Eur Respir J
1989, 2, 71–77

The effect of breath size and posture on calibration of the respiratory inductive plethysmograph by multiple linear regression

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ABSTRACT: The accuracy of the respiratory inductive plethysmograph (Respitrace) for estimation of lung volume changes during quiet breathing and vital capacity (VC) manoeuvres was evaluated using a variant of the multiple linear regression (MLR) technique. We applied this technique successively on quiet breathing, on the whole VC, and on each of the four quarters of the VC separately. This was carried out in six body positions. The best estimation of tidal volumes was obtained when calibration factors calculated during quiet breathing were used. The best estimation of VC was obtained when the calibration factors were adapted to the level of lung inflation. These results indicate that, using a single position MLR calibration method, the Respitrace measures tidal and VC mouth volumes very accurately. The accuracy of this MLR method for estimation of the rib cage and abdominal contributions was validated by comparison with isovolume calibration factors. Both techniques gave very similar results during tidal breathing. However, the MLR calibration factors may have no physiological meaning (*i.e.* for volume partitioning) when they are calculated from VC manoeuvres, in which more than two degrees of freedom are involved.
Eur Respir J., 1989, 2, 71–77.

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Keywords: Multiple linear regression; respiratory inductive plethysmograph (RIP); RIP calibration; Vital capacity manoeuvre.

Received: January, 1988; accepted after revision August 16, 1988.

The respiratory inductive plethysmograph (RIP) is generally considered a good, non-invasive monitor of respiration. The technique is based on the assumption of Konno and Mead [1] that the rib cage and abdomen behave with two degrees of freedom. Thus, volume changes of these two compartments should define lung expansion. This can be expressed by the equation:

$$\Delta V_M = a\Delta RC + b\Delta ABD$$

where (a) and (b) are the calibration factors, also called volume-motion (VM) coefficients which have to be multiplied with rib cage (RC) and abdominal (ABD) movement, respectively, to give volume changes. ΔV_M is the volume change at the mouth measured by pneumotachograph or spirometer.

Several techniques have been proposed to calculate these VM coefficients. Konno and Mead [1] proposed the isovolume method. This is based on the assumption that with the mouth occluded the system has only one degree of freedom, *i.e.* the volume change of the RC must be equal and opposite to that of the ABD. The simultaneous equation method [2, 3] and the least squares method [4] use the changes in contribution of RC and ABD to tidal volume measurement (especially between different body positions) to calculate the VM coefficients. However, these methods imply that changing position does not change VM coefficients, an assumption questioned by several authors [5–8].

Based on the dephasing between RC and ABD during breathing, the multiple linear regression (MLR) technique [7, 9] allows the calculation of VM coefficients using appropriate computer programmes [10]. This method has been applied already by several investigators for the assessment of tidal mouth volume by the RIP [9, 11, 12] and of the rib cage and abdominal contributions [7]. Only some of the studies have paid attention to calibration [6, 13] and validation of the Respitrace at larger tidal volumes [2, 6, 8] and during VC manoeuvres [3]. One conclusion [6] has been that calibration factors are changing when the tidal volume increases and that the RIP should be calibrated using volumes that approximate the breath sizes that have to be measured.

The purpose of the present study was to evaluate in more detail the effect of breath size (*i.e.* VC manoeuvres) and posture on the calibration of the RIP by multiple linear regression. Calibration factors obtained from quiet breathing and VC manoeuvres were studied and their ability to predict mouth volume and volume contributions of the rib cage and abdomen was tested. In this respect we were especially interested in VC manoeuvres because in this condition more than two degrees of freedom are involved [14], a fact which those who apply the Respitrace often neglect to take into consideration.

Methods

Subjects

We studied two groups of healthy male subjects (group 1: four subjects, mean age 22±4 yrs; group 2: ten subjects, mean age 30±7 yrs). They were nonsmokers with no history of lung disease and with normal pulmonary function tests.

