometry. Distortion was quantified as the displacement of RCp and RCab produced by diaphragmatic twitches made away from the relaxed configuration. We measured transdiaphragmatic pressure as the difference between gastric and esophageal pressures. Distortability was expressed as percent distortion per transdiaphragmatic pressure and varied among individuals from 0.02 to 0.23 cm H2O/\%distortion. Distortion correlated positively (r = 0.92) and Plink per percent distortion negatively (r = 0.90) with RCab compliance during the relaxation maneuver (ΔArc,ab/Δgas-tric pressure). We conclude that rib cage distortability varies widely among normal subjects and is closely linked to RCab compliance.

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The purpose of this study was to quantify human rib cage distortability. Ideally, this would be accomplished by measuring the rib cage hinging stiffness. Unfortunately, at present there is insufficient knowledge of the mechanical properties of muscle, bone, and connective tissue or degree of anisotropy of these tissues to make a reasonable estimate. We recently presented a method of estimating rib cage distortability by plotting the distortion against an index of the pressure producing that distortion (17). The pressure producing distortion is the difference between the pressures acting on RCp and RCab. During a pure diaphragmatic contraction, the pressure acting on RCp is pleural pressure (Ppl), whereas that acting on RCab is, to a close approximation, abdominal pressure (Pab) plus the insertional component of transdiaphragmatic pressure [xPdi, where 0 < x < 1] (8, 17). Therefore, the pressure producing distortion is δPab + xPdi − δPpl = (1 + x) Pdi. Thus the pressure producing distortion is directly proportional to Pdi. We define distortability for the purpose of this study as the amount of distortion produced per unit of Pdi.

In our previous study, we estimated distortability by a measure of distortion that did not allow for comparisons among subjects but only within a subject (17). In the present study, we quantify distortion by a dimensionless number that allows comparisons between individuals of different size, body habitus, and so forth and also among species. The method requires an accurate measurement of absolute values of cross-sectional area of RCab and RCp (Arc,ab and Arc,p, respectively) and how they change with distortion. The simplifying assumptions are 1) the rib cage is a system of two degrees of freedom, which can be represented as two compartments, RCp and RCab; 2) distortions only occur between RCp and RCab and not within the two compartments; 3) the pressures both producing and resulting from the distortions can be estimated by measuring esophageal pressure (Pes) as an index of Ppl over the surface of RCp and gastric pressure (Pga) as an index of Pab and Ppl in the area of apposition.

**METHODS**

**Subjects**

Five normal adult men 25–41 yr of age, all of whom except subject JS had experience in similar experiments, were recruited from laboratory personnel. None had a history of respiratory or neuromuscular diseases, and all were nonsmokers. They were selected from people whose body mass index was <26 kg/m2 (12) to minimize soft-tissue effects (11) on magnetometer tracings. Anthropometric data and inspiratory capacity of the subjects are summarized in Table 1.
Table 1. Anthropometric data and inspiratory capacity of subjects

<table>
<thead>
<tr>
<th>Subjects</th>
<th>FB</th>
<th>JS</th>
<th>SZ</th>
<th>SY</th>
<th>AG</th>
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<tbody>
<tr>
<td>Age, yr</td>
<td>41</td>
<td>36</td>
<td>36</td>
<td>39</td>
<td>25</td>
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<tr>
<td>Height, cm</td>
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<td>174</td>
<td>176</td>
<td>170</td>
<td>176</td>
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<tr>
<td>Weight, kg</td>
<td>67</td>
<td>65</td>
<td>75</td>
<td>58</td>
<td>81</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>22.9</td>
<td>21.5</td>
<td>24.2</td>
<td>20.1</td>
<td>25.6</td>
</tr>
<tr>
<td>RCp AP, cm</td>
<td>20.9</td>
<td>22.0</td>
<td>22.3</td>
<td>19.8</td>
<td>23.0</td>
</tr>
<tr>
<td>RCp Lat, cm</td>
<td>30.1</td>
<td>30.4</td>
<td>29.5</td>
<td>27.0</td>
<td>30.0</td>
</tr>
<tr>
<td>RCp AP/Lat</td>
<td>0.69</td>
<td>0.75</td>
<td>0.76</td>
<td>0.73</td>
<td>0.77</td>
</tr>
<tr>
<td>RCab AP, cm</td>
<td>21.2</td>
<td>22.4</td>
<td>22.0</td>
<td>19.9</td>
<td>21.7</td>
</tr>
<tr>
<td>RCab Lat, cm</td>
<td>28.9</td>
<td>29.3</td>
<td>29.7</td>
<td>26.9</td>
<td>29.9</td>
</tr>
<tr>
<td>RCab AP/Lat</td>
<td>0.73</td>
<td>0.70</td>
<td>0.77</td>
<td>0.74</td>
<td>0.73</td>
</tr>
<tr>
<td>IC, liters</td>
<td>2.60</td>
<td>2.40</td>
<td>3.00</td>
<td>2.41</td>
<td>2.81</td>
</tr>
</tbody>
</table>

BMI, body mass index; RCp, pulmonary rib cage; AP, anteroposterior; Lat, lateral; RCab, abdominal rib cage; IC, inspiratory capacity. AP and Lat diameters of RCp and RCab at functional residual capacity during sitting posture and values of AP/Lat diameters are listed.

