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Research Article

# A RAPID PLETHYSMOGRAPHIC METHOD FOR MEASURING THORACIC GAS VOLUME: A COMPARISON WITH A NITROGEN WASHOUT METHOD FOR MEASURING FUNCTIONAL RESIDUAL CAPACITY IN NORMAL SUBJECTS [1]

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In general, two principles have been employed in the measurement of the volume of gas in the lungs. The dilution techniques, using either a closed (rebreathing) or open (non-rebreathing) system are the most commonly used; the physical methods, based on Boyle's law relating pressure and volume, require special equipment and have been used relatively infrequently. This report presents a rapid, practical physical method for measuring lung volumes plethysmographically; it has been found to give reproducible values which, in healthy subjects, do not differ significantly from values obtained by the dilution method of Darling, Cournand, and Richards (1).

Two types of physical (pneumatometric) techniques have been described previously, both based on Boyle's law. One of these is the decompression method used by Hitchcock, Edelmann, Shelden, and Whitehorn (2), Willmon and Behnke (3), and DeJours and Rahn (4); it has been used in experimental animals (5, 6) as well as in normal man. In the decompression method, the pressure about the body and in the trachea and lungs is raised equally above atmospheric so as to compress the gas inside the lungs and outside the body. The total number of molecules is thereby increased in all parts of the lung in free communication with an open airway. The pressures in the chamber and in the trachea are then released simultaneously. During return to normal atmospheric pressure, the amount of gas which flows out of the trachea is measured; this is the amount of gas which had been added to the lung gas by the previous increment of pressure. The pulmonary gas volume at atmospheric pressure can then be calculated by application of Boyle's law. Since the method measures the gas volume which flows in and out of the trachea during compression and decompression, it measures the volume of lung gas which is in communication with the trachea.

The other type, based on voluntary compression or decompression of lung gas, was described in principle by Pflüger in 1882 (7). It requires measurements of changes in alveolar gas pressure and volume while the subject makes voluntary respiratory efforts against a closed airway. It gives values for the volume of gas in the lungs and thorax, whether in free communication with the airway or not. Despite attempts by several investigators to devise an accurate and practical method, it has not been considered to be reliable for clinical or physiological use (8). The development of new methods for measuring and recording pressure changes led us to reinvestigate this technique.

## METHOD

The method used is based on Boyle's law that the volume of a gas varies in inverse proportion to the pressure to which it is subjected. At the beginning of the test, the subject has an unknown volume of gas in his chest; at either end-inspiration or end-expiration, when there is no air flow, the pressure of this alveolar gas is known to be atmospheric. If his airway is then occluded so that no pulmonary gas can escape, and he compresses the pulmonary gas by a voluntary expiratory effort, the pulmonary gas now has a new pressure and volume. The change in pulmonary gas pressure can be measured readily during airway occlusion since mouth pressure equals alveolar pressure in a closed system. The change in pulmonary gas volume can be measured by utilizing an air-tight body plethysmograph and a sensitive electrical capacitance manometer. From knowl-

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edge of the original pulmonary gas pressure and of the change in pulmonary gas pressure and volume, the original volume of gas in the chest can be calculated; the derivation of the thoracic gas volume equation is given below.

*Details of the method*

The subject enters and sits in an airtight chamber, the body plethysmograph (Figure 1), which has the dimensions of a telephone booth (9). The door is closed and the subject breathes the ambient air during the five-minute period of the test. Since the volume of the box is about 600 liters, the oxygen concentration would drop from 20.93 per cent to only about 20.7 per cent and the carbon dioxide concentration would rise from 0.04 per cent to only 0.25 per cent during the test period.

