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A NEW METHOD FOR THE MEASUREMENT OF RIB CAGE AND ABDOMINAL VOLUME CHANGES

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ABSTRACT

Principle and instrumentation of two part body plethysmography (TBPG) are presented in this paper. This new method is employed for the separate measurement of rib cage and abdominal volume changes during breathing. The experimental results indicate that TBPG is more appropriate to analyse the respiratory mechanics than the past methods.

1. Introduction

Respiration is dependent on neural discharges which originate in the lower brain (medulla and pons) and are transmitted the respiratory muscles. The movement of repiratory muscles of chest wall changes the dimensions of thoracic and abdominal cavities. These volumetric changes are then transmitted to lungs. Chest wall includes rib cage, diaphragm and abdomen of which volume change is equivalent to the volumetric change due to the diaphragm movement. These volume changes are approximately proportional to the consequent changes of rib cage and abdominal anterior-posterior diameters as well as circumference changes.

MEAD and KONNO (1967) have presented a method for the measurement of rib cage and abdominal volume contributions to the total lung volume change in static state. WADE (1954) has measured the movements of thoracic cage and diaphragm in respiration by means of mercury tube strain gauge and X-ray kymograph. BERGOFSKY (1964) has constructed body plethysmograph box in the shape of diaphragm and measured the relative contributions of rib cage and diaphragm. AGOSTONI (1965) has also measured rib-cage volume change by the same method as WADE. The abdominal volume change has been estimated from the difference between lung volume and rib cage volume changes. As yet, however, the chest wall mechanics has never been clear.

Two part body plehtysmograph is an apparatus for the measurement of rib cage and abdominal volume contributions to the total lung volume change in dynamic state, that is, air flow exists in trachea. Both volume contributions are estimated from the anterior-posterior diameter changes of rib cage and abdomen which are calibrated from the total lung volume change.

From the results of the new method described here, it would be able to use broadly for the measurement of the respiratory mechanics.

2. Two part body plethysmography

2.1 Chest wall mechanics

Chest wall includes rib cage, diaphragm and abdomen which move actively or passively in accompanying with lung volume change. Volume relationships of these respiratory organs are expressed by the following equation,

$$\begin{aligned} V_{rs} = V_l = V_w &= (V_{rc} + V_{di\cdot ab}) = (V_{rc} + V_{di}) \\ &= (V_{rc} + V_{ab}) = (\alpha M_{rc} + \beta M_{ab}) \end{aligned} \tag{1}$$

where V_{rs}: volume change of the whole respiratory system, V_l: lung volume change, V_w: chest wall volume change, V_{di}: diaphragmatic volume change, V_{rc}: rib cage volume change, V_{ab}: abdominal volume change, M_{rc}: rib cage anterior-posterior displacement, Mab: abdominal anterior-posterior displacement, α: rib cage respiratory displacement coefficient and β: abdominal respiratory displacement coefficient.

In the static (airway closed) state the respiratory volume change measured by spirometer (V) is considered to be equal to V_l or V_w. But V is not equal to V_l or V_w, strictly speaking, when the air flow exists in trachea and the causal alveolar pressure expands or compresses the gas in lung.

During inspiration, the total lung volume $\bar{V}_l$ is expressed by the equation,

$$\begin{aligned} \bar{V}_l &= V_0 + \int |\dot{V}| dt - \Delta V_l \\ &= V_0 + \int |\dot{V}| dt - \frac{\bar{V}_l P_A}{P_0} \\ &= V_0 + \int |\dot{V}| dt - \frac{(V_0 + V_w) P_A}{P_0} \\ &= V_0 + V_w \end{aligned}$$

where

V_0: lung volume at the end of expiration,
$\dot{V}$: air flow velocity (positive at expiration and negative at inspiration),

ΔV_l: volume expansion of the gas in lung caused by alveolar pressure change,
P_A: alveolar pressure change, and
P_0: atmospheric pressure.

By the substitution of $\int|\dot{V}|dt=V$, $P_A=P_a-P_0$ and $P_a=kP_0$ $(0<k<1)$,

$$
\begin{aligned}
V_w&=\frac{(P_0V-V_0P_A)}{(P_0+P_A)}\\
&=\frac{P_0V-(P_a-P_0)V_0}{P_a}\\
&=\frac{V-(k-1)V_0}{k}\\
r_i&=\frac{V_w}{V}=\frac{V-(k-1)V_0}{kV}
\end{aligned}
\tag{2}
$$

where

P_a: alveolar pressure during inspiration,
k: alveolar pressure change rate during inspiration, and
r_i: ratio of chest wall volume change to the inhaled volume.

