

An accurate and rapid radiographic method of determining total lung capacity

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The accuracy and reliability of Barnhard's radiographic method of determining total lung capacity have been confirmed by several groups of investigators. Despite its simplicity and general reliability, it has several shortcomings, especially when used in large-scale epidemiological surveys. Of these, the most serious is related to film technique ; thus, when the cardiac and diaphragmatic shadows are poorly defined, the appropriate measurements cannot be made accurately. A further drawback involves the time needed to measure the segments and to perform the necessary calculations.

We therefore set out to develop an abbreviated and simpler radiographic method for determining total lung capacity. This uses a step-wise multiple regression model which allows total lung capacity to be derived as follows: posteroanterior and lateral films are divided into the standard sections as described in the text, the width, depth, and height of sections 1 and 4 are measured in centimetres, finally the necessary derivations and substitutions are made and applied to the formula $\hat{Y} = -1.41148 + (0.00479 X_1) + (0.00097 X_4)$, where \hat{Y} is the total lung capacity. In our hands this method has provided a simple, rapid, and acceptable method of determining total lung capacity.

The determination of total lung capacity (TLC) is helpful in the diagnosis of both restrictive and obstructive lung diseases. The methods most commonly used for determining this volume are the nitrogen washout, helium equilibration, and body plethysmography. However, none of these is entirely suitable for large-scale epidemiological surveys, mostly because complex and expensive equipment and sophisticated technical assistance are required. These and other drawbacks have prompted renewed interest in determining TLC from the chest film, a method that is both simple and inexpensive.

Early attempts to determine lung volumes from the chest film were made by Hurtado and Fray (1933). These workers combined planimetry with external measurements of chest size. Recently, methods for determining radiographic total lung capacity have compared volumes calculated from measurements of posteroanterior and lateral chest films with volumes obtained from the body plethysmograph. Rapid planimeter methods by Pratt and Klugh (1967) and by Harris, Pratt, and

Kilburn (1971) appear to have practical application. The ellipsoid method described by Barnhard, Pierce, Joyce, and Bates (1960) is fairly well accepted and, furthermore, has been confirmed as reliable in independent investigations by Loyd, String, and DuBois (1966), Reger and Jacobs (1970), and O'Shea *et al.* (1970).

Despite the simplicity of the ellipse method, it has several drawbacks, viz.:

1. In some instances the measurements made to assess the cardiac and diaphragmatic areas are intelligent estimates since the cardiac and diaphragmatic shadows are occasionally poorly defined, especially on the lateral film.

2. While little time is needed to take and develop the PA and lateral films, even an experienced measurer needs at least 15 to 20 minutes to make the necessary measurements. Another 5 to 10 minutes is necessary for the calculations despite the use of an electronic calculator.

Were it possible to lessen the number of measurements that are required to be made without suffering a significant loss in the way of

accuracy, much time could be saved. It therefore occurred to us that it might be feasible to derive an accurate estimate of the combined volume of the heart, diaphragmatic domes, lung blood, and lung tissue by using a standard multiple regression model. This paper describes a new and simplified adaptation of Barnhard's technique which uses the above principle.

METHODS

An understanding of the principles on which Barnhard's method is based is necessary before it is possible to appreciate the significance of the modifications that have been incorporated in the shortened method. Posteroanterior and lateral chest films taken at full inspiration in the standard fashion are required. Barnhard and his colleagues divided the thorax into a series of ellipses by means of horizontal sections. They expressed the area of each ellipse as $\frac{\pi}{4} w e$ with w as the width of the chest in the plane of the section and e its depth. Were the chest film to be divided into an infinitely large number of thin elliptical cross sections, the volume could be obtained readily by integration. Practical considerations, however, make it necessary to limit the number of sections used. Calculations are made on the assumption that each section is an elliptical cylindroid.

The chest is generally divided into five sections by six horizontal lines drawn on tracing paper placed over the posteroanterior film. The lines are drawn as follows (Fig. 1):

- (i) below the inner borders of the highest ribs,
- (ii) about 2.5 cm below i,
- (iii) about 2.5 cm below ii,
- (iv) at the upper border of the higher diaphragmatic segment,
- (v) midway between iii and iv,
- (vi) and finally between the lower limit of the costophrenic angles.