The pressure of the air in the plethysmograph, relative to atmospheric pressure, is measured by a sensitive Lilly capacitance manometer and is recorded on the horizontal axis of a cathode ray oscillograph (CRO).[2] The amplification is such that 0.025 cm. $H_2O$ pressure change produces a horizontal deflection of one inch on the screen; this corresponds to a volume change of 15 ml. in the 600-liter box. The system is calibrated directly in terms of a volume change, with the subject in the plethysmograph, by the rapid introduction and withdrawal of 30 ml. of air.

Immediately after the door is closed, the pressure in the box rises rapidly because air in the box is warmed and humidified by the subject. During this initial period, the box is vented periodically to the room outside by means of a solenoid operated valve until the pressure drift with the vent closed is so slight that it does not interfere with the measurement of the thoracic gas volume; this requires about two minutes. The subject then applies a nose clip and breathes through the mouthpiece-shutter system (*S*, Figure 1) similar to that described by Mead and Whittenberger (10). The solenoid-controlled shutter can be closed by the operator on the outside when it is desired to obstruct the flow of air into and out of the subject's lungs. At the end of a normal expiration, as judged by observing box pressure, the shutter is closed by the operator and the subject continues to make one or more respiratory efforts.

When the subject makes breathing motions against the closed shutter, he alternately compresses and decompresses the air within his chest by the action of his chest muscles. The pressure changes within the lung can be measured by means of a second electrical capacitance manometer which records pressure at the mouth on the pulmonary side of the closed shutter (*P*, Figure 1). In such a closed system, pressure at the mouth is considered to be the same as alveolar pressure if the subject's glottis remains open and his cheeks are held fairly rigid. Mouth pressure is recorded on the vertical axis of the cathode ray oscillograph (*O*, Figure 1). The sensitivity of this system is such that a 5 cm. $H_2O$ pressure change produces a vertical deflection of one inch on the CRO. With this recording system, during occlusion of the airway and continued breathing efforts, changes in pulmonary pressure are graphed continuously against changes in thoracic gas volume on the CRO and appear as a slanting line which can either be traced (Oscillotracer[3]) or photographed. The slope of this line is $\frac{\Delta P}{\Delta V}$.

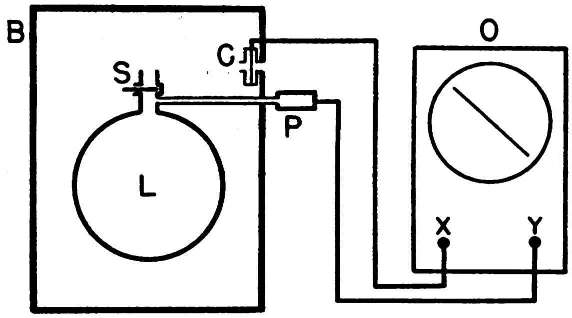


FIG. 1. DIAGRAM OF APPARATUS

S = shutter which occludes airway; L = lung; C = capacitance manometer to record pressure changes in the plethysmograph (which are proportional to change in body volume); P = capacitance manometer to record pressure changes in the mouth (which are equal to alveolar pressure when there is no airflow); O = cathode ray oscillograph with X and Y axes.

The subject may be requested to make one of two types of breathing efforts when the airway is obstructed: 1) The operator closes the shutter at the end of a normal expiration and the subject continues with the next inspiration until he senses that his breathing is obstructed. 2) The subject is asked to make respiratory efforts as though panting; the panting type of breathing is usually preferred because the pressure and volume changes are retraced very quickly several times on the screen and a representative slope is obtained. Furthermore, with the panting type of breathing, the intrathoracic pressure changes are smaller during the test period, and not unidirectional. In either case, after a rest period of a few seconds of unobstructed breathing, the shutter can be closed again and the measurement repeated; 4 to 5 determinations can be made easily in a minute and the average of the slopes is used in the calculations.