Experimental Protocol

The subjects were seated comfortably in a high-backed chair with both of their arms on rests to facilitate relaxation. They kept the same position throughout the experiment to minimize baseline shift in the magnetometer tracings and to avoid introduction of an additional degree of freedom by varying spinal flexion.

Relaxation maneuver. First, the subjects relaxed from TLC to FRC during deflations through a small orifice placed in the expiratory line. Relaxation was considered acceptable if curves were reproducible and diaphragmatic electrical activity and Pdi were zero.

Bilateral transcutaneous phrenic nerve stimulation (2). The optimal stimulation sites were determined bilaterally in the neck, whereas muscle action potential (M wave) produced by single phrenic shocks were monitored to confirm that the phrenic nerves were being stimulated. Supramaximal phrenic stimulation was assured by choice of a stimulus intensity 20-30% greater than that at which the amplitude of the M wave was maximal.

Rib cage distortion at FRC. A rapid-oclusion valve with opening and closing times <20 ms in the respiratory circuit at the mouthpiece was closed at FRC after several deep breaths. Then, five or six consecutive single twitches of 90–30 mA with a pulse duration of 0.1 ms were given every 2 s at an intensity adequate for supramaximal stimulation. Stimulations were started 2 s after airway occlusion, and the valve was opened after stimuli were completed. Because the time for airway occlusion was <20 s, subjects did not feel breathless during stimulation. Several different stimulus intensities were used by changing the electrical current to obtain a range of Pdi values and rib cage distortions. Finally, paired twitches separated by 0.1–0.06 s (10–20 Hz) were done in the same way to obtain bigger Pdi values than during a single twitch.

Rib cage distortion above FRC. Supramaximal single-twitch phrenic stimulation at the same intensity as that given at FRC was performed at different Vl values. The procedure was as follows. Subjects inspired actively to a predetermined Vl and then relaxed with a quasi-static expiration against an expiratory resistance. As their Vl reached the volume of interest, the airway was quickly closed by the occlusion valve without disturbance of relaxation. The first twitch was administered 3 s after airway occlusion, and the second twitch was done 5 s later. Then, the valve was opened and Vl returned to FRC, where subjects breathed quietly again. Vl values were chosen at 0.5-liter increments above FRC (0.5, 1.0, 1.5, and 2.0 liters above FRC) and near TLC. Rib cage distortions were induced two or three times at each Vl. The airway occlusion time for each Vl was <15 s.

Between twitch runs and relaxation maneuvers, the subjects breathed quietly at FRC to minimize baseline shift of magnetometer signals throughout the experiment.

Calibration for estimation of cross-sectional area of rib cage. First, the absolute values of AP and lateral diameters of both rib cage compartments at FRC were measured with calipers. Second, each pair of magnetometer coils was attached to the calipers in the same orientation as during the experiment and calibrated statically in terms of distance per unit voltage.

Data Analysis

The FM tapes containing the data were played back through an analog-to-digital converter (Data Translation DT2801-A), and data were sampled at 50 Hz during the relaxation maneuver and at 300 Hz during phrenic nerve
HUMAN RIB CAGE DISTORTABILITY

were performed by using scientific software (ANADAT, RHT-Infodat, Montreal, Quebec). When we assessed the frequency response of the magnetometers, we found a fixed time delay (or dead time) of 30 ms in three pairs and 50 ms in the remaining pair. These were corrected by the software so that dimensions and pressure were compared synchronously.

Absolute cross-sectional area of the rib cage. We converted the change in electrical voltage of each magnetometer pair into length by using the static calibration described above and added this length to the absolute dimension of the rib cage at FRC. This provided absolute AP and lateral (Lat) dimensions of the rib cage. We assumed that the shape of the rib cage could be approximated by an athletic track, which is a rectangle bounded by two semicircles at opposite sides. The formula for the area enclosed by the track is given by the sum of the area of the rectangle and the semicircles: thus area = AP(Lat - AP) + π(AP/2)^2 (3). We used this equation to measure the absolute cross-sectional areas of RCP (Arc,p) and of RCBa (Arc,ab). The methodology and its validation are given in greater detail in the APPENDIX. As magnetometer signals sometimes varied at FRC between maneuvers, the electrical signal at FRC during quiet breathing between each run was subtracted, and electrical change from FRC was converted to length. Here, the assumption is that FRC is constant, whereas the magnetometer signal at FRC might vary.

