Upsala J Med Sci 82: 31–37, 1977

# Thoraco-abdominal Perimetry for Partitioning of the Tidal Volume into Fractions due to Rib Cage Expansion and Diaphragmatic Descent

SVEN JAKOBSON and INGRID IVARSSON

*From the Departments of Anaesthesiology and Clinical Physiology, University Hospital, Uppsala, Sweden*

## ABSTRACT

**In 10 healthy males, respiratory variations in rib cage and abdominal circumferences were detected with mercury-in-rubber transducers. The volumes of respired air were measured by pneumotachography. The purpose was to divide quantitatively the tidal volume into fractions referable to rib cage expansion and to diaphragmatic descent (costal and abdominal breathing respectively). The main practical problem is to get the transducers properly scaled, the method of perimetry otherwise being easy to apply. For this purpose a manoeuvre producing deliberate variations in the partitioning of costal and abdominal breathing at different tidal volume levels proved satisfactory (the manoeuvre of variably combined costal and abdominal breathing). By calibrating the transducers in this way it was also possible to make fairly good estimates of the tidal volumes from the perimetric variations. The relation between changes in lung volumes and in circumferences was found to be approximately linear within a considerable range of tidal volumes. In the group investigated—under the condition of quiet respiration in the semirecumbent position—the fraction of abdominal breathing was found to be 0.64, on average.**

## INTRODUCTION

In the study of chest wall mechanics, the tidal volume is considered to consist of two portions that are displaceable independently of one another —one referable to rib cage expansion (or costal breathing) and the other to the descent of the diaphragm (or abdominal breathing). Though the degree of independence might be doubted, the concept is of great interest, and several methods for assessment of the portions have been employed. Bergofsky (2) determined the volume displaced by the descending diaphragm by enclosing the subject caudal to the costal margin in a body plethysmograph, i.e. he measured the changes in the distribution of the abdominal volume. Josenhans & Wang (8) determined the axial displacement of the abdominal mass—caused by the diaphragmatic descent—by means of a ballistograph on which the subject was placed in the supine position. They were then able to calculate the volume displaced by the diaphragm. Nisell (11) utilized the relation of the rib cage and the abdominal mechanics to derive the displacements of the abdomen during natural breathing. He thus calculated the impedance values from records of the tidal variations in lung volume and intragastric pressure—presuming the latter to indicate the pressure moving the rib cage and abdomen. These procedures required the inclusion of a trial of abdominal breathing. Konno & Mead (9) devised a method based on the assumption that the volumes displaced by the two parts could be estimated by linear motions in the rib cage and the abdomen, respectively, and they then introduced the "isovolume manoeuvre" for the quantification. Initially they intended to detect these linear motions in terms of changes in the circumferences, but preferred the antero-posterior diameters as being less disturbed by the hazards of soft tissue compliance.

However, respiratory variations in rib cage and abdominal circumferences have in fact been employed for similar purposes. Thus, Herxheimer (7) observed the rib cage circumferences and then estimated shifts in the ratio of rib cage to diaphragmatic volume displacements over the respiratory cycle. Staehelin & Schütze (13), and later Okinaka (12), observed both rib cage and abdominal circumferences and made qualitative or semiquantitative estimates of the two tidal volume portions. Enghoff (4) and Dornhorst & Leathart (3) reported good linear correlation between the tidal volume and the combined variations in rib cage and abdominal circumferences but made no attempt to assess the magnitude of the portions. Wade (14) introduced the mercury-in-rubber transducer for the detection of perimetric variations. Thus he combined rib cage perimetry with measurements of the respiratory movements of the diaphragm—by means of fluoroscopy—and was then able to present figures suggesting that in a full vital capacity about 75% of the volume is attributable to diaphragmatic movement. Agostoni et al. (1) defined a geometrical model of the chest. By means of rib cage perimetry —using the mercury-in-rubber transducer—they were then able to quantify the volume displaced by rib cage expansion. According to them this volume was a function of the difference between the squared end-inspiratory and end-expiratory circumferences, i.e. they settled the relation between the changes in volume and linear motions to be a function of second order.

In the present study the principles of Konno & Mead (9) have been adopted, but the linear motions have been measured as changes in the circumferences. In our opinion the hazards of soft tissue compliance can be largely avoided by using compliant, lightweight mercury-in-rubber transducers as measuring instruments. This technique will then afford at least the same convenience of application—both for the subject and for the investigator—as does the magnetometer technique described by Mead et al. (10) for the detection of changes in the anteroposterior diameters.

