MEASUREMENT OF THE RELATIVE CONTRIBUTIONS OF RIB CAGE AND ABDOMEN/DIAPHRAGM TO TIDAL BREATHING IN MAN

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SUMMARY

A simple mathematical model of the chest wall was constructed so that during tidal breathing the relative volume contributions of the rib cage and abdomen/diaphragm could be measured in man, using four mercury-in-rubber strain gauges around the trunk. From the dimensions of the trunk and the change in circumference determined by the four gauges, the separate contributions of rib cage and abdomen/diaphragm could be determined using a purpose-built analog computer. The system was evaluated in 13 laboratory personnel, and in 13 other subjects before and after anaesthesia. There was a linear relationship between tidal volumes computed and measured at the mouth, over the residual volume to (FRC+1 litre) range, with an error of ±8%. The relative contribution of rib cage to tidal breathing showed a large scatter from 5 to 42% with a non-significant tendency to decrease with age.

It has been known for more than a century that rib cage movement is impaired selectively during inhalation anaesthesia (Snow, 1858). These observations were extended by Miller in 1925 and incorporated into the well-known Guedel classification of anaesthesia in 1927. However, there has been little further interest shown by anaesthetists in the significance of this effect. This may be a result of the increasing realization of the complex interaction of the rib cage and diaphragm which deterred investigators from making more detailed studies of the chest wall during anaesthesia. Following the work of Konno and Mead (1967), techniques have been developed which enable further advances to be made in the understanding of chest wall function during anaesthesia. This study describes a technique designed to integrate chest wall movements and partition rib cage and abdomen/diaphragm contributions to tidal breathing so that the effects of inhalation anaesthesia on chest wall function may be examined in man.

METHODS AND RESULTS

The method was devised so that changes in lung volume could be derived from the change in circumference of the rib cage and abdomen, measured with a number of mercury-in-rubber strain gauges around the trunk. In this way the relative movements of rib cage and abdomen/diaphragm could be demonstrated with their respective contributions to any reduction in lung volume which follows induction of anaesthesia. Quantitative measurement over the vital capacity range was not required, hence mathematical complications arising from other dimensional changes at extremes of lung volume (e.g. vertebral column extension or elevation of the edge of the diaphragm) did not need consideration. All subjects were studied in the supine position, thus postural changes could be ignored.

A simple geometrical model of the chest wall was produced (fig. 1). The chest cavity is usually elliptical in cross section, but in this model it was assumed to be circular and in the form of a truncated cone. The error introduced by this assumption is discussed below. The abdominal cavity was also assumed to have a circular cross-section and be conical in shape. The abdominal contents were assumed to be incompressible and respiratory movements of the diaphragm and rib cage were analysed as a change in circumference of each cavity. At large lung volumes (Agostoni et al., 1965) descent of the dome of the diaphragm is accompanied by elevation of its edge and, over this volume range, change in abdominal circumference may no longer accurately reflect diaphragm movement. Breathing at high lung volume was not part of this study, and this was regarded as a small source of error when breathing over the range from maximum expiration up to 60% inspired vital capacity.


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A Inspiration - rib cage alone

B Inspiration - diaphragm alone

C Inspiration - joint action

Fig. 1. The mathematical modelling of rib cage and abdomen/diaphragm separately (A and B). When the interaction between rib cage and abdomen/diaphragm is taken into account (C) there is an additional volume (the joint volume contribution). This has to be computed and added to the change in volume of rib cage and abdomen/diaphragm to obtain the total volume.

\[ \delta V_{RC} = \frac{H_{RC}}{3\pi} [\delta C_{RC}^2 + \delta C_{RC} (2C_{RC} - C_t/2)] \]

where

- \(C_t\) is the circumference of the rib cage at the lung apices,
- \(C_{RC}\) is the mean circumference of the rib cage at its mid-point,
- \(H_{RC}\) is the total height of the thoracic cavity (from lung apices to diaphragm) and is constant if the diaphragm is assumed to be static.