Undistorted configuration of the rib cage. The undistorted configuration of the rib cage was obtained by plotting Arc,p against Arc,ab during relaxation from FRC to near TLC just before the first and second stimulations.

Elastic properties of RCP and RCBa. The relationships between Arc,p and Pes and between Arc,ab and Pga during relaxation were taken as the passive elastic properties of the two rib cage compartments under circumstances when ( neglecting gravitational effects) the pressure difference across both compartments was similar. However, these properties cannot be used to predict the cross-sectional areas of RCP and RCBa under conditions when the pressure difference across the two compartments is different.

Quantification of rib cage distortion. In the present study, we defined distortion as the perpendicular distance of the Arc,p-Arc,ab configuration from the relaxation line, normalized by the value of Arc,p at the point on the relaxation line where the perpendicular intersects (Fig. 1). The method of calculating distortion is shown in Fig. 1, where the loop indicated by the continuous line and arrows shows the dynamic changes in dimensions of RCP and RCBa produced by a twitch administered at FRC. The relaxation configuration is given by the solid line extending from FRC to TLC. Dashed lines give isopleths for various degrees of distortion. In this schematic expression, the twitch produced a 3% distortion at point A. Subsequently, a plot of magnitude of distortion against Pdi provided a measure of rib cage distortability. We define distortability as the slope of this relationship, which has the units of pressure^-1. Although our previous method provided a quantitative estimate within an individual, it did not allow for comparisons among individuals to determine whether one individual's rib cage was more or less distortable than another's (17). Because the present measure of distortion as a percent is dimensionless, this method allows such a comparison.

Arc,p always lagged behind Arc,ab, and each reached the maximum change at different times. The time courses of cross-sectional areas of the two compartments, pressures, distortion, and distortability of all subjects are illustrated in Fig. 2. Initially, RCBa expanded with little change in RCP dimensions. Then, as RCP contracted, Arc,ab diminished as well. At this point, when both rib cage compartments were contracting, Arc,p and Arc,ab moved along or close to a single isopleth in four of the five subjects, as shown in Fig. 3. In subject AG, the distortion increased progressively until Arc,p reached its minimum value. The displacement of RCBa was closely in phase with ΔPga, whereas that of RCP was closely in phase with ΔPes.

We think the phase lag between Arc,p and Arc,ab is due to differences in time constants for motion of RCP, RCBa, the lung, and abdomen. Because the airway was occluded, this was an isovolumic maneuver (ignoring small changes in lung gas volume). Under these circumstances, the time constant for lungs and rib cage to respond is short (17). During the time immediately after the maximal increase in Arc,ab, when both Arc,ab and Arc,p were decreasing near an isopleth as shown in Fig. 3, Pdi remained relatively constant, whereas Pes and Pga decreased simultaneously and approximately equally. As both Arc,ab and Arc,p were decreasing, rib cage volume as a whole must have been decreasing and (because Vl was constant) the abdominal wall must have been moving outward, although this was not measured. This would indicate a substantial phase lag between Pga and abdominal displacement, probably due to inertia. The phase lags between Arc,p and Pes and between Arc,ab and Pga were less and indicate a smaller degree of inertia for the rib cage compared with the abdominal contents. Although these phase lags posed problems in choosing the point in time to measure distortion, we decided on the longest time possible after a short period of nearly constant Pdi and distortion, when Arc,p was minimal. This ensured that there was sufficient time for our measuring devices to respond adequately. Thus we used the data set of cross-sectional areas and pressures when ΔArc,p reached its maximum deflection. Except in subject AG, this made little difference in the measurement of distortion magnitude because, when Arc,ab reached its maximum dimension and then started to decrease, the magnitude of distortion was nearly constant. Indeed, distortability also remained nearly constant, inasmuch as the ratio of distortion to Pdi from the point at which we measured it (vertical dashed line) changed little as Pdi declined (Fig. 2). This index of distortability changed somewhat more as Pdi approached zero in some subjects, presumably because ratios become unreliable as both numerator and denominator approach zero and because

Fig. 1. Relationship between absolute cross-sectional areas of pulmonary (Arc,p) and abdominal rib cage (Arc,ab), respectively, during relaxation (solid line given by y = ax + b) and bilateral phrenic stimulation (solid loop with arrows). Distortion is measured at point A with coordinates X and Y, which give the values of Arc,a and Arc,p, respectively, during each relaxation. Rib cage distortion is defined as (AB/BC) × 100%. Assigning the distance AB a unit value of 1, AB = AD sinθ = (aX + b - Y√(a^2 + 1), BC = (a^2Y + aX + b√(a^2 + 1)). Thus rib cage distortion = 100[(a^2 + 1)(aX + b - Y√(a^2 + 1)]/(a^2 + 1).