The primary aim of this investigation, however, was to study some manoeuvres for scaling the transducer signals. This is the main practical problem when thoraco-abdominal perimetry is used for partitioning the tidal volume into fractions due to rib cage expansion and diaphragmatic descent. A further purpose was to examine the fitness of the linear approach to the relation between tidal volumes and perimetric variations.

## MATERIAL AND METHODS

Ten healthy men were investigated. Their ages and some relevant anthropometric data are given in Table I. Although of different body sizes they were all of ordinary constitution.

Respiratory air flow was measured at the mouth (nose clips applied) with a heated pneumotachograph (Fleisch No. 2, Godart NV, Bilthoven, Netherlands). The pneumotachograph was connected to a differential pressure transducer (EMT 32, Siemens-Elema, Solna, Sweden) and the flow signals were integrated over time electronically (Respiration Analyser AN 2, Svenska Radio AB, Stockholm, Sweden), whereby the tidal volumes were obtained. The range of linearity (±2 litres/second) was never exceeded. Calibration was achieved by means of a special pump producing a known sinusoidal air flow (Pneumotachokalibrator, Elektromedizin und Respirator AG, Zug, Switzerland).

Respiratory variations in the rib cage and abdominal circumferences were measured at the level of the fourth costosternal joint and of the umbilicus respectively. A strain-gauge technique was used. The transducers were made of silicone rubber tubing (length 30 cm, outer diameter 1.5 mm) filled with mercury and in series with flexible, non-elastic cables (Park Electronics Laboratory, First Beaverton, Oregon, US). Each transducer was connected to a Wheatstone bridge (IKP Sträckplethysmograph, Siemens-Elema).

On application, the mercury-in-rubber tubes were stretched so as to cover symmetrically 40 cm of the frontal aspect of the thorax or abdomen. The remaining parts of the circumferences were covered by the non-elastic cables. To avoid cranio-caudal displacements, the transducers were passed through short plastic tubes which were attached to the skin by strips of adhesive tape.

The range of linearity of the system (±3 cm from zero balance) was never exceeded.

The tidal volume signals and the signals from the rib cage and abdominal transducers were recorded graphically (Mingograf 81, Siemens-Elema) for further manual processing.

### *Procedures*

The subjects were investigated in the semirecumbent position (the upper part of the body elevated 30° from the horizontal plane).

In each subject, five different trials, of which the latter three were calibration manoeuvres, were made in the following order:

1. Breathing at optional tidal volumes as well as with optional partitioning into costal and abdominal breathing, i.e. natural breathing.
2. Breathing at different tidal volume levels, but still with optional partitioning into costal and abdominal breathing. Five volume levels were practised: 0.4, 0.7, 1.0, 1.3 and 1.6 litres. The subjects approximated their tidal volume to these levels by watching the tidal volume signals on a graded oscilloscope.
3. Breathing at different tidal volume levels (0.4–1.6 litre) during deliberate variations of the partitioning into costal and abdominal breathing (the manoeuvre of variably combined costal and abdominal breathing).
4. Costal or abdominal breathing (performed in separate trials, forced to its extreme, at tidal volume levels of 0.4, 0.7 and 1.0 litres. During costal breathing the aim was that no changes should occur in the abdominal circumference, and during abdominal breathing the aim was that no changes should occur in the rib cage circumference (the manoeuvre of costal or abdominal breathing).
5. The subject was asked to inspire an ordinary tidal volume, close his glottis and start to make respiratory

movements. As no air was allowed to pass the glottis, expansions of the rib cage had to be compensated for by cranial displacements of the diaphragm. Rib cage expansions were thus reflected by decreases in the abdominal circumference. The reciprocal deflections of the transducer signals (the magnitudes were deliberately varied) were considered to reflect the same volume displacement (the single level isovolume manoeuvre).