On the other hand, during expiration,

$$
\begin{aligned}
\bar{V}_l&=V_0'-\int\dot{V}dt-\Delta V_l'\\
\bar{V}_l&=V_0'-V_w=V_0'-V-\frac{(V_0'-V_w)P_A}{P_0}\\
V_w&=\frac{(P_a'-P_0)V_0'+P_0V}{P_a'}\\
r_e&=\frac{V_w}{V}=\frac{(k'-1)V_0'+V}{k'V}
\end{aligned}
\tag{3}
$$

where $P_a'=k'P_0=P_A+P_0$ $(k'>1)$,

V_0': lung volume at the end of inspiration,
$\Delta V_l'$: volume compression of the gas in lung caused by alveolar pressure change,
P_a': alveolar pressure during expiration,
k': alveolar pressure change rate during expiration, and
r_e: ratio of chest wall volume change to the exhaled volume.

Relationships between the alveolar pressure, tidal volume and lung volume changes based on the equation (2) and (3) are shown in Fig. 1, (a) to (d). The shaded portion of the figures indicates the actual volume-pressure relationship in the respiratory system. The results measured by body plethysmograph are also

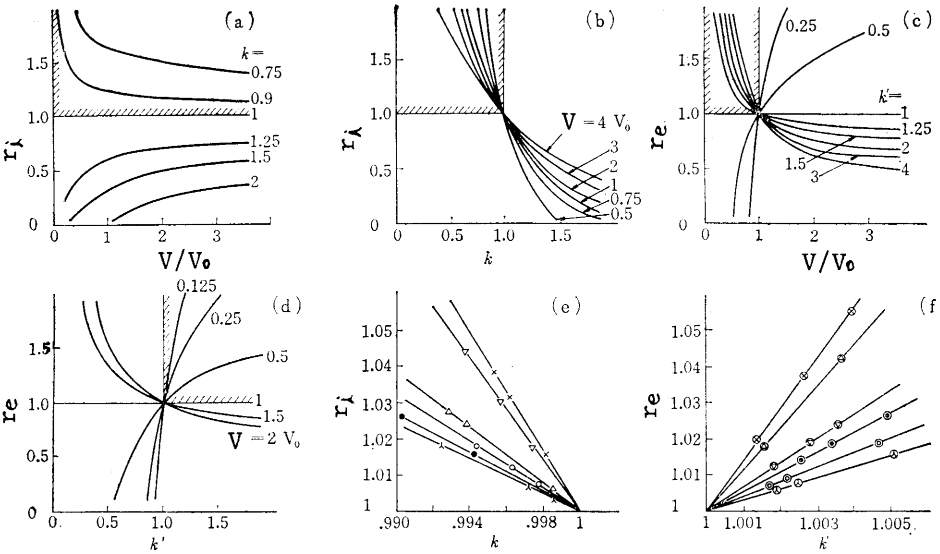


Fig. 1. Relationships of alveolar pressure, tidal volume and lung volume changes based on the equation (2) and (3).

(a), (c) : k (k') is considered as a parameter.
(b), (d) : V is considered as a parameter.
(e), (f) : are measured by body plethysmograph.

▽ : V =	330 cc	V_0 = 2 035 cc	○ : V =	265 cc	V_0 = 3 290 cc
• :	660 cc		⊙ :	530 cc	
⅄ :	1 320 cc		◎ :	795 cc	
× :	330 cc	V_0 = 2 495 cc	⊗ :	265 cc	V_0 = 3 950 cc
△ :	660 cc		⊘ :	530 cc	
○ :	990 cc		⊛ :	1 060 cc	

shown in Fig. 1, (e) and (f). Actually, V is not equal to V_l or V_w and yet the values of r_i and r_e are not more than 1.05. Gaseous volume change depends on the atmospheric temperature as shown in Charles' law. But it was not considered about the temperature effect on the analysis of chest wall mechanics since the ventilatory gaseous temperature was nearly kept at the body temperature; 37±2°C. The error due to temperature was not more than 1% in the range of 37±2°C (MINAMITANI 1971, 1972).

2.2 Method and Instrumentation

The chest wall volume change affects the rib cage and abdominal volume changes which are given by a linear approximation with the outward displacements as shown in equation (1). In a real system, the respiratory displacement coefficients

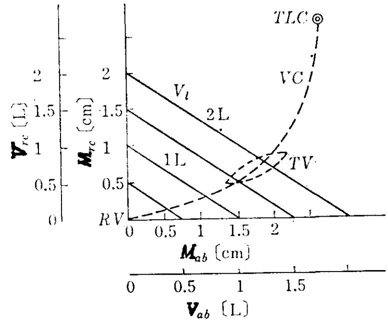


Fig. 2. Relationships of rib-cage and abdominal volume changes and their displacements. Slopes represent iso-lung volumes.