Unsatisfactory tracings result if the subject closes his glottis, since mouth pressure no longer equals alveolar pressure; in this case a horizontal line is produced on the CRO because box pressure changes while mouth pressure remains the same. Unsatisfactory tracings also result if the subject moves his cheeks with the breathing motions; in this case, the change in mouth pressure is less than alveolar pressure and lags in time because of a pressure fall across the trachea owing to air flow. This type of breathing is easy to detect visually; it can also be noted on the record which now consists of a loop instead of a straight line.

[2] Dumont CRO, type 304-A, which has satisfactory D. C. gain, persistent screen with flat tube face, bright line grid, and direct coupling of X and Y input.

[3] R. A. Waters, Inc., Waltham, Mass.

The pressure-volume changes can be recorded on a two channel ink-writer instead of on the CRO, but in this case the data can be plotted only after the test is over; thus an unsatisfactory record may be detected only after the subject has left the laboratory.

*Derivation of the thoracic gas volume equation for the plethysmographic method*

The record for measurement consists of a slanting straight line. The slope between two points is measured, one point representing initial pressure and volume and the other a final pressure and final volume. If $P_1$ is the initial pressure, $P_1 + \Delta P$ is the final pressure, $V_1$ the initial volume, and $V_1 + \Delta V$ the final volume, then from Boyle's law:

$$P_1V_1 = (P_1 + \Delta P)(V_1 + \Delta V) \quad (1)$$

Simplifying:

$$P_1 \Delta V + V_1 \Delta P + \Delta V \Delta P = 0 \quad (2)$$

Solving:

$$V_1 = -\frac{\Delta V}{\Delta P}(P_1 + \Delta P) \quad (3)$$

If $\Delta P$ is small compared to $P_1$, then $P_1 + \Delta P \rightarrow P_1$[4] and

$$V_1 = \frac{-P_1(\Delta V)}{(\Delta P)} \quad (4)$$

In this equation, $V_1$ is the initial thoracic gas volume or $V_{TG}$, and $P_1$ = 970 cm. $H_2O$, which is atmospheric pressure minus water vapor pressure.[5] Therefore, disregarding the sign:

$$V_{TG} = 970\frac{(\Delta V)}{(\Delta P)} \quad (5)$$

The slope of the record ($\lambda V_{TG}$) is the change in mouth pressure per unit change of box volume, or $\left(\frac{\Delta P}{\Delta V}\right)$. Then:

$$V_{TG} = \frac{970}{\lambda V_{TG}} \quad (6)$$

When the calibration factors are included, the final equation becomes:

$$V_{TG} = \frac{970 \times \text{box calibration}}{\lambda V_{TG} \times \text{pressure calibration}}$$

In practice the box calibration is usually 15 ml. per inch horizontal deflection and the pressure calibration is usually 5 cm. $H_2O$ per inch vertical deflection so that $\lambda V_{TG}$ would be 1.0 when the $V_{TG}$ is 2,910 ml. which is the most accurate range at these settings.

## RESULTS

### 1. *Accuracy of plethysmographic method*

Initial experiments were carried out to determine the accuracy with which known volumes of gas could be measured by the plethysmographic method. The apparatus was modified so that a subject seated inside the plethysmograph could increase or decrease his pulmonary gas volume by a known volume by inspiring from or expiring into a spirometer outside the plethysmograph. Thoracic gas volumes were measured first after a maximal expiration and then after stepwise inspiration from the spirometer. Then the experiment was repeated after the subject made a maximal inspiration and stepwise expirations into the spirometer. The results obtained in two subjects are as follows: The amount of air that was inspired from or expired into the spirometer on the outside ranged from 0.50 to 5.12 liters. The plethysmograph method measured the increment or decrement in the lung volume. In a total of 35 measurements, the difference of the means between spirometer volume and plethysmographic lung volume was 0.04 liter (S.D. ± 0.17 liter; S. E. ± 0.03 liter).