### *Calculations*

In the tidal volume range studied, the portions referable to costal ($V_{rc}$) and to abdominal ($V_{ab}$) breathing were considered to be linear functions of the variations in rib cage ($\Delta circ_{rc}$) and abdominal ($\Delta circ_{ab}$) circumferences, respectively. The following equations might be arranged:

$$V_{rc}=a\Delta circ_{rc}+M \qquad (1)$$

respectively

$$V_{ab}=b\Delta circ_{ab}+N \qquad (2)$$

where $a$ and $b$ are the slope coefficients and $M$ and $N$ the intercepts with the ordinate. In view of the fact that there will be no deflections in either rib cage or abdominal circumference during apnoea, the intercepts should equal zero. Any divergence from origo might therefore indicate a non-linear relation between changes in lung volumes and changes in circumferences. However, it should be pointed out that in this study any intercepts were arrived at by extrapolation below tidal volumes actually measured. Therefore, in the volume range studied, a linear approach might nevertheless be justified.

$V_{rc}+V_{ab}$ equals the tidal volume ($V_T$). Hence

$$V_T=a\Delta circ_{rc}+b\Delta circ_{ab}+M+N \qquad (3)$$

By the calibration manoeuvre of variably combined costal and abdominal breathing (trial 3), the constants of Eq. 3 were established by a least square fit of the three variables (multiple linear regression analysis). As the interceptual term ($M+N$) could not be split up into its components, it was excluded when $V_{ab}$ was calculated according to this calibration manoeuvre:

$$V_{ab}=V_T[b\Delta circ_{ab}/(a\Delta circ_{rc}+b\Delta circ_{ab})] \qquad (4)$$

By the calibration manoeuvre of costal or abdominal breathing (trial 4), the constants were established by least square fits of the variables according to Eq. 1 or Eq. 2. This time the interceptual terms $M$ and $N$ were obtained separately. $V_{ab}$ according to this calibration manoeuvre was then calculated as:

$$V_{ab}=V_T[(b\Delta circ_{ab}+N)/(a\Delta circ_{rc}+b\Delta circ_{ab}+M+N)] \qquad (5)$$

The single level isovolume manoeuvre (trial 5) corresponds to the situation when $V_T$ in Eq. 3 constantly equals zero. Any increase in $V_{rc}$ has then to be reflected by a similarly sized decrease in $V_{ab}$. Hence, Eq. 1=Eq. 2, or:

$$a\Delta circ_{rc}+M=b\Delta circ_{ab}+N$$

Rearrangement gives:

$$\Delta circ_{rc}=b\Delta circ_{ab}/a+(N-M)/a \qquad (6)$$

By a least square fit of the variables from trial 5 to Eq. 6, the deflections of the rib cage transducer could be scaled in terms of the abdominal transducer. $V_{ab}$ was then calculated as:

$$V_{ab}=V_T[\Delta circ_{ab}/[\Delta circ_{ab}+b\Delta circ_{ab}/a+(N-M)/a]] \qquad (7)$$

Besides the slope coefficients and the intercepts, derived from the linear regression analyses, standard errors of the estimates ($s_e$) as well as paired ($r$) and multiple ($R$) linear correlation coefficients were calculated.

From the records for each subject the following numbers of breaths were analysed: From trial 1, ten breaths; from trial 2, seven breaths at each tidal volume level (i.e. totally 35 breaths); from trial 3, about 20 breaths; from trial 4, seven breaths at each tidal volume level and mode of breathing (i.e. totally 42 breaths), and from trial 5, about 20 breaths.

## RESULTS

### *The calibration manoeuvres*

When the variables recorded during trial 3 were fitted to Eq. 3, $R$ of $V_T$ in relation to $\Delta circ_{rc}$ and $\Delta circ_{ab}$ was 0.99 in all 10 subjects, while $r$ of $\Delta circ_{rc}$ in relation to $\Delta circ_{ab}$ ranged from 0.02 to 0.43 (mean 0.18). The $s_e$ values ranged from 0.04 to 0.07 litres.

When the variables recorded during trial 4 were fitted to Eq. 1 (costal) or Eq. 2 (abdominal breathing), $r$ ranged from 0.97 to 0.99. The $s_e$ values ranged from 0.03 to 0.07 litres for costal breathing and from 0.02 to 0.06 litres for abdominal breathing.

When the variables recorded during trial 5 were fitted to Eq. 6, $r$ ranged from 0.96 to 0.99 in nine of the subjects. In the tenth (subject 4) it was 0.87. The $s_e$ values were obtained in cm. To get an approximate idea of their relative magnitudes, they were converted to litres by means of the values of the volume change per unit of perimetric change obtained by means of trial 3 (Fig. 1); the $s_e$ values then ranged from 0.04 to 0.12 litres in nine of the subjects, while a value of 0.18 litre was found in subject 4.