TLC: (total lung capacity)
VC: (vital capacity)
RV: (residual volume)
TV: (tidal volume)
$\alpha = 1$L/cm
$\beta = 0.67$L/cm

are unknown so that estimation of the volume changes has been done by means of extrapolation as shown in Fig. 2.

The signal of abdominal displacement M_{ab} is displayed on X axis of $X-Y$ recorder while rib cage displacement M_{rc} on Y axis. The residual volume level (RV) is considered as the original point of the displacement curve.

In the closed airway system the lung volume is kept constant so that the volume change of abdomen is equal to that of rib cage but their signs are opposite each other. The volume curve of V_{rc} and V_{ab} shows a negative gradient line which represents iso-lung volume. The displacement M_{rc} and M_{ab} are related with V_{rc} and V_{ab} by equation (1). Thus, the curve of M_{rc} and M_{ab} also shows the negative gradient line which represents the same iso-lung volume line. By repeating this process at known increments of lung volume the corresponding curve of M_{rc} and M_{ab} can be given on $X-Y$ plane. The extrapolated values of the negative gradient lines on X and Y axes represent the rib cage and abdominal volume contributions, that is $V_{rc}=\alpha M_{rc}$ ($M_{ab}=0$), $V_{ab}=\beta M_{ab}$ ($M_{rc}=0$). The respiratory displacement coefficient α and β are given by the ratio of the lung volume to the displacement M_{rc} and M_{ab} at the intersecting points of both axes and iso-lung volume lines. In Fig. 2, the respiratory displacement coefficients are $\alpha=1$ L/cm and $\beta=0.67$ L/cm.

On the other hand, the lung volume varies in the open airway system so that rib cage and abdominal diameters are extended or reduced during respiration. The volume changes of rib cage and abdomen show the volume change curves (VC) which cross the iso-lung volume lines. Since, as defined in equation (1), the displacement of chest wall should be in the fixed relationship to the volume change, the displacement M_{rc} and M_{ab} show the same as the volume change curves. If

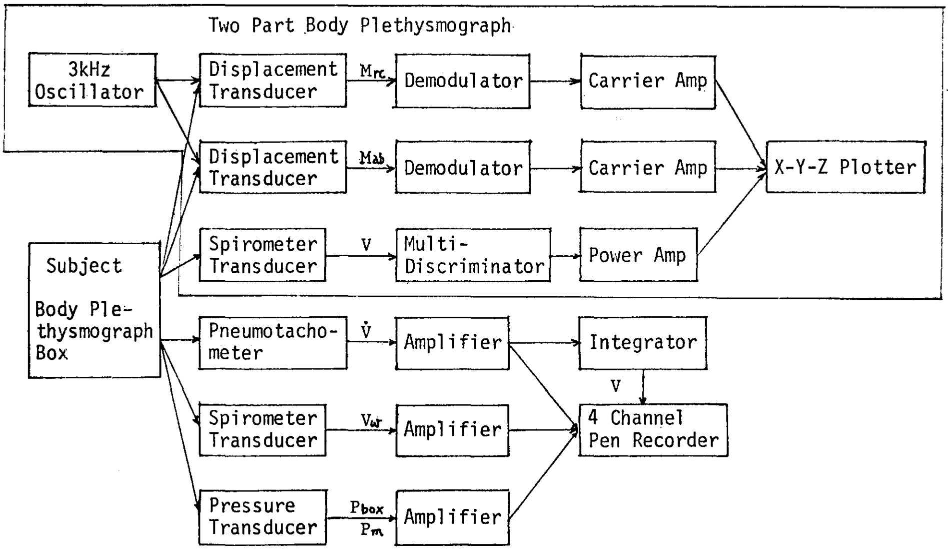


Fig. 3. Block diagram of two part body plethysmograph and supplementary apparatus

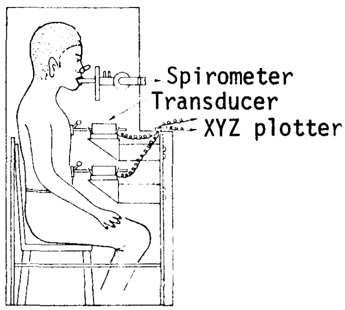


Fig. 4. Setting position of displacement transducer

it is marked by a signal which indicates a certain constant volume level such as 1L, 1.5L, 2L, on the curves of M_{rc} and M_{ab} during respiration, a set of iso-volume points can be shown on the curves. From the results the negative gradient line can be obtained. By repeating the same process at the other constant volume levels, another isovolume lines can be given. Estimation of rib cage and abdominal volume changes has been done from the intersections of both axes and iso-lung volume lines. The respiratory displacement coefficient α and β are obtained by the same way as mentioned above.