### 2. *Reproducibility of plethysmographic method*

The variation among repeated measurements in the same individual was checked by doing multiple determinations of the thoracic gas volume in each of three subjects. Subjects 1 and 2 were trained laboratory workers; subject 3 was an untrained patient with pulmonary arteriosclerosis. The number of measurements were 12, 12 and 23 in these three cases yielding mean values of 3.77, 2.87 and 4.31 liters; two standard deviations from the mean value represented an error of 4.8 per cent, 5.6 per cent, and 3.7 per cent of the mean value for the thoracic volume. Because of the ease in making repeated determinations, all values for thoracic gas volume in the remainder of this paper are the average of 3 to 5 individual determinations performed within a period of 1 to 3 minutes.

### 3. *Comparison of plethysmographic and dilution method in normal subjects*

Measurements of resting end-expiratory thoracic gas volume (plethysmographic method) and of FRC. (open circuit method of Darling, Cournand, and Richards [1]) were made in each of nine sitting subjects; measurements were usually made within an hour of one another. The subjects included three women and six men who ranged in age from 20 to 43 years. The results are shown in Table I. The mean values were 2.97 liters by

[4] As $\Delta P$ approaches zero, $P_1 + \Delta P$ approaches $P_1$, $\Delta P$ and $\Delta V$ each approach zero, but the ratio $\frac{\Delta V}{\Delta P}$ becomes the slope $\frac{dV}{dP}$, and the equation becomes $V_1 = \frac{-P_1\, dV}{dP}$.

[5] Water vapor saturated, when compressed, condenses to a liquid, so that its partial pressure is constant, and equal to 47 mm. Hg at 37° C.

TABLE I

*Comparison of resting end-expiratory thoracic gas volume measured by plethysmographic method and FRC measured by open circuit method in normal subjects*

| Subject | Age (yrs.) and sex | Height *inches* | Weight *pounds* | Thoracic gas volume (Plethysmographic) *liters* | FRC (Open circuit) *liters* | Plethysmographic minus Open circuit *liters* |
|---|---|---|---|---|---|---|
| PC | 23 F | 62 | 102 | 2.75 | 2.57 | +0.18 |
| MS | 22 F | 64 | 140 | 2.73 | 2.69 | +0.04 |
| MR | 34 M | 66 | 156 | 2.78 | 2.79 | −0.01 |
| GB | 32 M | 72 | 165 | 2.68 | 3.06 | −0.38 |
| DG | 43 M | 64 | 118 | 2.72 | 2.42 | +0.30 |
| ER | 35 M | 67 | 175 | 2.35 | 2.39 | −0.04 |
| RM | 32 M | 70 | 169 | 3.93 | 3.70 | +0.23 |
| RMM | 20 F | 64 | 116 | 2.46 | 2.73 | −0.27 |
| ABDB | 31 M | 75 | 199 | 4.30 | 4.35 | −0.05 |
| Mean | | | | 2.97 | 2.97 | 0.00 |
| | | | | | | S.D. ±0.22 |
| | | | | | | S.E. ±0.07 |

the open circuit method and 2.97 liters by the plethysmographic method; the standard deviation of the mean of the differences was ± 0.22 liter and the standard error of the mean of the differences was ± 0.07 liter. We conclude that in normal men and women, the open circuit method and the plethysmographic method measure essentially the same gas volume, the functional residual capacity.

4. *Effect of varying volumes of abdominal gas on the thoracic gas volume measured by the plethysmographic method.*

One of the principal objections to the plethysmographic method in the past has been that the gases in the gastro-intestinal tract may be compressed and decompressed along with the gas in the lungs by the voluntary efforts of the subject. By a modification of the technique just presented so that voluntary compression and decompression of the *abdomen* with an open glottis is used instead of respiratory efforts, we have been able to measure the volume of gas present in the abdomen (11); the average value in 60 subjects was 116 ml. This amount of gas could introduce only a very small error in the measurement of the thoracic gas volume by the plethysmographic technique. In order to study the effects of larger volumes of abdominal gas, we have introduced measured amounts of gas into the stomach and colon of normal subjects and studied the effect of this procedure on the value for thoracic gas volume measured by the plethysmographic method. The results (Table II) show that compressible gas volume was unaltered by the addition of large amounts of gas into the stomach and colon. This finding can be explained by one of two mechanisms: 1) The diaphragm was raised and we measured the unchanged total thoracic and abdominal gas volume. 2) The diaphragm was not raised and movement of the diaphragm did not compress and decompress the abdominal gas. On the basis of the data presented in this study we cannot tell which of these two mechanisms is effective when large amounts of gas are introduced into the gastro-intestinal tract.