### *Application of the calibration constants to trials 1 and 2*

The average tidal volumes recorded during trial 1 are shown in Table I. The group mean ±$s$ (standard

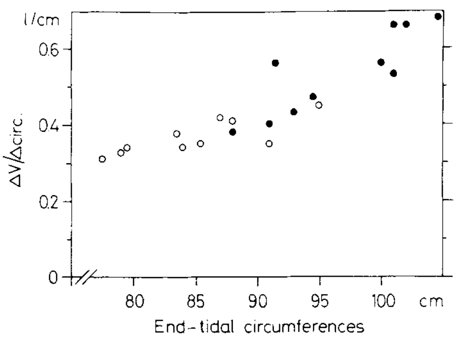

*Fig. 1.* Changes in respired air volume per unit of perimetric change ($\Delta V/\Delta$circ) in relation to circumferences at the end-tidal position. ○: $\Delta V_{ab}/\Delta \text{circ}_{ab}$ versus abdominal end-tidal circumference. ●: $\Delta V_{rc}/\Delta \text{circ}_{rc}$ versus rib cage end-tidal circumference.

deviation) for the 10 subjects was 0.73±0.16 litres. The fraction attributed to abdominal breathing ($F_{ab}$) was estimated from calibration of the transducers by trial 3 (Eq. 4). The group mean $\pm s$ was 0.64±0.10.

The volumes of 346 breaths ($n$) recorded from the 10 subjects during trial 2 were estimated from calibration of the transducers by trial 3 (Eq. 3). When they were taken as a linear function of the values measured by pneumotachography (Table II, A), the slope coefficient (0.92) deviated significantly ($P<0.001$) from 1.0 (the line of identity). However, due to the intercept (0.05 litre), the estimated and measured values in the tidal volume range 0.5 to 1.0 litres were, on the average, in good agreement (Fig. 2).

In addition, the volumes of the breaths recorded during trial 2 were estimated from calibration of the transducers by trial 4 (Eq. 3) and taken as a function of the values measured by pneumotachography (Table II, B). The slope coefficient (1.02) did not deviate significantly ($P>0.25$) from 1.0. The intercept (0.10 litre), however, was significantly separated from origo ($P<0.01$). Note the difference in the values of $s_e$ obtained in this and the former analysis (0.16 compared with 0.08 litres).

$V_{ab}$ of the breaths recorded during trial 2 were estimated by means of the constants from all three calibration manoeuvres.

When $V_{ab}$ estimated from calibration by trial (Eq. 4) was taken as a function of $V_{ab}$ estimated from calibration by trial 4 (Eq. 5) (Table II, C), the slope coefficient (1.10) deviated significantly from 1.0 ($P<0.001$). Due to a negative intercept (−0.03 litre), the values of the dependent variable were, on average, about 7% higher than those of the independent variable at the level of 0.5 litre.

When $V_{ab}$ estimated from calibration by trial 5 (Eq. 7), was taken as a function of $V_{ab}$ estimated from calibration by trial 4 (Table II, D), there was a deviation of the slope coefficient (1.04) from 1.0 ($P<0.025$), but due to a negative intercept (−0.03 litre) the concordance between the two variables was, on the average, fairly good. When applying the scaling factors of trial 5 to trial 2, ten breaths had to be excluded because $\Delta \text{circ}_{rc}$ became negative when converted into terms of $\Delta \text{circ}_{ab}$ and the total number of breaths included was thereby reduced from 346 to 336.

### *Examination of the relation between tidal volume and perimetric variations*

Agostoni et al. (1) derived this relationship—as far as it concerns the rib cage—by means of a dimensional analysis based on a geometrical model. Here the relationship will be examined in terms of a functional analysis utilizing the data available in the present investigation. It will concern both the rib cage and the abdomen.