The total lung capacity (TLC), residual volume (RV) and lung volume changes

(VC) are measured by spirometer (V), instead of V_l or V_w in this method.

Fig. 3 shows the block diagram of two part body plethysmograph and supplementary apparatus. Fig. 4 shows the setting position of displacement transducers which are set on midway between the right nipple line and midline at the nipple level for rib cage and just above the umbilicus for abdomen.

2.2.1 Displacement transducer

Differential transformer type is used for a displacement detector composed of three coils and a permalloy core. Table 1 shows the size of transducers and Fig. 5 gives a circuit diagram of Wien bridge type oscillator and output signal detector. 3 kHz current is applied to the central primary coil. Output signals are induced to the secondary coils L_1 and L_2 accompanying with the core movement. The voltage differece of both signals from the coils ($E_1 - E_2$) are rectified and recorded. Setting of the transducers on rib cage and abdominal wall has been done by sucker and plaster for assurance. Fig. 6 shows an output characteristic of the transducer. The minimum detectable displacement is 0.2 mm, and the linearity of 5 cm displacement can be obtained for the rib cage displacement as well as 7 cm for abdomen.

Table 1. Size of displacement transducers

	coil inner diameter	coil length	turn	transducer length	core length
No. 1	1.5cm	2.5cm	3000	7.5cm	5.0cm
No. 2	1.5cm	3.5cm	3500	10.5cm	7.5cm

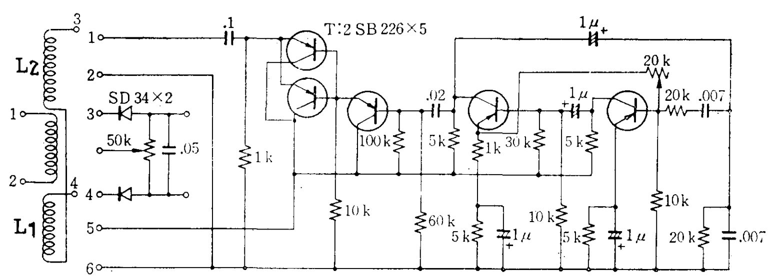


Fig. 5. 3kHz oscillator and output signal detector used for a transducer

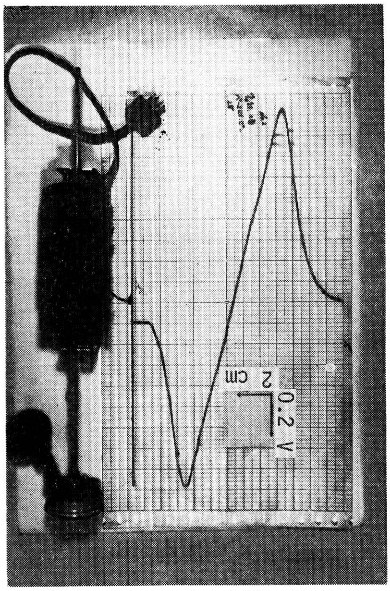
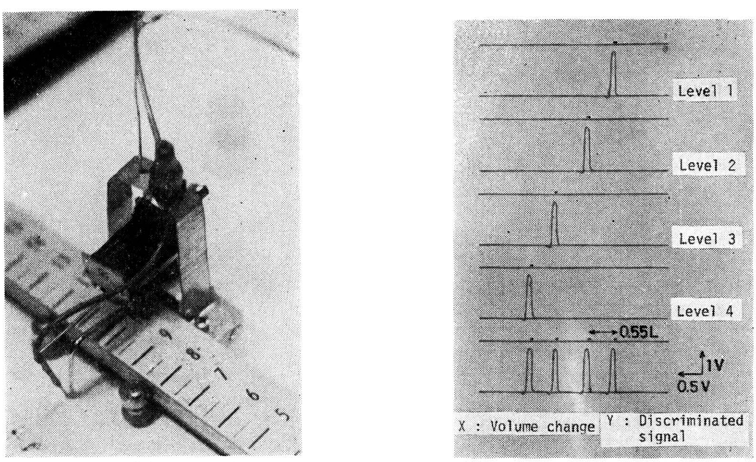