Procedure

The subjects of group 1 were examined in six body positions (standing, sitting, supine, prone, left and right lateral decubitus). For the measurements in decubitus position no pillow was used. In each body position quiet breathing for 180 s at functional residual capacity (FRC) and three slow VC manoeuvres were recorded, from which rib cage (RC) and abdominal (ABD) volume-motion (VM) coefficients were calculated using the multiple linear regression (MLR) method.

The subjects of group 2 were examined in the standing position and performed two types of manoeuvre: 1) an isovolume (ISV) manoeuvre at FRC, recorded on an X-Y recorder, in order to obtain accurate RC and ABD volume-motion coefficients; and 2) quiet breathing for 1.5 min from which RC and ABD VM coefficients were calculated using the MLR method.

Equipment

A commercial respiratory inductive plethysmograph (RIP, Respitrace) was used. The rib cage coil was positioned as high as possible under the axilla. The abdominal coil was positioned at the level of the umbilicus. Slippage of the bands was prevented by a net.

Signals from the RIP coils and from a pneumotachograph ($0.5\ l{\cdot}s^{-1}=2.5$ V) were converted into digital data (every 50 ms). The digitized data, represented by numbers ranging from 0 to 4,000 (which correspond with a ±5 volt input) were stored on disk and processed off-line in several steps.

Data handling

Multiple linear regression: the calibration factors or volume-motion coefficients of rib cage (a) and abdomen (b) were calculated from the equation:

$$\Delta V_M = a\Delta RC + b\Delta ABD$$

in which ΔV_M is the change in mouth volume and ΔRC and ΔABD are the changes in self-inductance of the coils. Providing that there is a small dephasing between ΔRC and ΔABD the multiple linear regression (MLR) method applied to several chosen parts of the respiratory manoeuvre, allows the calculation of (a) and (b).

In group 1, the chosen parts of the respiratory manoeuvres were:

- for quiet breathing at FRC: 1) the inspirations; 2) the expirations; 3) the inspirations plus expirations, all measured during 180 s quiet breathing.
- for VC manoeuvres: 1) the inspiratory VC; 2) the expiratory VC; 3) the inspiratory plus expiratory VC; 4) 0–25, 25–50, 50–75 and 75–100% inspiratory VC; and 5) 100–75, 75–50, 50–25 and 25–0% expiratory VC, all measured on three VC manoeuvres.

Fourteen sets of calibration factors were determined for each subject. This was carried out in six body positions, thus amounting to a total of 6x14=84 sets. Each of these sets of calibration factors were then applied to tidal volumes and VC manoeuvres. Within each body position, all RIP volumes were compared with their corresponding V_M.

In group 2 ISV VM coefficients were obtained by adjusting the gains of the X-Y recorder during the ISV manoeuvre, until a slope of -1 (*i.e.* an angle of -45°) was achieved. The ratio of these gains, representing the ratio of the ISV VM coefficients was then compared with the ratio of the VM coefficients obtained with the MLR method during quiet breathing. Comparison of these ratios is a measure of the accuracy of the MLR VM coefficients obtained during quiet breathing in the calculation of the volume partitioning between ABD and RC.

Statistical analysis

Means±1 SD were calculated and three way analyses of variance were applied. Differences between two factors were also analysed using Student's t-test for paired and unpaired samples. Correlation coefficients between ΔV_M and ΔRC and between ΔV_M and ΔABD were calculated.