As shown in Fig. 1, the volume change per unit of perimetric change increased with increasing circumferences. This indicates a non-linear relation between changes in lung volumes and circumferences. To evaluate the order of non-linearity the following operations were performed. First it should be noted that the values presented on the ordinate in Fig. 1 were arrived at by fitting the variables recorded during trial 3 to a linear function (Eq. 3). However, the relation between the values on the

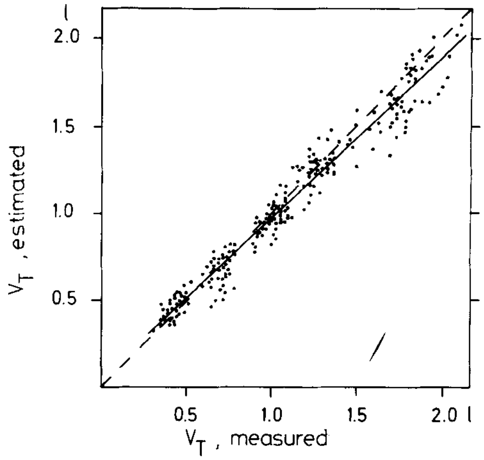

*Fig. 2.* Tidal volumes estimated by perimetry (calibration by variably combined costal and abdominal breathing) in relation to tidal volumes measured by pneumotachography. ——=linear regression line. - - -=line of identity (for further details, see Table II, A).

Table I. *Ages and some anthropometric data of the 10 subjects investigated, as well as their average tidal volumes ($V_T$) and fractions of $V_T$ referable to abdominal breathing ($F_{ab}$) recorded during trial 1*

The group mean ±*s* (standard deviation) of $V_T$ was 0.73±0.16 litre and of $F_{ab}$ 0.64±0.10

| | | | | End-tidal circumferences | | | |
|---|---|---|---|---|---|---|---|
| Subject | Age (yrs) | Height (cm) | Weight (kg) | Rib cage (cm) | Abdomen (cm) | $V_{T_{BTPS}}$ (l) | $F_{ab}$ |
| 1 | 35 | 173 | 62 | 88 | 79 | 0.74 | 0.39 |
| 2 | 35 | 177 | 65 | 91 | 77.5 | 0.55 | 0.65 |
| 3 | 41 | 177 | 76 | 101 | 87 | 0.53 | 0.72 |
| 4 | 32 | 178 | 85 | 104.5 | 95 | 0.72 | 0.59 |
| 5 | 32 | 180 | 81 | 100 | 88 | 0.88 | 0.76 |
| 6 | 33 | 182 | 69 | 93 | 79.5 | 1.02 | 0.65 |
| 7 | 35 | 182 | 75 | 94.5 | 85.5 | 0.58 | 0.74 |
| 8 | 39 | 182.5 | 71.5 | 91.5 | 84 | 0.63 | 0.63 |
| 9 | 30 | 186 | 85 | 101 | 83.5 | 0.82 | 0.67 |
| 10 | 36 | 188 | 89 | 102 | 91 | 0.81 | 0.67 |

co-ordinates in Fig. 1 was then analysed according to the exponential function $\Delta V/\Delta\text{circ}=k\cdot\text{circ}^z$, or, in a logarithmic arrangement, $\log(\Delta V/\Delta\text{circ})=z\cdot\log\text{circ}+\log k$. The exponent $z$ was established by a linear regression analysis of the logarithmic variables. It was found that $z$ should be 3.13 ($r=0.87$) for the values referable to costal breathing and 1.49 ($r=0.81$) for those referable to abdominal breathing. The values of the exponent $z$ were then applied to the range of the end-tidal circumferences given in Table I. By starting at the lowest figure observed and then continuing, with increments of 1 cm, through the largest, the relative increase in lung volume ($\Delta V_{rel}$) over this interval of perimetric expansion (Δcirc) could be derived. The relation of $\Delta V_{rel}$ to Δcirc was analysed according to $\Delta V_{rel}=k'\cdot\Delta\text{circ}^{z'}$. The exponent $z'$ was 1.12 for values referable to costal breathing and 1.06 for those referable to abdominal breathing. This meant that at these circumference levels, an increase of the circumferences by 3 cm would cause the relation between changes in lung volume and changes in circumference to deviate about 5% from linearity. It may be added that the deviation would not have been appreciably greater even if the exponent $z$ had been found equal 5.

## COMMENTS

To avoid any misunderstanding, it should immediately be stated that when rib cage expansion has been referred to above as costal breathing, this does not mean that rib cage expansion is produced exclusively by the action of the intercostal muscles—and the accessory muscles. The rib cage expanding effect of the contracting diaphragm is included as well.