Point A in this schematic expression showed 3% distortion.

Fig. 2. Initially, RCBa expanded with little change in RCP dimensions. Then, as RCP contracted, Arc,ab diminished as well. At this point, when both rib cage compartments were contracting, Arc,p and Arc,ab moved along or close to a single isopleth in four of the five subjects, as shown in Fig. 3. In subject AG, the distortion increased progressively until Arc,p reached its minimum value. The displacement of RCBa was closely in phase with ΔPga, whereas that of RCP was closely in phase with ΔPes.
Fig. 2. Changes in Arc,p and Arc,ab pressures (esophageal (Pes), gastric (Pga), and transdiaphragmatic (Pdi)), distortion, and distortability during a single twitch at functional residual capacity (FRC) in 5 subjects (initials shown on each panel).

Fig. 3. Relationship between Arc,p and Arc,ab during a single twitch at FRC along with isopleths of several degrees of distortion in 5 subjects.
the relationship between distortion and Pdi is not necessarily linear.

Restoring pressure. To the extent that the rib cage resists distortion, there is a restoring force during distortion that tends to minimize it. We estimated this in terms of a pressure (Plink) (17). Plink for RCp can be estimated by the equation Prc,p = Ppl + Plink, where Prc,p is elastic recoil pressure of RCp at any value of Arc,p obtained from the relaxation curve described above. Plink was obtained as the difference between Pes during a diaphragmatic twitch at the point of maximum distortion and Prc,p obtained from the Arc,p/Pes relaxation line at the same value of Arc,p (17).

Effect of VL on distortability. The role of VL on rib cage distortability was assessed by plotting distortability normalized by distortability at FRC against VL for identical supra-maximal stimuli.

RESULTS

Undistorted Configuration of Rib Cage and Its Passive Properties

The relationship between Arc,p and Arc,ab during relaxation was linear ($r^2 > 0.950$). The regression line of Arc,p and Arc,ab from near TLC to FRC before the second twitch was selected as the undistorted configuration because Pes and Pga were stable and Pdi was zero. Using the least squares method, we obtained the slopes of the regression lines relating cross-sectional areas of RCp and RCab to their respective elastic recoil pressures between FRC and FRC + 0.5 liter during relaxation; these are given in Table 2.

Distortion at FRC

Relationship between distortion and Pdi. Figure 4 shows Arc,p/Pes and Arc,ab/Pga plots starting from FRC during a single twitch and paired twitches in each subject. The two lines in the figure give the relationship between rib cage cross-sectional area and rib cage elastic recoil pressure (Pes for Arc,p and Pga for Arc,ab) for each rib cage compartment during relaxation. Although each loop actually started from the same point at FRC on the relaxation line, the loops were shifted vertically for better clarity. During the twitch, Arc,p decreased while Arc,ab increased, decreased, or remained nearly constant. Except in one subject, the slope of the Arc,p-Pes relationship was much less during the twitch than during relaxation. These slopes measured as the change in area per unit change in pressure between the extremes of pressure during twitches ($\Delta A_{arc,p}/\Delta Pes$ and $\Delta A_{arc,ab}/\Delta Pga$, respectively) along with the ratio of the slopes during phrenic stimulation to that during relaxation ($C_{arc,p}/C_{arc,p}$ and $C_{arc,ab}/C_{arc,ab}$, respectively) are given in Table 2. (The primes indicate values of area and compliance obtained during twitches to distinguish them from values obtained during relaxation.) These measurements were

Table 2. Mechanical properties of RCp and RCab compartments

<table>
<thead>
<tr>
<th>Subjects</th>
<th>FB</th>
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<th>SZ</th>
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<tr>
<td>$\Delta A_{arc,p}/\Delta Pes$, cm$^2$/cmH$_2$O</td>
<td>3.11</td>
<td>2.27</td>
<td>3.50</td>
<td>5.42</td>
<td>3.12</td>
<td>3.48</td>
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<tr>
<td>$\Delta A_{arc,ab}/\Delta Pga$, cm$^2$/cmH$_2$O</td>
<td>7.08</td>
<td>3.66</td>
<td>3.66</td>
<td>5.54</td>
<td>7.69</td>
<td>5.53</td>
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<td>Phren. stim.</td>
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<tr>
<td>$\Delta A_{arc,p}/\Delta Pes$, cm$^2$/cmH$_2$O</td>
<td>0.95</td>
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<td>0.47</td>
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<tr>
<td>Phren. stim./relaxation</td>
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<td></td>
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<tr>
<td>$C_{arc,p}/C_{arc,p}$</td>
<td>0.31</td>
<td>0.13</td>
<td>0.08</td>
<td>0.09</td>
<td>0.99</td>
<td>0.32</td>
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<tr>
<td>$C_{arc,ab}/C_{arc,ab}$</td>
<td>0.07</td>
<td>0.03</td>
<td>0.09</td>
<td>-0.08</td>
<td>0.02</td>
<td></td>
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</table>