Results

VM coefficients

Rib cage (a) and abdominal (b) volume-motion (VM) coefficients in six body positions are presented in figure 1 for quiet breathing and in figure 2 for VC manoeuvres. During quiet breathing (b) is statistically smaller than (a) for each body position and for each breathing cycle (inspiration, expiration, inspiration plus expiration) ($p<0.05$). During VC manoeuvres there is an overall significant difference between (a) and (b) ($p<0.05$) and this difference is larger for inspiratory than for expiratory manoeuvres; in the former (b) may even be negative. However, this difference between (a) and (b) is not significant in each body position or breathing cycle. When the effect of breathing cycle on (a) and (b) was analysed separately, during quiet breathing only (a) is significantly different between expiration (E) and expiration plus inspiration (E+I) ($p<0.05$). There is no

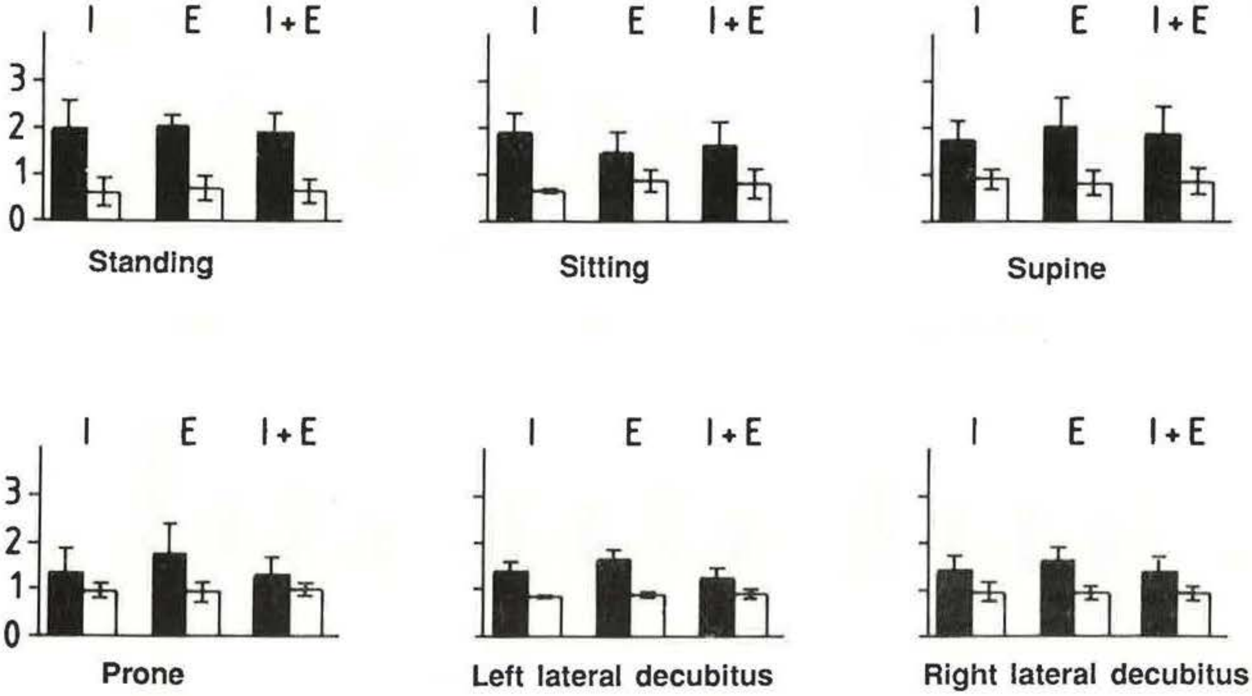

Fig. 1. – Volume motion (VM) coefficients (mean±SD) calculated during the inspiratory (I), expiratory (E) and expiratory plus inspiratory (I+E) part of quiet breathing. Black blocks are coefficients for Rib cage movement (RC) (a). White blocks are coefficients for abdominal movement (ABD) (b).