Fig. 6. Output characteristic of Displacement transducer

2.2.2 *X-Y-Z* plotter

As shown in Fig. 7 (a), *X-Y-Z* plotter is a modified type of $X-Y$ recorder on which another colored pen, *Z* plotter, is set. It is possible to describe $X-Y$ in-



(a) (b)

Fig. 7. *X-Y-Z* plotter and its input-output characteristics.

formation with the relative Z signal. In experiment, X and Y signals are given by outputs of displacement transducers. Z signal pulse is also used from discriminating the volume signal of spirogram. The response time of Z plotter is 10 msec with 55 mV driving power.

In Fig. 7 (b), the volume signal of spirogram is displayed on X axis and the discriminated pulse of Z signal is on Y axis. The dotted points in the figure show the Z plotting of pulse signals while X axis displays the volume signal. Levels 1 to 4 represent the discrimination levels of volume signal where each interval between the levels is given by nearly 0.55L

By using the output of a relaxation oscillator time mark recording can be done on the tracings of $X-Y$ information.

2.2.3 Four channel volume discriminator

Fig. 8 shows a four channel volume discriminator which originates the constant volume signals. The output of helical potentiometer set on a spirometer is transfered to Schmitt circuits through buffer amplifiers. Input voltages to the

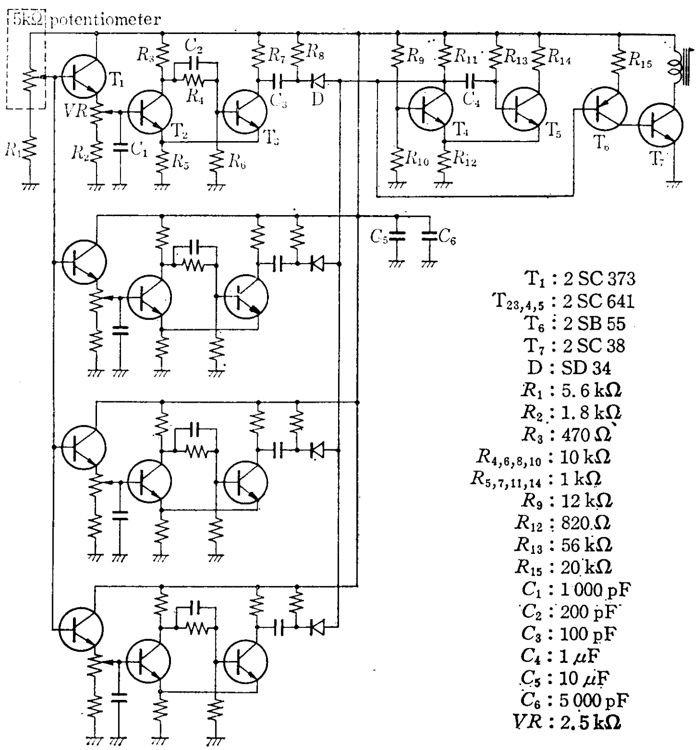


Fig. 8. Four channel multi-discriminator and Z plotting driver.

Schmitt circuits are varied by the level controller (VR). Discriminated pulse signals are obtained at inspiration and expiration during a single breathing but only negative pulse is useful for the actual Z plotting because of hysteresis of Schmitt circuit. By changing the polarity of applied voltage of the spirometer, the volume discrimination is possible either at inspiration or at expiration. Discriminated pulse sequences are amplified by a power amplifier for driving the $X-Y-Z$ plotter

3. Results

Both measurements can be done in static and in dynamic states. The measurements for suspected airway disease by applying air flow resistances were also made by the dynamic method and compared with the results of normal state.

After setting the apparatuses, the static measurement is done by shutting the cock of spirometer at any volume level between RV and TLC in order to hold lung volume constant and changing slowly rib cage and abdominal anterior-posterior diameters. At that time the subjects must keep the pressure in mouth within $\pm 20\ cmH_2O$ to avoid influences of gas compression and expansion in lung.

For the dynamic measurement the subjects must breathe up to their maximum ($RV-TLC$) at the begining. After that, they must be carried out various movements of their rib cage and abdomen. The measurements with the air flow resistant pieces are also done by the same way. Diameters of the pieces are 0.55 cm ($R_1=15.5\ cmH_2O/L/sec$, at $\dot{V}=0.5\ L/sec$) and 0.35 cm ($R_2=45.5\ cmH_2O/L/sec$, at $\dot{V}=0.5\ L/sec$) whearas normal mouthpiece has 1.1 cm in diameter.