Arc,p, cross-sectional area of RCp; Pes, esophageal pressure; Arc,ab, cross-sectional area of RCab; Pga, gastric pressure; phren. stim., phrenic stimulation. Primes indicate values of area (A) and compliance (C) obtained during twitches.
straightforward in four of the five subjects. In subject AG, as can be seen in Fig. 4, the loops had complex shapes and were noisier than in the other subjects. This may account for the negative values of Plink we found in this subject (Fig. 7).

The resulting plot of distortion against Pdi revealed that rib cage distortion increased as Pdi increased in all subjects (Fig. 5). Distortability showed variability among the subjects. From greatest to least, they were in the following order: AG > FB > SY > JS > SZ. The relationship between distortion and Pdi at FRC appeared nearly linear in four subjects, whereas it was curvilinear in the remaining subject (subject AG). In this subject, distortability decreased as distortion increased. The variability in distortability among subjects was ~12-fold. Age, body mass index, and AP-to-Lat ratio of both compartments of the rib cage at FRC were not correlated with the distortability of the rib cage (Table 1). However, the passive elastic characteris-

tics of RCab (ΔArc,ab/ΔPga) may be a determinant of distortability among subjects. The higher ΔArc,ab/ΔPga of RCab, the more distortable the rib cage appears to be (Fig. 6). Abdominal rib cage compliance in subject AG was the highest among the subjects. In contrast, subject SZ had the smallest. There was no apparent relationship between the elastic properties of RCp and rib cage distortability.

Relationship between distortion and Plink. Plink increased as distortion increased in subjects FB, SY, JS, and SZ (Fig. 7). In subject AG, the pulmonary rib cage deflated during phrenic nerve stimulation close to the relaxation line. The resulting Plink was almost nil and in some instances negative, as stated above. In subjects JS and SZ, RCp deflated during phrenic stimulation far from the relaxation line (Fig. 4). Subject SZ had the greatest Plink, and subject JS had the second greatest. Plink in the other two subjects was intermediate. Their values of RCab compliance were similarly intermediate. The relationship between Plink per unit of distortion and abdominal rib cage compliance is shown in Fig. 8. No other correlations between Plink per unit distortion and other variables were found.

Effect of VL on Distortability

As shown in Fig. 9, there was no clear-cut relationship between distortability and VL. In subjects SZ, SY, and FB distortability appeared to be less at high VL compared with FRC but the relationship did not increase systematically as VL increased. In the other two subjects, there was no apparent change in distortability as VL increased. Unfortunately, we have no information
on the changes in internal surface area of RCp and RCab with VL. For a given pressure difference acting on RCp and RCab, such changes would alter the force acting on each compartment, increasing it on RCp and decreasing it on RCab as volume increased. We do not know how this might affect distortability, and our experiments cast little light on this problem.

**DISCUSSION**

**Two-Compartment Rib Cage Model**

The concept that the rib cage is a compartment with a single degree of freedom has achieved broad acceptance. The idea was introduced by Konno and Mead (7), who demonstrated its validity within fairly narrow limits. The validity of treating the nonhuman rib cage as a system with a single degree of freedom has never been critically examined. It is frequently assumed that the human rib cage is less distortable than that of other animals. Jiang et al. (6) have shown significant distortions of the canine rib cage during isolated diaphragmatic contraction. Similar distortions of the human rib cage occur with phrenic stimulation. The human rib cage even departs from single degree of freedom behavior under conditions that are within the limits proposed by Konno and Mead (7). Evidently, the rib cage of both humans and other animals demonstrates significant departures from single-compartment behavior. Thus further advances in quantification of rib cage mechanics appear to require a reexamination of the idea that the rib cage can be modeled as a single compartment.