In fact, no methods designed for the partitioning of the tidal volume, based on the detection of rib cage and abdominal movements, will distinguish whether an expansion of the lower rib cage should be attributed to the action of the intercostals or of the diaphragm. In the study of chest wall mechanics, such a distinction is certainly of just as much interest as knowledge of the tidal volume portion displaced by rib cage expansion. Nisell (11) and Goldman & Mead (6) have elaborated this problem and according to them the forces involved can be divided, even quantitatively, by means of registration of the respiratory variations in the intra-oesophageal and the intragastric pressures. Unfortunately, the information obtainable by another conceivable technique—electromyography–cannot be quantified into terms of forces—or volumes—unless the muscular tissues are made accessible

Table II

*A* and *B*. Tidal volumes, in litres, estimated by perimetry ($y$) in relation to tidal volumes measured by pneumotoachography ($x$):$y=ax+b$. In *A*, $y$ was estimated from calibration by variably combined costal and abdominal breathin (trial 3). In *B*, $y$ was estimated from calibration by costal or abdominal breathing (trial 4)

*C* and *D*. The relation between tidal volume portions referable to abdominal breathing, in litres, estimated from different calibration manoeuvres: $y=ax+b$, where $x$ is estimated from calibration by costal or abdominal breathing (trial 4). In *C*, $y$ was estimated from calibration by variably combined costal and abdominal breathing (trial 3). In *D*, $y$ was estimated from calibration by the isovolume manoeuvre (trial 5)

| | $n$ | $a\pm s_a$ | $b\pm s_b$ | $r$ | $s_e$ |
|---|---|---|---|---|---|
| *A* | 346 | 0.92±0.01 | 0.05±0.01 | 0.98 | 0.08 |
| *B* | 346 | 1.02±0.02 | 0.10±0.02 | 0.95 | 0.16 |
| *C* | 346 | 1.10±0.01 | −0.03±0.01 | 0.98 | 0.05 |
| *D* | 336 | 1.04±0.01 | −0.03±0.01 | 0.97 | 0.06 |

in a way which makes the method unsuitable for clinical studies.

Neither, in fact, can any of the methods designed for partitioning of the tidal volume, based on the detection of rib cage and abdominal movements, be considered truly valid. The choice of method may therefore, especially when intraindividual variations are being studied, be largely reduced to a matter of convenience of application. From this point of view, thoraco-abdominal perimetry will prove to be a good alternative.

Among the sources of error of this method, the problem of soft tissue distortion has already been mentioned. As an additional comment, it might be pointed out that in all probability the detection of variations in the rib cage circumference will be as reliable in women as in men when the lightweight and compliant transducer is placed at the level of the fourth costosternal joint.

Furthermore, it has to be presupposed that the cross-sectional area enclosed by the perimeter should increase approximately congruently on inspiration. If not, it is possible that in spite of an increasing area, i.e. an increasing volume, the circumference might still be unchanged. However, the fairly good estimates of the tidal volume apparently obtainable by the method might serve as an indication of the validity of this presumption—at least for a reasonable tidal volume range in subjects without any significant pulmonary disorder.

One error inherent in the method becomes evident when it is used to fractionate the tidal volume portions. This concern the matter of independency between the two volume fractions when they are detected in terms of linear motions in the rib cage and abdomen. If the domes of the diaphragm are visualized fluoroscopically during costal breathing defined as breathing in which no changes in the abdominal circumference occur, they will be found to descend with inspiration. If, on the other hand costal breathing is defined as breathing in which no, or only minimal, displacement of the domes occurs there will be decreases in the abdominal circumference with inspiration. Obviously this is due to a widening of the caudal aperture of the rib cage, which in turn will cause a deformation of the abdominal volume. But it means that during combined costal and abdominal breathing, descents of the diaphragm, i.e. abdominal breathing, will not necessarily be reflected by increases in the abdominal circumference at the umbilical level. Consequently, $V_{ab}$ will be constantly underestimated and, furthermore, this tendency will be augmented with increasing tidal volumes and, probably, by a decreasing abdominal wall compliance. In principle this error is common to all partitioning methods based on the detection of rib cage and abdominal movements. Neither does it matter what calibration manoeuvre is used.

However, of the three types of calibration manoeuvres studied, the manoeuvre of variably combined costal and abdominal breathing produced slightly larger estimates of $V_{ab}$ than the other two. With respect to the above mentioned tendency, underestimation of $V_{ab}$ might be lower with this manoeuvre. It cannot be denied that this is, at least partly, due to the exclusion of the intercepts (Eq. 4).