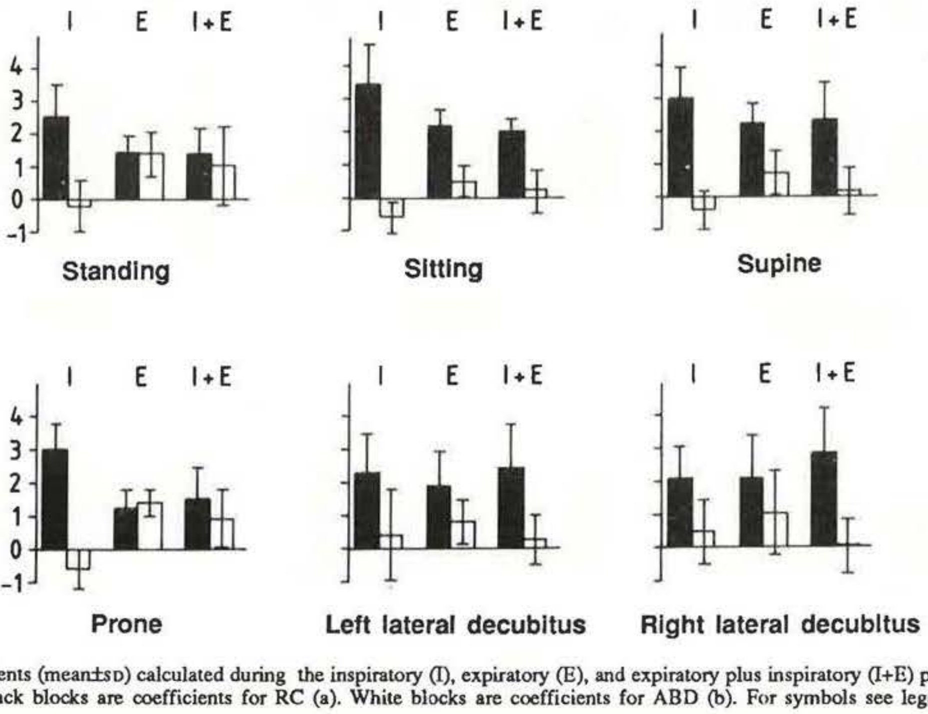

Fig. 2. – VM coefficients (mean±SD) calculated during the inspiratory (I), expiratory (E), and expiratory plus inspiratory (I+E) part of vital capacity (VC) manoeuvre. Black blocks are coefficients for RC (a). White blocks are coefficients for ABD (b). For symbols see legend Fig. 1.

significant influence of body position on (a) and (b) and there are no significant inter-individual differences. In addition both RC and ABD correlated accurately with the V_m (r>0.97) in all subjects. During VC manoeuvres both (a) and (b), calculated during inspiration (I), expiration (E), and inspiration plus expiration (I+E), are significantly different (p<0.001). Also the differences between body positions and between individuals are significant during VC manoeuvres (p<0.001). During the inspiratory VC the mean correlation coefficients between