This reexamination is particularly important because of the fact that the distribution of pressure on the inner rib cage surface can be highly nonuniform. Over the lung-apposed rib cage surface, it is Ppl over the costal surface of the lung. Over the diaphragm-apposed surface, it is Ppl in the area of the apposition. The latter can be quite nonuniform from point to point but on average is probably close to Pab (9, 15). The nonuniformity of pressure distribution led Agostoni and D'Angelo (1) to suggest that the rib cage could be usefully regarded as consisting of two compartments, RCp and RCab, a suggestion taken up by Jiang et al. (6) and Ward et al. (17). Jiang et al. (6) showed that the mechanical linkage between RCp and RCab was loose in dogs and that the canine rib cage had little resistance to distortion. Ward et al. (17) showed a much tighter mechanical coupling between RCp and RCab in humans and a significant resistance to distortion. The present work is an attempt to quantify human rib cage distortability by establishing the relationship between
Fig. 9. Lung volume effect on rib cage distortability in 5 subjects. Rib cage distortability above FRC is normalized by that at FRC and expressed as a function of % inspiratory capacity (%IC).

a dimensionless measure of distortion and an index of the pressure producing distortion (Pdi) during isolated diaphragmatic contraction. The units of distortability are thus pressure⁻¹, which allows comparisons between individuals and species and within an individual under different physiological conditions.

**Critique of Methods**

Ideally, we would have measured absolute volume of the rib cage compartments. Instead of volume, we measured cross-sectional area by measuring AP and Lat dimensions and assuming that the cross-sectional shape of the rib cage could be approximated by an athletic track (3). This model is presented in detail and defended in the APPENDIX. Thus we use area compliance rather than the change in volume per unit pressure change to measure the parameters we estimate.

We obtained the elastic properties of RCp and RCab during relaxation, when the pressure distributions over the pleural surfaces of RCab and RCp are nearly the same. To obtain dimensions, we used magnetometers rather than Respitrace bands because the latter are sensitive to changes in ellipticity at constant cross-sectional area (10). We took great pains to ensure that the phase angle between magnetometer pairs was zero, that errors due to misalignment of magnetometer coils were minimized, and that the frequency response of our measuring equipment was adequate for the frequency content of the signals we were measuring. The observation that distortability changed little during the decay in Pdi (Fig. 2) after a twitch suggests that both rib cage compartments were in elastic equilibrium.

**Determinants of Rib Cage Distortability**

One of the most striking findings of this study was the large between-individual variability in distortability. This ranged from a value as high as 0.23 cmH₂O in subject AG to a low value of 0.02 cmH₂O in subject SZ, a 12-fold range among only five subjects of roughly similar build (Table 1, Figs. 5 and 6). Figure 6 also reveals a remarkable correlation between Crc,ab and distortability. As can be seen by an inspection of Table 2, correlations between distortability and other parameters such as Crc,p and Crc,p/Crc,ab were not as tight.

We can only speculate as to why Crc,ab might be an important determinant of distortability. Just as the elastic properties of a rod are an important determinant of its bending stiffness, highly compliant rib cage compartments are likely to result in an easily distortable rib cage.

RCp is relatively tightly linked to the sternum through short costal cartilage at the ends of ribs 1–6 inclusively. As a result, the value of Crc,p is, in each individual, less than the value of Crc,ab (Table 2). Ribs 7–12, the ventral ends of which constitute much of RCab, are much more loosely linked through considerably longer cartilages. We think that it is possible that elastic properties and lengths of the costal cartilages of ribs may be important determinants of Crc,ab and explain why Crc,ab is consistently greater than Crc,p. In fact, because of the loose linkages of ribs 7–12 with the sternum, the constraints on the elastic properties of RCab may be less than for RCp, allowing for greater between individual variability in Crc,ab than in Crc,p.

If so, the correlation between distortability and Crc,ab might be explained. Although the between-individual variability in Crc,p was just as great as it was for Crc,ab, the limited number of subjects in the present study does not provide sufficient evidence to either support or reject this speculation.

Here, we must specify that we are referring exclusively to distortions produced by different pressures acting on RCab and RCp but not when the same force acts on both simultaneously. The distortions we refer to include various respiratory maneuvers, including isolated diaphragmatic contraction, which acts directly
only on RCab, and isolated contraction of inspiratory rib cage muscles, which acts predominantly on RCp (17); we are not referring to distortions of the rib cage resulting from gravitational forces or from immersion in water.

**Physiological Significance of Rib Cage Distortability**

During quiet breathing in upright humans, shape distortion between the rib cage and abdomen is minimal. This requires simultaneous contraction of the diaphragm and inspiratory muscles of the rib cage in a coordinated action so that the relaxation configuration is maintained (4, 5, 11). Similarly, rib cage distortions during quiet breathing, although measurable, are small, particularly compared with the distortions produced by isolated diaphragmatic contraction (17). This also requires a coordinated contraction of the diaphragm and inspiratory rib cage muscles. For a rib cage with a given degree of distortability, the less the pressure applied by the inspiratory rib cage muscles, the more will be the distortion. A large contribution of the inspiratory rib cage muscles to rib cage inflation would produce a distortion in the opposite sense, i.e., a greater expansion of RCp for a given expansion of RCab than during relaxation. An expansion without distortion reduces Plink to zero and, according to the analysis of Ward et al. (17), the fall in Ppl over the costal surface of the lung is attributable entirely to the inspiratory rib cage muscles. Ward et al. (17) found distortions during quiet breathing in the subjects they studied, and these distortions accounted for about one-half of the inspiratory function of the diaphragm. The remainder was due to the inspiratory rib cage muscles. Thus, whenever distortion is present, Plink contributes to \( \Delta Ppl \) over the costal lung surface. However, in a subject with an easily distortable rib cage (such as subject AG), Plink would be small, and this individual would require a greater contribution of his inspiratory rib cage muscles to produce a given expansion of RCp in the presence of diaphragmatic contraction than an individual with a more rigid rib cage, all else being equal.