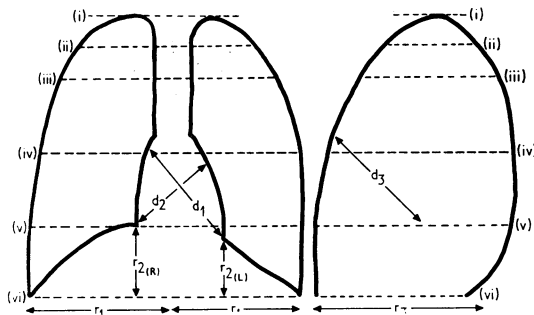


FIG. 1. Barnhard's method; measurements to be made on PA and lateral films.

The PA and lateral films are aligned under the tracing paper so that line iv is at the same level on both films. The other horizontal lines are then extended over the lateral film. The total volume of these five elliptical cylindroids is taken as $\frac{\pi}{4} \sum_1^5 w e h$,

where h was the sectional height, w was measured between the inner borders of the ribs, and e between the inner borders of the posterior ribs and the sternum (or a line drawn downward from the xiphoid process).

Each diaphragmatic segment is considered as one-eighth of an ellipsoid. The volume of the right is $\frac{\pi}{6} r_1 r_2(R) r_3$ and that of the left $\frac{\pi}{6} r_1 r_2(L) r_3$ where r_1 represents one-half of line vi over the posteroanterior film $r_2(R)$ and $r_2(L)$ the heights of the right and left diaphragm areas, and r_3 the length of line vi over the lateral film.

The heart is considered as a whole ellipsoid with a volume of $\frac{\pi}{6} d_1 d_2 d_3$. The line d_1 on the PA film is the greatest possible distance from the junction of the superior venous pedicle with the right antrum to the left heart border, usually where it meets the diaphragm. The line d_2 is drawn perpendicular to d_1 in such a position that it reflects the greatest distance between the right and left cardiac borders. On the lateral film and parallel to d_1 , d_3 is the greatest distance between the anterior and posterior borders of the heart. To compensate for the divergence of the x-ray beam, all linear measurements are reduced by 10%.

The lung parenchyma is assumed to occupy 130 ml. The blood volume is derived from the data in the paper of Barnhard *et al.* (1960).

TLC is then calculated in the following manner.

The expression $\frac{\pi}{4} \sum_1^5 w e h$ gives the volume of the whole thoracic cage. From this are subtracted:

- (1) $\frac{\pi}{6} r_1 r_2(R) r_3$, the volume of the right diaphragmatic segment
- (2) $\frac{\pi}{6} r_1 r_2(L) r_3$, the volume of the left diaphragmatic segment
- (3) $\frac{\pi}{6} d_1 d_2 d_3$, the volume of the heart
- (4) 130 ml, the volume of the lung parenchyma
- (5) V_p ml, the volume of the blood in the lungs.

The volume remaining after the necessary subtractions represents the total lung capacity.

Our study group consisted of 24 coal miners whose films all showed some evidence of simple pneumoconiosis. The group was selected firstly because previous work had shown no appreciable difference in TLC as determined by Barnhard's and the plethysmographic techniques and secondly, because the plethysmographic determinations of TLC for the entire group were known. The multiple regression model was $(Y = b_0 + b_1 X_1 + b_2 X_2 + \dots + b_5 X_5)$ where b_i equalled the weights in the regression equation and X_i were the

$w_i e_i h_i$ of each segment (taken from the PA and lateral) where w is the width and e is the depth of the chest in the plane of an elliptical cross section, and h is the height of a section. The plethysmographic TLCs of the 24 subjects were used to represent the dependent vector Y in solving for the b_i s in the equation (Steele and Torrie, 1960). Since the regression model used was a step-wise sequence, we had the opportunity to consider several equations using different combinations of film-measured segments as the independent variables. As a last but much needed exercise in the study, we determined the TLCs of the 24 subjects using Barnhard's ellipsoid method.