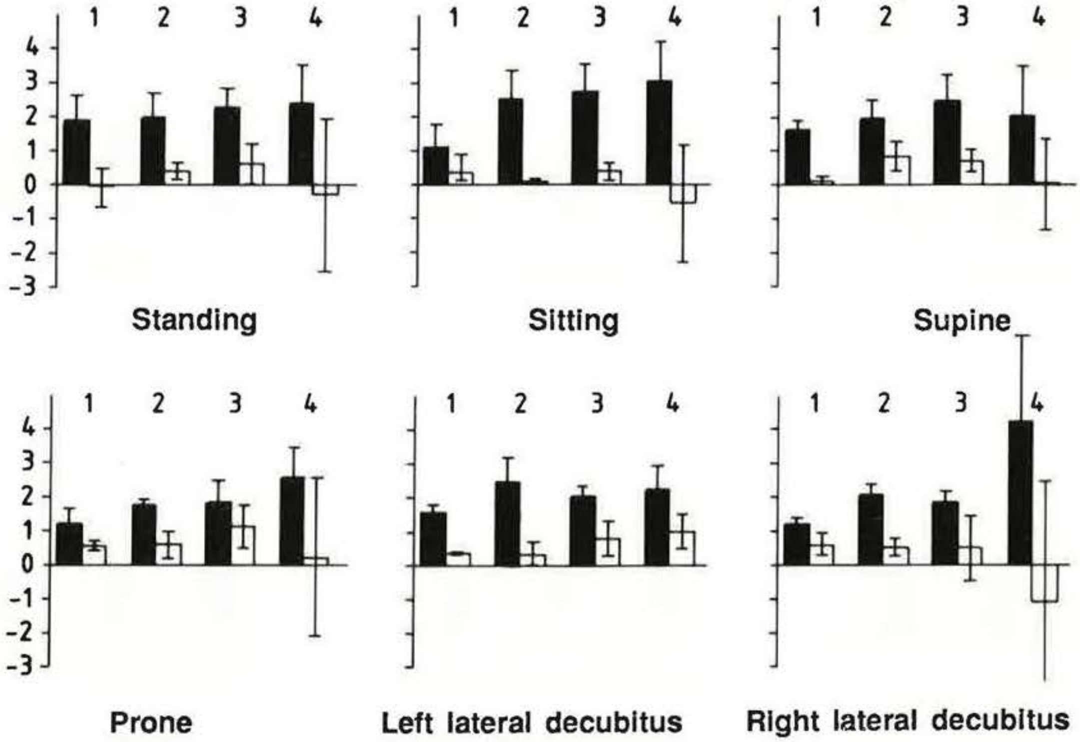

Fig. 3. – VM coefficients (mean±SD) calculated during: 1) 0–25; 2) 25–50, 3) 50–75, 4) 75–100% inspiratory VC. Black blocks are RC (a). White blocks are ABD (b). See legend Fig. 1 for symbols.