The difference between \(C_{RC}\) and \(C_t\) may be significant and hence the equation cannot be simplified. However, if the thoracic cavity is divided into smaller sections and the volume change of each considered separately, a geometrical approximation is possible. The smaller each section is made, the more nearly cylindrical each becomes and the errors in computation resulting from assumptions of uniformity of shape over the section diminish. A compromise has to be made between increased accuracy and the increased complexity resulting from greater numbers of sections.

If each section is considered to be cylindrical, then the volume change resulting from rib cage enlargement is that of a cylindrical annulus. Since the volume of such an annulus is given by

\[ V = \frac{H}{4\pi} (C_{outer}^2 - C_{inner}^2) \]

where

\(H\) is the annulus height and \(C_{outer}\) and \(C_{inner}\) the outer and inner circumferences respectively, then for any section of the rib cage:

\[ \delta V_{RC} = \frac{H_{RC}}{4\pi} [(C_{RC} + \delta C_{RC})^2 - C_{RC}^2] \]

this reduces to

\[ \delta V_{RC} = \frac{H_{RC}}{4\pi} [28C_{RC} \cdot \delta C_{RC} + 8\delta C_{RC}^2] \]

Typically, \(\delta C_{RC}\) may be \(<1\) cm during tidal breathing and \(C_{RC}\) of the order of 100 cm. Hence the factor \(28C_{RC} \cdot \delta C_{RC}\) is approximately 100 times larger than \(\delta C_{RC}^2\), which can therefore be ignored. Thus,

\[ \delta V_{RC} = \frac{H_{RC}}{2\pi} \cdot \delta C_{RC} \cdot C_{RC} \]

If the rib cage is divided into two sections, each of circumference \(C_{RC1}\) and \(C_{RC2}\) and height \(H_{RC1}\) and \(H_{RC2}\), the total rib cage volume change is given by

\[ \delta V_{RC} = 1/2\pi [H_{RC1} \cdot \delta C_{RC1} \cdot C_{RC1} + H_{RC2} \cdot \delta C_{RC2} \cdot C_{RC2}] \]

(i)
when the sections change in circumference by $\delta C_{RC_1}$ and $\delta C_{RC_2}$.

(2) Abdomen/diaphragm alone (fig. 1B). For the derivation of (i) it was assumed that the diaphragm was static so that the height of the thoracic cavity, $H_{RC_1}+H_{RC_2}$, remained constant. The contribution from the abdomen/diaphragm can be determined in the following manner.

With the rib cage held static at end-expiration, and the diaphragm free to move, the abdomen volume contribution is approximately equivalent to a cylinder of height equal to the amount of diaphragm lowering, and circumference equal to that of the bottom of the rib cage. This volume is shown as $V_A$ in figure 1B.

To compute the diaphragm contribution, the extent of diaphragm movement $\delta D$ from end-expiration must be known. Since the abdominal contents are incompressible, this can be shown to be

$$\delta D = \frac{(2\delta C_A \cdot H_A)}{(C_A + 2\delta C_A)}$$

where

$H_A$ = height of abdominal cavity from pelvic basin to position of diaphragm at end-expiration,
$C_A$ = abdominal circumference at end-expiration,

and using an expression similar to that used for the rib cage (equation (i)), the abdomen/diaphragm contribution can be calculated:

$$\delta V_A = \frac{(H_A - \delta D) \cdot \delta C_A \cdot C_A}{2\pi}$$

(3) Joint volume contribution (JVC). Figure 1C shows the more realistic situation where, because of the coupling of the diaphragm to the rib cage, diaphragm lowering during inspiration is responsible for rib cage enlargement. The shaded area, termed the Joint Volume Contribution, is unaccounted for in either equation (i) or (ii). This joint volume contribution can be approximated to a cylindrical annulus at the junction of the rib cage and the abdomen so that

$$JVC = \frac{\delta D \cdot \delta C_{RC_2} \cdot C_{RC}}{2\pi}$$

Substituting for $\delta D$:

$$JVC = \frac{1}{\pi} \cdot \frac{\delta C_A \cdot \delta C_{RC_2} \cdot H_A \cdot C_{RC}}{C_A \cdot 2\delta C_A}$$