TABLE II

*Effect of gas in stomach and colon on the measurement of resting end-expiratory thoracic gas volume by the plethysmographic method*

A. Effects of Adding Gas to Stomach

| Subject No. 1 Gas added *ml.* | Thoracic gas volume *L.* | Subject No. 2 Gas added *ml.* | Thoracic gas volume *L.* |
|---|---|---|---|
| Control | 4.39 | Control | 3.51 |
| +200 | 4.32 | +200 | 3.26 |
| +400 | 4.28 | +400 | 3.45 |
| +600 | 4.36 | +600 | 3.57 |
| +800 | 4.36 | +800 | 3.18 |
| | | +1,000 | 3.27 |

B. Effects of Adding Gas to Colon

| Subject No. 1 Gas added *ml.* | Thoracic gas volume *L.* | Subject No. 2 Gas added *ml.* | Thoracic gas volume *L.* |
|---|---|---|---|
| Control | 4.30 | Control | 3.37 |
| +300 | 4.45 | +300 | 3.47 |
| +600 | 4.47 | +600 | 3.28 |
| +900 | 4.45 | +900 | 3.42 |
| +1,200 | 4.35 | +1,200 | 3.14 |
| +1,500 | 4.78 | | |

## DISCUSSION

Many methods are available for measuring with reasonable accuracy the functional residual capacity of the lungs and a new method should have definite advantages over existing techniques if it is to become useful for physiological or clinical purposes. These are two major advantages of this new method using a body plethysmograph:

1. The test is the most rapid of present methods and requires no more than a few minutes of the patient's time. No gas samples are needed. The test is easy to perform, requires no unusual cooperation on the part of the subject and is safe. In normal subjects, it gives values which do not differ significantly from the values for FRC obtained by an open circuit washout method. The plethysmographic method can be repeated as frequently as desired and so can be used to follow rapid changes in FRC.

The test does require apparatus not usually found in a pulmonary function laboratory (two sensitive manometers, a body plethysmograph, a shutter and a cathode ray oscilloscope). However, in industrial health departments where it is desirable to make measurements on large numbers of employees, the method, despite the initial expenditure involved, may well be more economical than those involving longer periods of testing and many chemical analyses. Furthermore, the identical apparatus used for this measurement may also be used for the quantitative measurement of airway resistance (9), of pulmonary non-elastic tissue resistance (12), of pulmonary capillary blood flow (13), and of abdominal gas volumes (11).

2. Other methods for measuring FRC measure the volume of pulmonary gas in free communication with the airway. This technique measures the volume of gas within the thorax that is compressed and decompressed with expiration and inspiration. Use of this method simultaneously with a dilution method should permit accurate determination of the volume of non-ventilated gas and lead to a better understanding of this somewhat neglected subject.

## CONCLUSIONS

A new plethysmographic method for measuring thoracic gas volume is described. It is rapid, safe, uninfluenced by the usual quantities of abdominal gas, requires no gas samples for chemical analysis and has been found to give reproducible and accurate values which, in normal individuals, are essentially the same as those measured by the open circuit method of Darling, Cournand, and Richards (1). A major advantage of the new technique is that it measures the total volume of compressible gas in the thorax, whether in communication with the airway or not, and therefore should provide the basis for the quantitative measurement of non-ventilated gas.

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