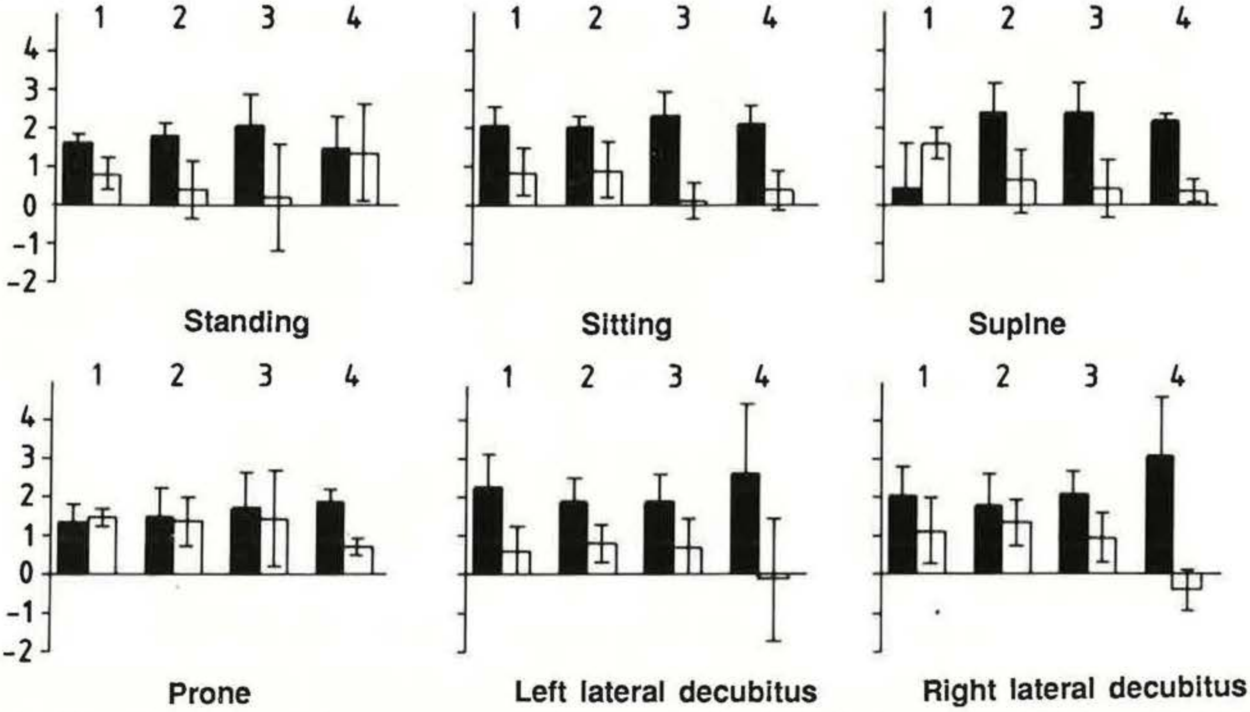

Fig 4. – VM coefficients (mean±SD) calculated during: 1) 100–75; 2) 75–50, 3) 50–25, 4) 25–0% expiratory VC. Black blocks are RC (a). White blocks are ABD (b). See legend Fig. 1 for symbols.

RC and V_M were 0.998±0.012 and between ABD and V_M 0.920±0.096. During expiration these coefficients were 0.987±0.024 and 0.948±0.045, respectively.

In figures 3 and 4 (a) and (b) calculated for the different quarters of VC in six body positions are presented. In both inspiration (fig. 3) and expiration (fig. 4), (a) is significantly different from (b) ($p<0.05$). Whilst for 100–75% VC in supine and prone posture (fig. 4) (b) is larger than (a), the opposite is true for all other conditions. During inspiration the VM coefficients change significantly with lung volume ($p<0.001$) except for (a) between 25–50% and 50–75% VC and for (b) between 0–25% and 25–50% VC. There is a general tendency in the different body positions for (a) to increase with volume and for (b) to show a large standard deviation at 75–100% VC. During expiration (a) calculated at 25–0% VC is different ($p<0.001$) from (a) calculated during the other parts of the VC. The abdominal VM coefficients are significantly different for the different parts of the VC manoeuvre ($p<0.001$) except for the levels 50–25 and 25–0% VC during expiration.

V_{RIP} differs by less than 10% from V_M). Using calibration factors corresponding with the considered level of expiration or inspiration of a VC manoeuvre gives the best results: 100% of V_{RIP} is within ±10% of V_M for inspiration and 89% of V_{RIP} is within ±10% of V_M for expiration.

Comparison of ISV and MLR VM coefficients

Table 2 shows the ratios between the MLR VM coefficients and the ISV VM coefficients calculated at FRC for group 2. The mean ratio was 0.99±0.19. Four subjects out of ten fell between 0.9 and 1.1, corresponding with an over- or underestimation of the relative

Table 1. – Percentage of Respitrace volumes that are equal to mouth volume ±5, 10 and 20% during tidal breathing and during VC manoeuvres

Calibration	Breathing volumes to which calibration is applied:											
	Quiet breathing						VC manoeuvres					
	Inspiration			Expiration			Inspiration			Expiration		
	5%	10%	20%	5%	10%	20%	5%	10%	20%	5%	10%	20%
On quiet breathing												
Inspiration	100	100	100	58	100	100	31	49	76	11	35	84
Expiration	75	92	100	100	100	100	35	60	82	29	58	84
Inspiration+expiration	83	92	100	42	79	100	16	29	76	16	22	58
On VC manoeuvre												
Inspiration	0	0	8	0	5	11	42	65	100	34	56	93
Expiration	12	17	42	10	18	48	24	47	100	49	69	100
Inspiration+expiration	17	25	42	18	26	52	31	54	100	40	40	100
Variable calibration factor							71	100	100	51	89	100

VC: Vital capacity.

Respitrace and mouth volume

In table 1 mouth volumes (V_M) are compared with Respitrace volumes (V_{RIP}) using different pairs of calibrating factors. The percentages of RIP tidal volumes that are equal to mouth volume ±5, 10 and 20% during tidal breathing and during VC manoeuvres are presented.