RESULTS

The TLCs of the 24 subjects as determined by Barnhard's ellipsoid were compared with the plethysmographic values and are plotted in Figure 2. As might be expected, the relationship was fairly consistent and a correlation coefficient of 0.955 was found. Next, we attempted to form a common estimate for volumes associated with the heart, diaphragm areas, lung blood, and lung tissue, and thus derive an equation which considered only measurements of five segments of the thoracic cage (see method V in the text table). Since a step-wise multiple regression model was used in determining this equation, our next step was to consider a condensed equation which deleted the one variable (segment) which contributed the least in reducing the residual sums of squares to a minimum, i.e. (plethysmographic readings minus calculated values)². Method IV

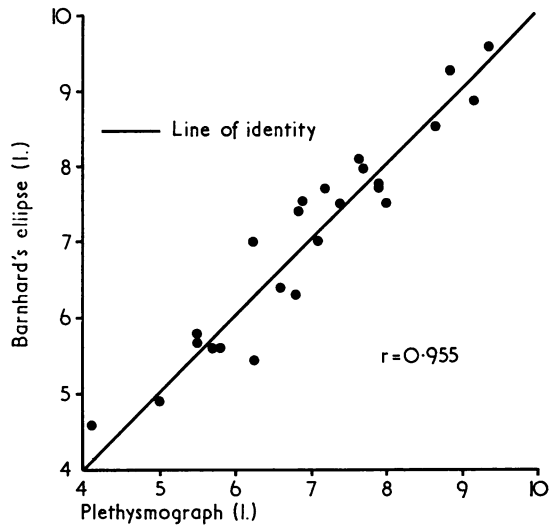


FIG. 2. Total lung capacity. Plethysmograph v. Barnhard's ellipse.

depicts this condensation. From this point in the regression analysis each condensed equation that was generated deleted one more variable that contributed the next least amount in reducing the residual sums of squares, etc., until the point was reached where but one variable (segment) remained. Table II outlines the various combinations studied using the step-wise model in determining TLC by the abbreviated methods.

TABLE I
TOTAL LUNG CAPACITY ALTERNATIVES AND RESIDUALS (LITRES)

Subject	Total Lung Capacity					Residuals			
	Plethysmograph (P)	Barnhard's Ellipsoid (B)	(I) Alford Method	(II)	(V)	P-B	P-I	P-II	P-V
1	7.90	7.74	7.74	7.62	7.67	0.16	0.16	0.28	0.23
2	6.86	7.41	7.45	7.20	7.20	-0.55	-0.59	-0.34	-0.34
3	9.14	8.86	9.43	9.47	9.66	0.28	-0.29	-0.33	-0.52
4	9.35	9.57	9.00	8.73	8.78	-0.22	0.35	0.62	0.57
5	7.88	7.72	8.25	8.12	7.88	0.16	-0.37	-0.24	0.00
6	5.50	5.80	6.48	6.08	6.24	-0.30	-0.98	-0.58	-0.74
7	4.99	4.87	5.68	5.47	5.23	0.12	-0.69	-0.48	-0.24
8	5.70	5.57	5.12	5.40	5.38	0.13	0.58	0.30	0.32
9	6.79	6.29	6.85	6.52	6.35	0.50	-0.06	0.27	0.44
10	6.26	7.00	6.13	6.26	6.57	-0.74	0.13	0.00	-0.31
11	7.13	7.02	7.25	7.32	7.25	0.11	-0.12	-0.19	-0.12
12	6.24	5.44	5.60	5.55	5.62	0.80	0.64	0.69	0.62
13	7.18	7.73	7.35	7.54	7.61	-0.55	-0.17	-0.36	-0.43
14	7.40	7.53	6.79	6.67	6.83	-0.13	0.61	0.73	0.57
15	4.10	4.63	5.18	4.48	4.34	-0.53	-1.08	-0.38	-0.24
16	8.86	9.26	8.56	8.23	8.41	-0.40	0.30	0.63	0.45
17	8.67	8.53	7.77	8.07	8.02	0.14	0.90	0.60	0.65
18	5.50	5.68	5.41	5.22	5.48	-0.16	0.09	0.28	0.02
19	7.70	7.97	7.87	8.08	8.11	-0.27	-0.17	-0.38	-0.41
20	6.61	6.39	6.65	6.65	6.73	0.22	-0.04	-0.04	-0.12
21	8.04	7.48	7.40	7.54	7.58	0.56	0.64	0.50	0.46
22	6.90	7.54	7.15	6.98	7.10	-0.64	-0.25	-0.08	-0.20
23	7.65	8.09	8.26	8.40	8.19	-0.44	-0.61	-0.75	-0.54
24	5.78	5.59	5.25	5.97	5.90	0.19	0.53	-0.19	-0.12