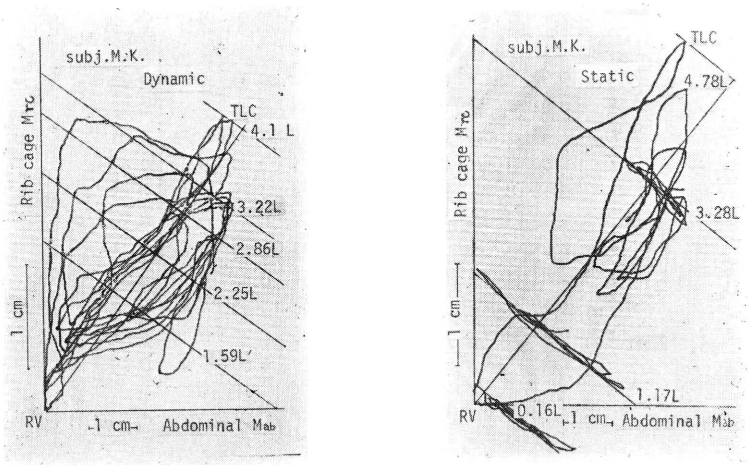
subj.	Yrs.		H [cm]	W [kg]	Lrc [cm]	Lab [cm]	Max ΔA-P [cm]	
H. M.	26	♂	172	63	89	73	rc3.03	ab4.98
M. K.	22	♂	170.8	65.5	98	81	2.87	4.01
A. F.	23	♂	167.5	53	81.5	67	3.23	2.98
Y. H.	21	♂	169	65	93	81	3.52	2.79
O. Y.	22	♂	160	52	78	63.5	2.53	4.37
S. S.	22	♂	168	58	87	72.5	3.39	3.48
F. T.	22	♂	175	63	90	77	2.75	4.63
Y. K.	24	♂	170	57	89	73	3.46	3.79
K. M.	22	♂	165	59	92	83.5	4.16	4.46
M. K.	23	♂	168	53	88	76	2.50	3.01
K. Y.	23	♂	165	56	89	75	2.22	2.81
N. S.	24	♂	165	53	80	66	1.23	2.90

Table 2. Physical characteristics of twelve subjects. Rib cage and abdominal circumferences are measured at FRC (Functional Residual Capacity)

H: height, W: weight, L_{rc} and L_{ab}: rib cage and abdominal circumferences and MaxΔ A−P: maximum anterior-posterior diameter change.

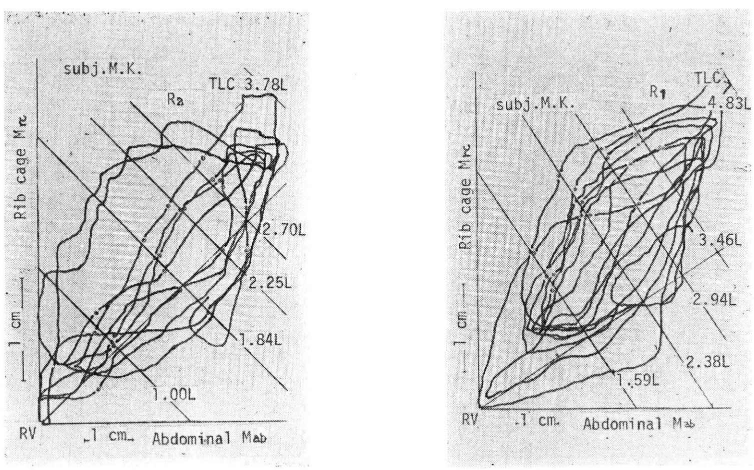
The physical characteristics of twelve subjects are presented in Table 2, i.e., height, weight, rib cage and abdominal circumferences measured at the functional residual capacity level (*FRC*) and maximum anterior-posterior displacements of rib cage and abdomen.

Figs. 9 and 10 show the results of rib cage and abdominal volume measure-



(a) static (b) dynamic

Fig. 9. Anterior-posterior displacements of rib cage and abdomen and their volume contributions measured by two part body plethysmograph.