If rib cage distortability determines how much Ppl falls when the diaphragm contracts, it follows that distortability is an important determinant of the inspiratory function of the diaphragm. We define the inspiratory function of the diaphragm as the fraction of Pdi that is converted into a fall in Ppl. With a pure diaphragmatic contraction against a closed airway, there is no change in lung volume and thus

\[
\Delta V_{rc,p} + \Delta V_{rc,ab} + \Delta V_{ab} = 0 \tag{1}
\]

where \( \Delta V_{rc,p} \) and \( \Delta V_{rc,ab} \) are the volume changes of the pulmonary and abdominal rib cages, respectively, and \( \Delta V_{ab} \) is the volume displaced by the abdominal wall.

It is evident from the small values of \( C'_{rc,ab} \) in Table 2 that there is little motion of RCab during phrenic stimulation of the diaphragm against a closed airway. This is not surprising because the increase in Pab acts to expand RCab, whereas the obligatory decrease in the volume of RCp acts to deflate RCab through Plink. It would seem that \( \Delta V_{rc,ab} \) in Eq. 1 is so small that it can be neglected. We have subsequently confirmed this by using an optical tracking system to measure the absolute volumes of RCp, RCab, and the abdomen during diaphragmatic twitches in collaboration with Drs. A. Scano and R. Durante (unpublished observations). Thus Eq. 1 simplifies to

\[
\Delta V_{rc,p} - \Delta V_{ab} = 0 \tag{2}
\]

Substituting the product of compliance and pressure for volume yields

\[
C'_{rc,p} \cdot \Delta Ppl + C'_{ab} \cdot \Delta Pab = 0
\]

where \( C'_{rc,p} \) and \( C'_{ab} \) are the volume compliances of RCp and abdomen, respectively, under conditions of phrenic stimulation. Thus

\[
-\Delta Ppl/\Delta Pab = -C'_{ab}/C'_{rc,p}
\]

and

\[
-\Delta Ppl/\Delta Pdi = C'_{ab}/(C'_{rc,p} + C'_{ab}) \tag{3}
\]

Thus we predict that the inspiratory function of the diaphragm depends nearly exclusively on the volumetric \( C'_{rc,p} \) and \( C'_{ab} \) under conditions of considerable rib cage distortion. The values of \( C'_{rc,p} / C_{rc,p} \) shown in Table 2 suggest that \( C'_{rc,p} \) is only ~30% of what it would be under relaxation conditions. The between-individual variability of \( C'_{rc,p} / C_{rc,p} \), which was >10 fold, indicates that there is probably a similar variability in \( C_{rc,p} \). Because rib cage distortability is an important determinant of \( C'_{rc,p} / C_{rc,p} \), we conclude that it is an important determinant of the inspiratory function of the diaphragm.

**Equation 3** states that when \( C'_{rc,p} \to 0 \), the inspiratory function of the diaphragm \( \to 1 \) and \( \to 0 \) when \( C'_{ab} \to 0 \). This suggests the possibility that the supernormal inspiratory function of the diaphragm in chronic obstructive pulmonary disease (14) may be related to a relatively undistortable rib cage.

**Speculation on Rib Cage Distortability and Dyspnea**

It is clear that at least some forms of dyspnea are related to the pressures required to breathe in relationship to the maximum pressures available; in other words, the load relative to inspiratory muscle strength. However, Ward et al. (16) have shown that under fatiguing conditions when dyspnea progressively increases during the fatiguing task, the sensation is closely correlated with the degree of parasternal and sternocleidomastoid recruitment but not with recruitment of the diaphragm. Furthermore, there is wide interindividual susceptibility to the sensation of dyspnea. Our findings suggest a possible explanation for this. Individuals with highly distortable rib cages will require considerably more rib cage muscle recruitment to minimize paradoxical rib cage displacement and overcome a particular load to inspiration than individuals with less distortable rib cages. Our results lead us to speculate that when rib cage distortion is present, the
greater the distortability of the rib cage, the greater the degree of recruitment of inspiratory rib cage muscles and the greater predisposition to dyspnea for a given load and strength. Further research is necessary to determine whether this speculation is valid or not.