The regression equations generated as a result of the combinations shown in Table II yielded:

$$\begin{aligned}
 \text{I } \hat{Y} &= -1.49431 + (0.00093 X_4) X_1, X_2, X_3, X_5 \text{ deleted} \\
 \text{II } \hat{Y} &= -1.41148 + (0.00479 X_1) + (0.00097 X_4) X_2, X_3, X_5 \text{ deleted} \\
 \text{III } \hat{Y} &= -1.63185 + (0.00433 X_1) + (0.00096 X_4) + (0.00008 X_5) X_2, X_3 \text{ deleted} \\
 \text{IV } \hat{Y} &= -2.14938 + (0.00499 X_1) + (0.00022 X_2) + (0.00096 X_4) + (0.00009 X_5) X_3 \text{ deleted} \\
 \text{V } \hat{Y} &= -2.12151 + (0.00474 X_1) + (0.00020 X_2) + (0.00012 X_3) + (0.00087 X_4) + (0.00010 X_5)
 \end{aligned}$$

Our first inclination was to develop an abbreviated radiographic method which would eliminate the need for determining volumes in the thoracic cage associated with the heart, diaphragmatic areas, lung blood, and lung parenchyma. Method V does exactly this and has essentially the same correlation with the standard plethysmographic readings (i.e., $r=0.949$ —see Fig. 3) as does Barnhard's method. Accordingly, we can legitimately assume we are operating within practical limits of reliability using this abbreviated method, providing the films of the subjects exhibited no marked infiltration and that the heart and diaphragmatic areas were neither extremely large nor extremely small. The relatively high correlations shown in the text table prompted us to consider two alternatives, namely, methods I and II. Methods III and IV were not considered further since their correlations with the plethysmograph were approximately the same as exhibited by method II. When we study the equation generated in the extreme case, using segment 4 as the independent variable (method I), we were able to obtain a correlation of 0.918 with the

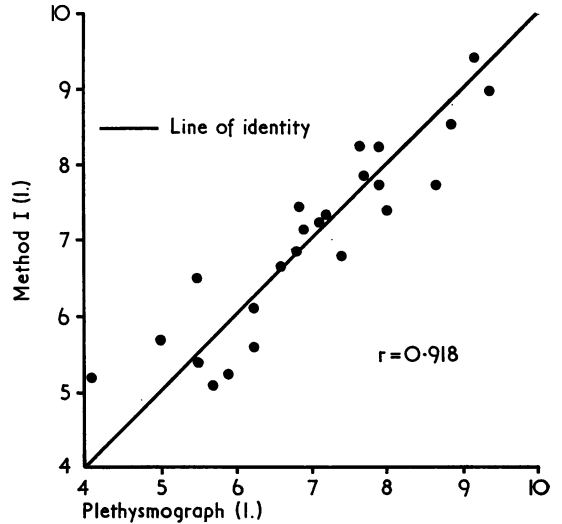


FIG. 4. Total lung capacity. Plethysmograph v. method I.