(a) R_1: 15.5 $cmH_2O/L/sec$ (V=0.5 L/sec) (b) R_2: 45.5 $cmH_2O/L/sec$ (V=0.5 L/sec)

Fig. 10. Measurements of rib cage and abdominal displacements with the air flow resistant pieces.

ments. The values of iso-lung volumes and total lung capacity were correctly checked from the spirogram. It should be noted that each of iso-lung volume lines has a negative gradient. The decreased total lung capacity (*TLC*) shown in Fig

subj.	static		dynamic		with R_1		with R_2	
	α[L/cm]	β	α[L/cm]	β	α[L/cm]	β	α[L/cm]	β
H. M.	1.18	0.3	1.17	0.24	1.16	0.28	1.03	0.32
M. K.	0.92	0.35	0.94	0.33	0.72	0.34	0.68	0.33
A. F.	0.94	0.40	0.84	0.34	0.83	0.31	0.75	0.22
Y. H.	1.15	0.32	0.95	0.44	0.85	0.32	0.78	0.23
O. Y.	0.90	0.40	0.89	0.38	0.79	0.43	0.49	0.60
S. S.	0.79	0.42	0.75	0.48	0.72	0.48	0.66	0.48
F. T.	1.13	0.36	1.09	0.36	0.78	0.45	0.70	0.40
Y. K.	1.05	0.58	1.03	0.52	0.93	0.38	0.84	0.43
K. M.	1.93	0.27	1.41	0.26	0.81	0.33	0.79	0.36
M. K.	1.13	0.49	1.125	0.47	1.01	0.49	0.86	0.50
K. Y.	0.88	0.72	0.86	0.69	0.83	0.70	0.74	0.68
N. S.	1.90	0.46	1.875	0.46	1.12	0.59	0.85	0.55

Table 3. Displacement coefficients of rib-cage and abdomen.

subj.	static contri./cm		dynamic contri./cm		with R_1 contri./cm		with R_2 contri./cm	
	A	B	A	B	A	B	A	B
H. M.	79.7%	20.3%	83.0%	17.0%	80.5%	19.5%	76.3%	23.7%
M. K.	72.4	27.6	74.0	26.0	67.9	32.1	67.3	32.7
A. F.	70.15	29.85	71.2	28.8	72.8	27.2	77.3	22.7
Y. H.	78.2	21.8	68.3	31.7	72.6	27.4	77.2	22.8
O. Y.	69.2	30.8	70.1	29.9	64.75	35.25	45.0	55.0
S. S.	65.3	34.7	61.0	39.0	60.0	40.0	57.9	42.1
F. T.	75.8	24.2	75.2	24.8	63.4	36.6	63.6	36.4
Y. K.	64.4	35.6	66.4	33.6	70.9	29.1	66.1	33.9
K. M.	87.7	12.3	84.4	15.6	71.05	28.95	68.7	31.3
M. K.	69.75	30.25	70.5	29.5	67.3	32.7	63.2	36.8
K. Y.	55.0	45.0	55.4	44.6	54.25	45.75	52.1	47.9
N. S.	80.5	19.5	80.1	19.9	65.5	34.5	60.7	39.3
Mean	72.3	27.7	71.6	28.4	67.6	32.4	64.6	35.4

Table 4. Volume contributions of 1 cm displacements of rib-cage and abdomen to the total volume change.

$$A=\frac{V_{rc}}{V_{rc}+V_{ab}}=\frac{\alpha M_{rc}}{\alpha M_{rc}+\beta M_{ab}}$$

$$B=\frac{V_{ab}}{V_{rc}+V_{ab}}=\frac{\beta M_{ab}}{\alpha M_{rc}+\beta M_{ab}}$$

$$(M_{rc}=M_{ab}=1\ \mathrm{cm})$$

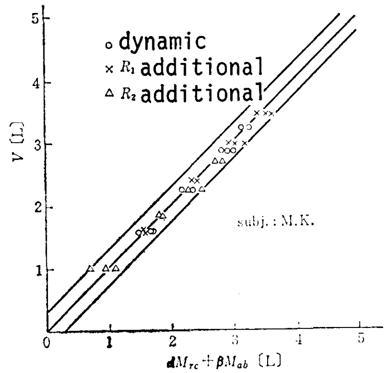


Fig. 11. Comparison of direct and indirect estimates of lung volume change (relationship between V and $\alpha M_{rc}+\beta M_{ab}$)

9 (b) and Fig. 10 (b) would be caused by imperfect inhalation.

Rib cage and abdominal respiratory displacement coefficients of each subject are presented in Table 3. Table 4 represents the volume contributions of rib cage and abdomen to the total volume change when each part is moved in 1 cm. The respiratory displacement coefficients measured by dynamic method are nearly equal to the coefficients by static method and then we could find that dynamic method is more appropriate than static method.

Decreasing the rib cage respiratory displacement coefficient due to the additional resistant piece is meant that rib cage must be moved more excessively to ventilate the same volume of lung than the normal state. On the contrary abdominal respiratory displacement coefficient is not always decreased as the resistance increased.