(4) Total volume change. The total volume change, the tidal volume, is the sum of the rib cage, abdomen and joint contributions. Hence:

$$V_{total} = V_{RC} + V_A + JVC$$

Because both the abdomen/diaphragm and the joint volume contributions result from diaphragm contraction, $\delta V_A$ and $JVC$ can be combined to give the actual volume contributed by diaphragm contraction, $\delta V_{Actual}$. To simplify the computational steps in the analog computer, the expression solved was

$$\delta V_{Actual} = \frac{H_A \cdot \delta C_A \cdot C_A}{2\pi}$$

This describes the sum of the volumes of equations (ii) and (iii) and assumes that, at the junction of rib cage and abdomen:

$$C_A = C_{RC_1}$$
$$\delta C_A = \delta C_{RC_2}$$

It must be emphasized that this equation is only a good approximation when circumference changes are small.

**Analog computer**

Equation (iv) was solved using a purpose-built analog computer. The overall scheme is shown in figure 2. Variable inputs to the system are the signals from the four gauge amplifiers. The circumferences at each gauge position were measured and set up on the appropriate multiturn potentiometer (set $C_{RC_2}$, $C_{RC_2}$, $C_A$, and $C_A$). The height of the trunk was measured between the suprasternal notch and symphysis pubis. The diaphragm position was estimated by percussion of the upper margin of the liver, enabling partitioning of the trunk height into the appropriate sections ($H_{RC_2}$, $H_{RC_2}$, $H_A$) which were also entered as parameters. Adjustments of the height parameters were made following the method of Konno and Mead (1967) so that, with the glottis closed, moving the abdomen/diaphragm gave equal and opposite movements of the rib cage. In this way $H_A$ and $H_{RC_1}$ could be varied separately, keeping the sum $H_A + H_{RC_1}$ constant until, with glottis closed, rib cage and abdominal volume contributions were equal.

The volume contributions of rib cage and abdomen/diaphragm, the joint volume contribution and the sum of the rib cage and abdomen/diaphragm were displayed separately on a Devices chart recorder.
Evaluation of the system

Initial work showed that in some subjects non-uniform abdominal shape changes occurred during tidal breathing. This potential source of error was reduced by the application of a second gauge to the abdomen, hence the additional parameters $C_{Al}$ and $C_{A2}$.

Thirteen male laboratory personnel were studied in the supine position while breathing into a bag-in-box system connected to an Ohio electronic spirometer. The tidal volume measured with the spirometer was compared with the computed $\Delta V_{total}$. Ventilation was increased by adding carbon dioxide to the system and the spirometric and computed tidal volumes were recorded on the Devices recorder. The mean of four consecutive breaths at each of three different tidal volumes was used to prepare a composite plot of computed against measured tidal volume (fig. 3). These data were supplemented by tidal volume measurements in a group of four female and nine male patients with a larger age range than the laboratory personnel. These patients gave informed consent to the non-invasive procedure. The mean ($\pm 1$ SD) of the dimensions of the trunk for this group of 26 subjects is shown in table I. The patients were studied immediately before and after the induction of anaesthesia with thiopentone and 1% halothane in a nitrous oxide in oxygen mixture. In the patients, tidal volume was determined by electronic integration of flow at the mouth, which was measured using a Fleisch II pneumotachograph and Validyne Pressure transducer. This system was calibrated with the anaesthetic gas mixture using a 1-litre Hamilton syringe. The results show that the reduced tidal volume during anaesthesia is accurately computed from the movements of the surface of the body (fig. 3). In this group of 26 subjects, 94% of the computed values were within $\pm 8\%$ of the
RIB CAGE AND ABDOMINAL MOVEMENT

Fig. 3. Comparison of measured tidal volume and computed tidal volume in 26 subjects. Closed circles represent data from conscious subjects and open circles those from anaesthetized subjects. Each closed circle represents the mean of four consecutive breaths. An increase in tidal volume was obtained by increasing alveolar carbon dioxide.

Sources of system error are shown in table II.