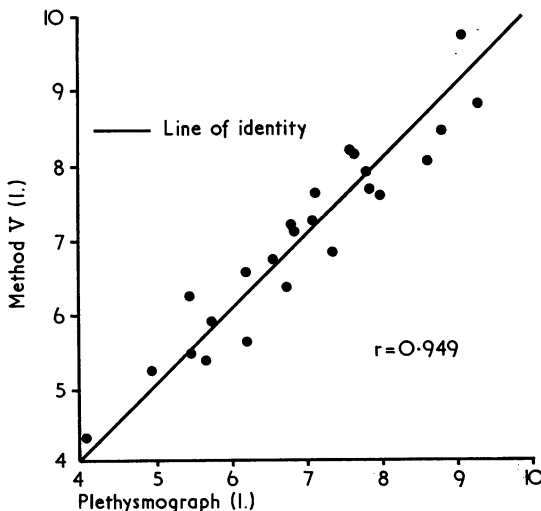


FIG. 3. Total lung capacity. Plethysmograph v. method V.

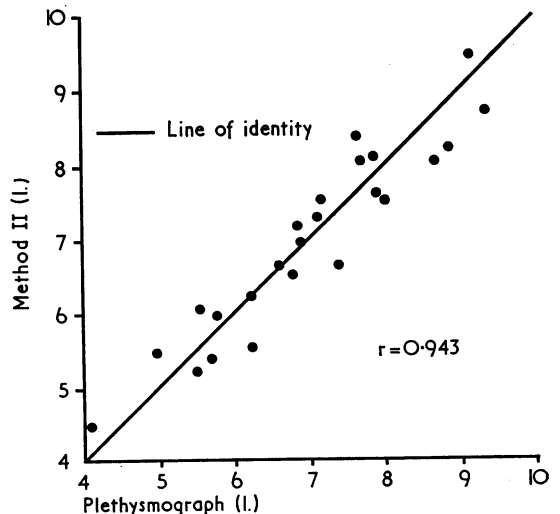


FIG. 5. Total lung capacity. Plethysmograph v. method II.

plethysmograph (Fig. 4). This high a correlation was obtained despite the fact that 3 of the 24 subjects showed differences of around 1 litre between this method and the plethysmograph. It is not recommended to sacrifice so much accuracy for speed by using such a brief condensation as method I. The equation derived from using the measurements of segments 1 and 4 (method II) has a correlation of 0.943 with the plethysmograph (Fig. 5). This is nearly equal to that obtained by using all segments. Segment 5 appears to contribute little in the multiple regression model, and in that segments 2 and 3 have relatively high intercorrelations with segments 1 and 4, their contributions to the equations are also minute. The matrix of intercorrelations is given as:

	Y	X ₁	X ₂	X ₃	X ₄	X ₅
Y	1.000	0.014	0.051	0.871	0.918	0.189
X ₁		1.000	-0.554	-0.149	-0.214	0.186
X ₂			1.000	0.145	0.143	-0.136
X ₃				1.000	0.955	-0.155
X ₄					1.000	0.052
X ₅						1.000

The TLCs of the 24 subjects as determined by the plethysmograph, Barnhard's method, and the shortened methods (I, II, and V) are shown in Table I. The residuals of the latter four methods from the plethysmograph for each subject are also given.

A note of caution regarding the magnitude of the correlation coefficients should be given at this point. These coefficients as derived from a sample of 24 subjects should by no means be regarded as absolute. For example, an approximation of a 95% confidence interval for $r=0.94$, $n=24$ yields a lower limit of around 0.86 and an upper limit in the neighbourhood of 0.97.

DISCUSSION

We feel safe with method V for our general use since the TLCs as determined by this method have a correlation of 0.949 with the plethysmograph. This is comparable to Barnhard's standard technique; however, the abbreviated method excludes the need to make measurements of the heart, diaphragmatic areas, lung blood, and lung tissue. Thus it shortens the time necessary to make the calculation by about 25 to 50%. On the other hand, method I, although it saves even more time, is not sufficiently accurate. If method V is regarded as acceptable, method II must also be to be preferred. Nevertheless, we should state that

TABLE II

Methods	Segments Used in Equation	*R	**R ²	Increases in R ²
I	4	0.9179	0.8426	—
II	4, 1	0.9428	0.8889	0.0462
III	4, 1, 5	0.9481	0.8989	0.0101
IV	4, 1, 5, 2	0.9493	0.9011	0.0022
V	4, 1, 5, 2, 3	0.9494	0.9014	0.0003