When the VM coefficients are calculated on quiet breathing (inspiration or expiration), generally 100% of V_{RIP} differs by less than 10% from V_M for quiet breathing; yet for the VC manoeuvre only about 35–60% of V_{RIP} differs by less than 10% of V_M. These data are worse when using calibration factors calculated on both expiration and inspiration: 79–92% of V_{RIP} differs by less than 10% V_M for quiet breathing and 22–29% of V_{RIP} for VC manoeuvres.

When the VM coefficients calculated on VC manoeuvres are applied to the VC manoeuvres the data are slightly better (40–69% of V_{RIP} differs by less than 10% from V_M). When these VM coefficients are applied to quiet breathing, the data are clearly worse (0–26% of

Table 2. – Comparison of the ratios MLR and ISV VM coefficients. The MLR calibration method was applied to the inspiratory and expiratory part of tidal breath

	$\frac{a_{MLR}/b_{MLR}}{a_{ISV}/b_{ISV}}$		
Subject	Inspiration	Expiration	Mean
VT	1.21	1.04	1.14
RF	1.09	1.08	1.08
GG	0.69	0.80	0.75
VF	0.70	0.68	0.69
VJ	1.49	1.19	1.30
DM	0.99	0.92	0.95
CP	0.73	0.89	0.81
VJo	0.93	1.15	1.03
PB	1.13	1.18	1.16
LP	1.00	1.09	1.04
Mean±SD	0.99±0.24	0.99±0.16	0.99±0.19

MLR: multiple linear regression; ISV: isovolume; VM: volume-motion; a, b: ribcage and abdominal VM coefficients, respectively.

contributions of RC and ABD by less than 10%. However, three out of ten fell outside 0.8 and 1.2 and thus over- or underestimated the relative RC and ABD contributions by more than 20%.

Discussion

The purpose of the present study was to examine the variability of calibration factors calculated with the MLR method and derived from different respiratory manoeuvres, and to evaluate their accuracy for estimating mouth volume and predicting volume partitioning of RC and ABD. Our calibration method is closely related to the MLR technique used by other authors [7, 10]. In this technique data from all parts of the respiratory cycle are used, and a small dephasing between ABD and RC movement within one body position allows the calculation of the VM coefficients.

We consider changes in volume of mouth, of RC and of ABD, and have to solve an equation with two unknown factors:

$$\Delta V_M = a\Delta RC + b\Delta ABD$$

This equation can be derived from any part of any respiratory manoeuvre. The method is similar to that used by Heldt and McIlroy [11] and McCool *et al.* [12] and is related to the technique of Stagg *et al.* [15].

We found that calibration factors calculated on inspiration, expiration and inspiration plus expiration of quiet breathing vary little (fig. 1) and that changing position does not influence the results. There are, also, only small differences between the four subjects. The calibration factor for RC (a) is always larger than that for ABD (b). V_M coefficients on VC manoeuvres differ more: there are larger inter-individual differences and also the ratios between (a) and (b) are more variable. If the VM coefficients are calculated on different parts of the inspiratory VC manoeuvre, there is an overall tendency for the rib cage VM coefficient to increase at higher lung volumes (fig. 3). Millman *et al.* [6] recently described the importance of breath size on the calibration of RIP. They concluded that the RIP volumes most clearly approximated the spirometric volumes when the calibration breaths and validation breaths are of the same size. We calibrated on VC manoeuvres instead of increasing tidal volumes, but we also noticed the influence of the lung volume on the calibration factors.

There is no significant influence of body position on the VM coefficients during quiet breathing, but the VM coefficients calculated on VC manoeuvres change significantly when body position is altered.