TABLE I. The mean (± 1 SD) of rib cage, abdominal circumference and height and the change in circumference (cm) during tidal and vital capacity breathing (n = 26)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Rib cage</th>
<th>Abdomen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height (cm)</td>
<td>26.5 ± 4.5</td>
<td>29.2 ± 6.2</td>
</tr>
<tr>
<td>Circumference (cm)</td>
<td>92.6 ± 6.9</td>
<td>82.4 ± 8.8</td>
</tr>
<tr>
<td>Δ Circumference (tidal)</td>
<td>0.41 ± 0.33</td>
<td>1.39 ± 0.4</td>
</tr>
<tr>
<td>Δ Circumference (VC)</td>
<td>3.31 ± 1.74</td>
<td>3.78 ± 1.38</td>
</tr>
</tbody>
</table>

directly measured tidal volume. The sources of system errors are shown in table II.

The 13 laboratory personnel were also studied while breathing predominantly with rib cage or abdomen. Ten of these subjects were able to achieve 85% of tidal ventilation with either rib cage or abdomen. In those subjects breathing predominantly with the abdomen, there was a close fit between spirometric measurements and computed volumes, the measurement error being less than ±4%. With predominant rib cage breathing the error increased, with a tendency to overestimate the tidal volume by 15% in two subjects. The mean computed tidal volume for rib cage breathing was 9% greater than the spirometer volume with a range of 2-15%. The data from the laboratory personnel were also displayed as an X-Y plot of spirometer volume against computed volume while the subjects breathed slowly from functional residual capacity (FRC) to residual volume (RV) and then to total lung capacity. Two of 13 subjects showed non-linearity near RV, beginning at about 100 ml above RV, and these subjects showed gross deformity of the abdominal wall shape at this stage of the manoeuvre. Five subjects showed non-linearity beginning at about 60% vital capacity, the computed volume underestimating the real change in lung volume. The remaining subjects showed a linear relationship similar to that shown in figure 4.

TABLE II. Effect of system errors on computed tidal volume

<table>
<thead>
<tr>
<th>Variable</th>
<th>Error in computed volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement of circumference</td>
<td>±1%</td>
</tr>
<tr>
<td>Measurement of height</td>
<td>±5%</td>
</tr>
<tr>
<td>Cross sectional shape of rib cage</td>
<td>±6%</td>
</tr>
<tr>
<td>Gauge non-linearity</td>
<td>±4%</td>
</tr>
<tr>
<td>Computational errors</td>
<td>±9%</td>
</tr>
</tbody>
</table>

volume for rib cage breathing was 9% greater than the spirometer volume with a range of 2-15%. The data from the laboratory personnel were also displayed as an X-Y plot of spirometer volume against computed volume while the subjects breathed slowly from functional residual capacity (FRC) to residual volume (RV) and then to total lung capacity. Two of 13 subjects showed non-linearity near RV, beginning at about 100 ml above RV, and these subjects showed gross deformity of the abdominal wall shape at this stage of the manoeuvre. Five subjects showed non-linearity beginning at about 60% vital capacity, the computed volume underestimating the real change in lung volume. The remaining subjects showed a linear relationship similar to that shown in figure 4.

Fig. 4. Vital capacity manoeuvre in one subject to show linear computation of volume. Similar results were found in four other subjects although the design specification of the system did not require measurement of large changes in lung volume.
$X$–$Y$ plots were made of rib cage v. abdomen during tidal breathing in all 26 subjects. This showed a wide variability of rib cage contribution ranging from 5 to 42% of tidal volume in these non-anaesthetized subjects (fig. 5). This seemed to be age-related, in that no subject over 50 years of age had a rib cage contribution exceeding 20% of tidal volume. However, this relationship was not statistically significant. There was no consistent difference in the rib cage contribution between male and female patients, but the number of female patients was small.

To see if this large variability could be explained by differences in breathing rate, a study was carried out in three subjects, on the effect of varying breathing frequency on the rib cage contribution to tidal volume. Each subject breathed first at his normal rate then in time to a metronome. Two of the three subjects showed a small increase in rib cage contribution with increasing frequency while the third showed a slight decrease (fig. 6). Variations in frequency over the normal physiological range produced only trivial changes in rib cage contribution. One of the subjects breathed through a constricted tube equivalent to a resistance of 1 kPa litre$^{-1}$s. This subject showed quite a large increase in rib cage contribution until the respiratory rate reached 50 b.p.m., when a large phase lag of about 90° appeared between the two signals (fig. 6).