The magnitude of the difference, however, makes this point of secondary importance to the problem of having a calibration manoeuvre properly performed. In practice this is the real obstacle of the method. But even from this point of view, the manoeuvre of variably combined costal and abdominal breathing can be recommended, as it seems to entail fewer difficulties than the other two, which is also indicated by a smaller residual deviation of the linked calibration constants. It should be added that essentially this is the same calibration manoeuvre as described by Gilbert et al. (5). Similarly, the single level isovolume manoeuvre (trial 5) is a modification of the isovolume manoeuvre described by Konno & Mead (9). With their version, trial 5 should be performed not only at one but at several known levels of inspired volume. In addition to a mutual scaling—the only thing which can be revealed by the single-level version—this affords a volumetric calibration of the transducers.

Concerning the values of $F_{ab}$ obtained in this study, the figure of the group mean value (0.64) is not representative of anything more than the group investigated during—which is important—the actual experimental conditions. Conclusions of probably more general validity might be drawn from the range of the fractions (0.39–0.76). This considerable variability, obtained within a relatively homogeneous group, might be thought to indicate that the fractions should rather be confined to individuals than to groups. As a further consequence it will make any comparison of results obtained in different studies precarious. In addition, according to our experience the fractions might vary intraindividually when determined at different trials—in spite of "unchanged" conditions. This variability, however, will decrease once the subject has become acquainted with the measuring instruments.

Finally, a comment on the relation between changes in lung volume and circumference. Rationally this relation should be non-linear. Nevertheless, it was found that a linear approach was justifiable for any reasonable tidal volume in adults. Evidently the range of circumferences observed in this study falls within an approximately linear region of a basically non-linear relation. The function describing the relation in general cannot be revealed from the data obtained in this investigation, unless they are used for unreliable extensive extrapolations.

## ACKNOWLEDGEMENTS

We wish to thank Professor Gunnar Grimby for valuable discussions during the preparation of this report. The study was supported by grants from the Swedish Medical Research Council (Project No. B-76-14X-02127-10B) and the Tore Nilsson Fund for Medical Research.

## REFERENCES

1. Agostoni, E., Mognoni, P., Torri, G. & Saracino, F.: Relation between changes of rib cage circumferences and lung volume. J Appl Physiol *20* (6): 1179, 1965.
2. Bergofsky, E. H.: Relative contributions of the rib cage and the diaphragm to ventilation in man. J Appl Physiol *19* (4): 698, 1964.
3. Dornhorst, A. C. & Leathart, G. L.: A method of assessing the mechanical properties of lungs and air passages. Lancet *ii:* 109, 1952.
4. Enghoff, H.: Der Barospirator. Skand Arch f Physiol *51:* 1, 1927.
5. Gilbert, R., Auchincloss, J. H., Baule, G., Peppi, D. & Long, D.: Breathing pattern during $CO_2$ inhalation obtained from motion of the chest and abdomen. Respir Physiol *13:* 238, 1971.
6. Goldman, M. D. & Mead, J.: Mechanical interaction between the diaphragm and rib cage. J Appl Physiol *35* (2): 197, 1973.
7. Herxheimer, H.: Some observations on the co-ordination of diaphragmatic and rib movement in respiration. Thorax *4:* 65, 1949.
8. Josenhans, W. T. & Wang, C. S.: A modified ballistic method for measuring axial mass displacement caused by breathing. J Appl Physiol *28* (5): 679, 1970.
9. Konno, K. & Mead, J.: Measurement of the separate volume changes of rib cage and abdomen during breathing. J Appl Physiol *22* (3): 407, 1967.
10. Mead, J., Peterson, N., Grimby, G. & Mead, J.: Pulmonary ventilation measured from body surface movements. Science *156:* 1383, 1967.
11. Nisell, O.: Mechanics of abdomen and thorax in man during natural breathing. Acta physiol scand *59:* 85, 1963.
12. Okinaka, A. J.: Postoperative pattern of breathing and compliance. Arch Surg *92:* 887, 1966.
13. Staehelin, R. & Schütze, A.: Spirographische Untersuchungen an Gesunden, Emphysematikern und Asthmatikern. Z klin Med *75:* 15, 1912.
14. Wade, O. L.: Movements of the thoracic cage and diaphragm in respiration. J Physiol *124:* 193, 1964.

*Received January 13, 1977*

Address for reprints:

Sven Jakobson, M.D.
Department of Anaesthesiology
University Hospital
S-750 14 Uppsala
Sweden