APPENDIX

Measurement of Cross-Sectional Area of the Chest Wall

We assumed that the cross-sectional shape of the human rib cage and abdomen was approximated by an athletic track, namely two semicircles attached to the Lat walls of a rectangle, and compared the cross-sectional areas estimated by using this shape with those assuming the shape of an ellipse or a rectangle. The area of the semicircles of the track is obtained by the AP dimension, which gives their diameter. The area of the rectangle is given by the product of the AP dimension and the Lat minus the AP dimension. The formula for calculating the cross-sectional area by using the track model is the following: area = AP(Lat - AP) + π(AP/2)^2. For the area of an ellipse we used area = πAP·Lat/4; and for the rectangle, area = AP·Lat.

From normal men in the supine posture, we obtained precise cross-sectional shapes of the chest wall from CT scans. This was done with various configurations of the rib cage and abdomen at TLC, FRC, and residual volume. In these experiments, we measured the cross-sectional shape of RCp at the nipple level and of the abdomen at the level of the umbilicus. We used a planimeter (plan) to measure the cross-sectional areas of RCp and abdomen and these values were used as the gold standard (Arc,plan and Aab,plan). We also obtained Arc,plan of RCp, RCab, and Aab,plan by planimetry of 43 published CT pictures in three books. Scans containing images from both main bronchi down to the heart were taken as RCp, whereas rib cage images containing diaphragm, liver, and other organs were taken as RCab. To calculate cross-sectional areas by the track, ellipse, and rectangle models (Arc_t, Arc_e, and Arc_r for rib cage and Aab_t, Aab_e, and Aab_r for abdomen, respectively), we measured the AP diameter of the scans by a ruler at the midline and the Lat diameter at the middle of the AP measurement.

We obtained the cross-sectional shape of the chest wall in the seated posture by molding two tubular bean bags, each 60 cm long and 12 cm wide, around the rib cage and then subjected them to a negative pressure, which made them rigid. The bags were connected by a hinge that allowed their removal from the body and chest wall shape to be reconstructed. The inside perimeter of the bean bag was traced, and its cross-sectional area was obtained by planimetry. This was the gold standard for this posture.

Measurements were made during relaxation at FRC and TLC at the nipple level to obtain the cross-sectional area of RCp and the upper level of the zone of apposition of the diaphragm to the rib cage at TLC as determined by percussion to obtain the cross-sectional area of RCab. AP dimension at the midline and the maximal Lat diameter were used to calculate cross-sectional area based on three models.

Results

Figure 10A shows Arc_t (○), Arc_e (●), and Arc_r (▲) on the y-axis plotted against Arc,plan on the x-axis for RCp in the seated posture. Figure 10B shows data for RCab. Figure 11 shows similar data for all the CT scans in the supine posture for RCp (A), RCab (B), and abdomen (C).
Estimation based on the track model was the closest to the line of identity for the rib cage and abdomen in both postures.

The error \( E \) of the data was calculated by the equation

\[
E = 100 \left( \frac{\text{Arc,estimated} - \text{Arc,plan}}{\text{Arc,plan}} \right).
\]

Mean \( E \) values of each model estimation in the seated and supine postures were calculated. The mean \( E \) values of the track model were <2% for both parts of the rib cage and the abdomen. The 95% confidence interval of \( \text{Arc,t} \) for \( \text{RCp} \) included zero in the seated posture, whereas that of \( \text{Arc,t} \) for \( \text{RCab} \) did not. However, the difference between the interval of \( \text{Arc,t} \) for \( \text{RCp} \) and zero was 0.4%. In the supine posture, the 95% confidence interval of \( \text{Arc,t} \) included zero for both rib cage compartments as well as that of \( \text{Aab,t} \) for abdomen. The ellipse model systematically underestimated the true cross-sectional area, whereas the rectangular models, as would be expected, systematically overestimated it. For both postures and all VL values, configurations, and compartments, the track model provides more accurate measurements of the chest wall cross-sectional area than either the ellipse or rectangle. The error was independent of the AP-to-Lat ratio of chest wall cross-sectional area than either an ellipse or a rectangle and that this is so whatever the VL, posture, configuration, or compartment measured.

We conclude that the track model provides more accurate estimates of cross-sectional area than either an ellipse or a rectangle and that this so whatever the VL, posture, configuration, or compartment measured.

We are indebted to Drs. S. Yan and M. E. Ward for assistance and advice, C. Dubord for secretarial services, and S. Filiatrault for technical help.

This study was supported by the Medical Research Council of Canada and the Respiratory Health Network of Centres of Excellence. K. Chihara was supported in part by Chest Disease Research Canada and the Respiratory Health Network of Centres of Excellence.

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