**Fig. 5.** Fractional contribution of rib cage to tidal volume against age for the 26 subjects studied. Open circles: laboratory personnel; closed circles: patients studied before anaesthesia.

**Fig. 6.** Effect of breathing frequency on fractional rib cage contribution in three subjects, A (●), B (■) and C (▲). Subject A was also studied while breathing through a constricted tube of resistance 1 kPa litre$^{-1}$s (○). The data from this latter study are represented as $X$–$Y$ plots of rib cage (RC) against abdomen in the top part of the figure. The respiratory rate (b.p.m.) is indicated. Note the large phase lag when breathing at 50 b.p.m.

**DISCUSSION**

Detailed studies of the relative contributions of the rib cage and abdomen/diaphragm have only been made in the past decade, but these have been confined to studies of conscious subjects. A notable advance was made by Konno and Mead (1967) who showed that, in conscious man, the relative volume contribution to breathing of the rib cage and abdomen could be measured from changes in the anterior–posterior diameters at only two points, using magnetometers, one on the rib cage and the other on the abdomen. A fundamental assumption was that, although the chest wall was quite irregular in shape, the movement of one part of the rib cage bore a constant relationship to the movement of any other part and, similarly, the movement of one part of
the abdomen was in constant proportion to that of any other part of the abdomen. When the glottis closed, the subjects changed the shape of the chest and abdomen, displacing volume from one compartment to another. In this system (with one degree of freedom) the gains of the abdominal and rib cage signals could be made equal so that, with the glottis open, the sum of rib cage and abdominal signal could be made equal to tidal volume. As Konno and Mead (1967) and later Mead (1974) have pointed out, this method relies on the chest wall changing its shape uniformly, and in conscious subjects this is probably the case in most circumstances. The method is invalid if the shape of the chest wall changes in a non-uniform fashion, which occurs with changes in pleural pressure beyond the limits of ordinary breathing, such as during muscular efforts against a closed airway and during loaded breathing. These pleural pressure changes affect adversely the stability of the chest wall shape which is normally maintained by a highly integrated reflex control system (Sears, 1973). Impairment of this uniform movement of the chest wall is likely when the reflexes stabilizing the position of the rib cage are attenuated during anaesthesia, although errors induced by non-uniform movements of the rib cage may not be recognized because of its small contribution to tidal breathing. However, if the phase relationships between rib cage and abdomen are to be studied, then considerable errors may arise if one part of the rib cage such as the sternum is being displaced inwards while the rib margins in the mid-axillary line are displaced outwards. This study describes a technique designed to overcome this objection by integrating chest wall movement from measurements of changes in circumference of the trunk at four sections in awake and anaesthetized man. However, using this technique two potential sources of error remain.

The first of these is the assumption that the trunk is of circular cross-section. Our model also assumed a cylindrical rather than a conical shape for the chest wall. With typical parameter values found in our subjects, the assumption of a cylindrical rather than conical shape can be shown to produce an underestimation of tidal volume of about 0.6%. Agostoni and colleagues (1965) made lateral and anterior-posterior measurements of the trunk which showed that an elliptical cross section is a better approximation. The average ratio of these measurements in both sitting and supine positions was found to be 1.42:1 (range 1.18–1.49). It is possible to calculate that, in assuming a circular cross-section, the error in computed volume for this average ratio is an overestimation of about 6%. This assumes that equal relative changes occur in both the major and minor axes of the elliptical cross section.

The second potential source of error arises from the basic geometrical assumptions made about the diaphragm. We were not sure what effects non-planar movements of the diaphragm would have on the computation of the abdominal contribution. In theory, since the abdominal contents are incompressible, whatever contribution the diaphragm makes to tidal volume should be accurately reflected in the change in the circumference of the abdomen. It is the effective diaphragm position, therefore, that is important and this is represented as the plane in our model. The implication is that this effective position can be determined accurately. This is obviously difficult and may well have contributed to the computational errors. In order to determine the effect of errors in estimation of diaphragm position we have computed the change in rib cage, abdominal and total volume (tidal volume) (fig. 7) using the mean values for rib cage and abdominal circumference and height shown in table I. The total height of the rib cage and abdomen is kept constant and the diaphragm position is altered ±4 cm.