With the MLR method a good estimation of mouth volume can be obtained. During quiet breathing it is preferable to calculate the VM coefficients on this tested run itself. Moreover, when the inspiratory volumes are considered it is, according to our results, better to use the corresponding inspiratory VM coefficients. When expiration is considered one should use expiratory coefficients. During VC manoeuvres the best estimation of mouth volume was obtained when calibration factors were adapted to each of the four quarters of the VC. Since the two compartment model is not valid through large lung volumes [14, Deschepper *et al.*, unpublished observations], the very good estimation of mouth volume obtained by the MLR method implies that in these instances the pairs of calibration factors cannot be used to calculate volume partitioning of RC and ABD. The negative abdominal VM coefficient, obtained in some body positions at 75–100% VC together with the large inter- and intra-individual differences of the VM coefficients calculated from VC manoeuvres, illustrate that some VM coefficients have a mathematical value (*i.e.* optimal estimation of mouth volume), but are physiologically meaningless (*i.e.* estimating volume partitioning).

Loveridge *et al.* [9] reported that, using the MLR method, the true contributions of RC and ABD cannot be revealed since this method assigns the greatest VM coefficient to the variable that correlates best with mouth volume. During VC manoeuvre, the correlation between RC and V_M was indeed higher than the correlation between ABD and V_M and, therefore, the greatest value was assigned to the RC VM coefficients. However, during quiet breathing both RC and ABD correlated accurately with the V_M (r>0.97), hence no preference is assigned to one of them, so that the VM coefficients can apparently be used to estimate volume partitioning as stressed by other authors [7, 11]. As a control we compared, at FRC, the ISV calibration coefficients with the VM coefficients obtained with the MLR method. In the present experiment four out of ten data points fell within the range where RC displacement relative to ABD is over- or underestimated by 10%. However, three out of ten fell outside the range where RC displacement relative to ABD displacement is over- or underestimated by 20%.

When used for estimation of volume partitioning the MLR method has to be considered as a semiquantitative method and is only valuable when a good correlation between V_M and both RC and ABD changes exists, *i.e.* when only two degrees of freedom are involved during breathing. The latter situation occurs mostly during quiet breathing, and is seldom present during VC.

We conclude that the MLR method is a good single posture calibration technique to estimate mouth volume from RC and ABD Respitrace signals. In order to obtain the best estimate one should calibrate on the respiratory manoeuvre itself. When this manoeuvre is a VC it is better to adapt the VM coefficients to the corresponding degree of lung inflation. However, it is important to realize that some of the calibration factors (*i.e.* those which are calculated on VC manoeuvres) have no physiological meaning and can not be used to study volume partitioning.

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Effet du volume respiré et de la position sur la calibration du pléthysmographe d'induction respiratoire, étudié par régression linéaire multiple. J.A. Verschakelen, K. Deschepper, I. Clarysse, M. Demedts.

RÉSUMÉ: La précision du pléthysmographe d'induction respiratoire (Respitrace) pour l'estimation des modifications de volumes pulmonaires au cours de la respiration calme et des manoeuvres de capacité vitale, a été évaluée en utilisant une variante de la technique de régression linéaire multiple (MLR). Nous avons appliqué cette technique successivement à la respiration calme, à la capacité vitale globale, et séparément à chacun de 4 quarts de la capacité vitale. Ceci a été fait dans six positions corporelles différentes. La meilleure estimation des volumes courants a été obtenue quand les facteurs de calibration, calculés au cours de la respiration calme, ont été utilisés. La meilleure estimation de la capacité vitale a été obtenue quand les facteurs de calibration étaient adaptés au niveau d'inflation pulmonaire. Ces résultats indiquent que le Respitrace, utilisant une méthode de calibration à régression linéaire multiple en une seule position, mesure de façon précise les volumes courants et la capacité vitale à la bouche. La précision de la méthode de régression linéaire multiple pour estimer les contributions respectives de la cage thoracique et de l'abdomen, a été validée par comparaison avec des facteurs de calibration isovolume. Les deux techniques ont donné des résultats très semblables pendant la respiration aux volumes courants. Les facteurs de calibration en régression linéaire multiple peuvent être dépourvus de signification physiologique, c'est-à-dire pour la répartition des volumes, quand ils sont calculés à partir de manoeuvres de capacité vitale, dans lesquelles plus de deux degrés de liberté sont en cause.
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