*Multiple correlation coefficient (abbreviated method v plethysmograph)
 **Coefficient of determination (explained variation).

regarded as such, since it has an almost identical correlation coefficient (0.943) with the plethysmograph as does method V. The determination of TLC by this method can be done in five minutes and thus has advantages over both method V and the standard Barnhard method and is therefore

[to be preferred. Nevertheless, we should state we do not necessarily recommend the same equation (i.e., numerically), nor do we necessarily advocate the use of the same segments, viz., 1 and 4. What we do advocate is the basic methodology employed in this study to generate 'short-cut' equations using Barnhard's ellipse method as a base. The equations generated will certainly tend to differ depending upon the population of patients being studied. One of the more important points that should be emphasized regards the position of the cross sections (i.e., X₁ through X₅) in relation to the axis of the lung. Though stated in the methods section of this paper, the intended user should refer to the original work of Barnhard *et al.* (1960) for a more detailed explanation on measurement techniques.

REFERENCES

Barnhard, H. J., Pierce, J. A., Joyce, J. W., and Bates, J. H. (1960). Roentgenographic determination of total lung capacity. *Amer. J. Med.*, 28, 51.
 Harris, T. R., Pratt, P. C., and Kilburn, K. H. (1971). Total lung capacity measured by roentgenograms. *Amer. J. Med.*, 50, 756.
 Hurtado, A., and Fray, W. W. (1933). Studies of total pulmonary capacity and its subdivisions. II. Correlation with physical and radiological measurements. *J. clin. Invest.*, 12, 807.
 Loyd, H. M., String, S. T., and DuBois, A. B. (1966). Radiographic and plethysmographic determination of total lung capacity. *Radiology*, 86, 7.

- O'Shea, J., Lapp, N. L., Russakoff, A. D., Reger, R., and Morgan, W. K. C. (1970). Determination of lung volumes from chest films. *Thorax*, **25**, 544.
- Pratt, P. C., and Klugh, G. A. (1967). A method for the determination of total lung capacity from postero-anterior and lateral chest roentgenograms. *Amer. Rev. resp. Dis.*, **96**, 548.
- Reger, R. B., and Jacobs, A. C. (1970). Analysis of components of variation in a radiological method for determining total lung capacity. *Arch. environm. Hlth*, **21**, 778.
- Steel, R. G. D., and Torrie, J. H. (1960). *Principles and Procedures of Statistics*, pp. 289-296. McGraw-Hill, New York.

APPENDIX

It is a standard method of integral calculus to determine the volume of a body by expressing the area of the cross section perpendicular to an axis as a function of distance along the axis and then integrating the function. If, instead of taking cross sections at infinitesimal distances apart, we take them at finite intervals, we can consider the body to be made up of a set of cylinders whose volumes are proportional to $w e h$, where w is the width, and e the depth of the cross section and h is the height of the cylinder. Thus, the volume will be approximately:

$$V = \sum_{i=1}^n b_i w_i e_i h_i$$

where b_i is a factor of proportionality. It is not necessary for geometrically similar bodies to be regular in shape. If they are not, the expression for V is still true in the sense of the theory of dimensional analysis. The expression can be made more accurate by considering it as being a replacement of a formula of integration by a summation whereupon it becomes a problem of determining the best factors b_i for a given number of sections n , in order to make the expression a formula of numerical quadrature which is as accurate as possible. A method of doing this is to make the measurements of V , w_i , e_i , and h_i for many similar bodies and carry out a multiple regression to determine the best values of b_i .

By a simple appeal to dimensional analysis, the external measurements of similar hollow bodies will suffice to measure the internal volumes provided the regression analysis is performed with a sufficient number of cases on which external linear sizes and internal cubic volumes have been measured.

Within limits, the lungs of human beings are geometrically similar bodies. Thus, it should be possible to estimate the capacity of lungs from their external measurements. This paper shows the results associated with using this general mathematical approach for determining total lung volumes.