The means of the volume contributions of rib cage and abdomen are accounted for 71.6% and 28.4% of the total volume change (Table 4). Rib cage contribution is decreased and abdominal contribution is increased as the resistance increased. Fig. 11 shows the comparison of V and $\alpha M_{rc}+\beta M_{ab}$ and its dispersion is given by $V=(\alpha M_{rc}+\beta M_{ab})\pm 0.3\text{L}$.

4. Discussion

Respiratory displacement coefficients measured by dynamic method is smaller than the static ones in spite of no time delay between volume change (V) and displacements (M_{rc}, M_{ab}) as well as small change of the alveolar pressure ($r_i=r_e=1$). It is supposed that rib cage and abdominal muscles are in action and the anterior-posterior displacements become larger than the static state. The measurement shows that at the total lung capacity level (TLC) the anterior-posterior diameter of rib cage is more increased and the transversal diameter is more reduced in active state (airway open) than in the static relaxed state (airway closed). Amount of the increase is given by 0.58 cm as well as amount of the decrease 0.35 cm in the average for twelve subjects. At the residual volume level (RV) the anterior-posterior diameter of rib cage is also more increased and the transversal diameter is more reduced in active state than in the static relaxed state. Amount of the increase presents 0.52 cm as well as amount of the decrease 0.32 cm.

The same observation is obtained on the abdominal diameters in active state. Amounts of the increase of anterior-posterior diameter present 0.45 cm at TLC and 0.42 cm at RV in the average for twelve subjects. On the other hand, amounts of the decrease of transversal diameter present 0.20 cm at TLC and 0.27 cm at RV. The similar results are shown in the literature (MEAD and KONNO 1967). Both of rib cage and abdominal displacements in active state are more increased than the relaxed state values and, therefore, the respiratory displacement coefficients measured by dynamic method would be more decreased than the static ones. Maximum transversal displacement is 0.6cm at abdomen, which could be neglisible small compared with anterior-posterior displacement. In this study the measurements of anterior-posterior displacements are only considered in the result.

Respiratory displacement coefficient of rib cage tends to decrease as the air flow resistance increases. It is apparently indicates that rib cage displacement is significantly increased with increasing of the air flow resistance. Abdominal displacement coefficient is generally increased with the air flow resistance increasing but the reason of decreasing the coefficient is hardly explained at this stage of experiments. It is supposed that abdominal wall is more flexible than rib cage so that increasing and decreasing of abdominal coefficient can be seen.

According to the anatomical observation of KEITH (1909), the area of diaphragm in contact with the lung constitutes approximately 28% of the lung's external pleural surface. MEAD and KONNO (1967) refered that the abdominal volume contribution was 28–30% of the total lung volume change in static state. In this measurement, it is approved that the abdominal volume contribution is 28.4% in the average given in Table 4. Disphragm movement, however, affects the rib cage displacement and it can not move so uniform that a plane moves. Dispersion of abdominal displacement coefficient would be estimated by closely studying on this matter. It is also supposed that the respiratory displacement coefficients of rib cage and abdomen would depend on the compliances of both parts. These coefficients must be therefore discussed with the relationships between driving pressure and lung volume change, intrathoracic pressure and rib cage volume change, and abdominal pressure and abdominal volume change for the further reliable estimation of rib cage and abdominal mechanics.

Measurements have been done only in sitting position and expiratory phase so that it is necessary to discuss the coefficient variations caused by postures and respiratory conditions.

5. Conclusion

The new method described herein gives good results which have been obtained by the dynamic method instead of anatomical or static method. Average volume contributions of rib cage and abdomen per 1cm displacement are 71.6% and 28.4% of the total lung volume change. These volume contributions is affected by the additional airway resistances, especially rib cage contribution is remarkably decreased as airway resistance increased. Amount of change in these volume contributions can be expressed by,

$$\text{Rib cage } 67.6\%,\ \text{Abdomen } 32.4\%:\ R_1=15.5\ \mathrm{cmH_2O/L/sec}$$

$$\text{Rib cage } 64.6\%,\ \text{Abdomen } 35.4\%:\ R_2=45.5\ \mathrm{cmH_2O/L/sec}$$

Some disease information could be found from the standard values and the deviations of rib cage and abdominal respiratory displacement coefficients. By using two part body plethysmograph and pressure transducers it is able to measure hereafter the rib cage and abdominal compliances. This new method is useful to analyse the respiratory mechanics in biophysics, hygiencs, human engineering and the clinical fields.

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