![Graph](https://example.com/graph.png)

**FIG. 7.** Computed error in fractional rib cage contribution to tidal volume and in change in rib cage, abdominal and tidal volume when the diaphragm position is estimated incorrectly. Data used to calculate these errors are given in table I. The total height of the rib cage and abdomen is kept constant and the diaphragm position is altered ±4 cm.
breathing tended to increase and produced a consistent over-estimate of the directly measured tidal volume. It was felt that, because the range of movement of the rib cage in these manoeuvres was different from that expected during anaesthesia, this effect was acceptable for the purpose of the study.

The relative contribution of the rib cage to tidal breathing varied widely in the subjects in this study. It has been reported previously that in the supine position the rib cage contribution is about 30% of tidal volume, whereas the mean value for our subjects was 22% (range 5-42%). That this was not a result of differences in breathing frequency was suggested by a study of the effect of breathing rate on rib cage contribution in these subjects. This showed only minute changes over the physiological range in patients who had normal airway resistance. It was also noted that the laboratory staff group had a higher mean rib cage contribution (28%) than the patients (15%) and although the patients were older than the laboratory group, there was no statistically significant relationship with age.

REFERENCES

MESURE DES CONTRIBUTIONS RELATIVES DE LA CAGE THORACIQUE ET DE L'ABDOMEN/DIAFRAGMA A LA RESPIRATION DE CHEYNE-STOKES CHEZ L'HOMME

**RESUME**

Un modèle mathématique simple de la paroi de la poitrine a été construit afin que l'on puisse mesurer, chez l'homme, le volume relatif des contributions de la cage thoracique et de l'abdomen/diaaphragme pendant la respiration de Cheyne-Stokes, et ce à l'aide de quatre extensiomètres à mercure dans du caoutchouc placés autour du tronc. A partir des dimensions du tronc et des variations de la circonférence déterminées par les quatre extensiomètres, on a pu déterminer les contributions individuelles de la cage thoracique et de l'abdomen/diaaphragme grâce à un ordinateur analogique construit dans ce but. Le système a été évalué sur 13 membres du personnel du laboratoire et sur 13 autres avant et après anesthésie. Il y eu une relation linéaire entre les quantités d'air expiré à chaque respiration, calculées et mesurées à la bouche, par rapport au volume résiduel (FRC +1 litre), avec un écart de ±8%. La contribution relative de la cage thoracique par rapport à la respiration de Cheyne-Stokes a montré une grande dispersion allant de 5 à 42% ainsi qu'une tendance non significative à décroître avec l'âge.

MESSUNG DER RELATIVEN BEITRÄGE VON BRUSTKORB UND UNTERLEIB/ZWERCHFELL ZUM MENSCHLICHEN ATMUNGSVORGANG

**ZUSAMMENFASSUNG**


MEDICION DE LAS CONTRIBUCIONES RELATIVAS DEL COSTILLAJE Y EL ABDOMEN/DIAFRAGMA A LA RESPIRACIÓN CORRIENTE EN EL HOMBRE

**SUMARIO**

Se construyó un modelo matemático sencillo de la pared del tórax con el fin de poder medir durante la respiración corriente en el hombre las contribuciones relativas de volúmen del costillaje y el abdomen/diafragama, utilizando cuatro deformímetros de "mercurio en caucho", colocados alrededor del tronco. De las dimensiones del tronco y el cambio en su circunferencia determinado por los cuatro deformímetros, pudieron determinarse las contribuciones separadas del costillaje y el abdomen/diafragama, empleando un computador analógico de construcción especial. El sistema fue evaluado con 13 miembros del personal del laboratorio y en 13 sujetos más antes y después de anestesia. Hubo una relación lineal entre los volúmenes de respiración computados y medidos en la boca y el volumen residual (FRC +1litro), con un error de ±8%. La contribución relativa del costillaje a la respiración corriente indicó una mayor variación, entre 5 y 42%, con una tendencia no significativa a disminuir a medida que avanza la edad.