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# Predictive equations for total lung capacity and residual volume calculated from radiographs in a random sample of the Michigan population

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**Abstract**

***Background*** **Published predicted values for total lung capacity and residual volume are often based on a small number of subjects and derive from different populations from predicted spirometric values. Equations from the only two large studies gave smaller predicted values for total lung capacity than the smaller studies. A large number of subjects have been studied from a population which has already provided predicted values for spirometry and transfer factor for carbon monoxide.**

***Methods*** **Total lung capacity was measured from standard postero-anterior and lateral chest radiographs and forced vital capacity by spirometry in a population sample of 771 subjects. Prediction equations were developed for total lung capacity (TLC), residual volume (RV) and RV/TLC in two groups—normal and total. Subjects with signs or symptoms of cardiopulmonary disease were combined with the normal subjects and equations for all subjects were also modelled.**

***Results*** **Prediction equations for TLC and RV in non-smoking normal men and women were square root transformations which included height and weight but not age. They included a coefficient for duration of smoking in current smokers. The predictive equation for RV/TLC included weight, age, age$^2$ and duration of smoking for current smokers and ex-smokers of both sexes. For the total population the equations took the same form but the height coefficients and constants were slightly different.**

***Conclusion*** **These population based prediction equations for TLC, RV and RV/TLC provide reference standards in a population that has provided reference standards for spirometry and single breath transfer factor for carbon monoxide.**



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Measurements of lung volume from postero-anterior and lateral chest radiographs[1] provide estimates of total lung capacity (TLC) and, by subtraction of forced vital capacity (FVC), residual volume (RV) can be calculated. This helps to distinguish a reduction in vital capacity due to a reduction in TLC from a reduction of vital capacity due to air trapping as in emphysema and asthma. Total lung capacity measured by chest radiographs gives similar values to those measured by body plethysmography.[1] An engineer's planimeter and a hand calculator make this method readily available to clinicians and small laboratories. The measurement could also be used in epidemiological studies as it takes less time than measurements using body plethysmography or gas dilution and does not require equipment beyond that needed for quality chest radiographs. The use of radiographic TLC, RV, and RV/TLC would be facilitated if population based prediction equations were available. The purpose of our study was to produce prediction equations based on volumes measured from chest radiographs in a population which has already provided predictive equations for FVC, flows obtained from spirometry[2] and single breath transfer factor for carbon monoxide (TLCO) and alveolar volume.[3]

## Methods

### POPULATION SAMPLING

A random sample of the population in the state of Michigan was obtained by the Institute for Social Research (University of Michigan) on the basis of randomly selected telephone numbers. The field study was conducted by the environmental sciences laboratory of Mount Sinai School of Medicine. Details of the procedures and methods have been published.[2,3]

A total of 357 white men and 315 white women with complete data, including a chest radiograph during inspiration in which the diaphragm was at or below the ninth posterior mid intercostal space, were included in the model. Medical, occupational, and smoking histories were obtained; physical examinations, anthropometry, posteroanterior and lateral chest radiography, and haematological and clinical chemistry tests were performed; and reproducible maximal expiratory flow-volume curves were produced.[3] Subjects were considered to be normal if they had none of the following: (1) sputum production for three months or more; (2) dyspnoea walking with people of the same age on level ground; (3) wheezing on most days or nights, or attacks of dyspnoea and wheezing (asthma); (4) angina pectoris; (5) a previous diagnosis by a physician of chronic bronchitis, emphysema, asthma, tuberculosis, pneumoconiosis, or coronary artery disease; (6) diastolic blood pressure greater than 100 mm Hg; (7) wheezing, rales, clubbing, or cyanosis. Smoking status was categorised as: (1) non-smokers: those who had never smoked or had smoked fewer than one cigarette a day or who had smoked no more than ten cigarettes per day for less than six months and had stopped more than two years previously (exclusive pipe and cigar smokers were included in this group); (2) present smokers: those who exceeded the non-smokers' limits and, (3) ex-smokers: those who had exceeded the non-smokers' limits but had not smoked for at least two years.

The population selected for the study of lung volumes was carefully screened for pulmonary normality, which included their inclusion in the study in which prediction equations for spirometry and TLCO were developed.[2,3] Subjects with a high diaphragm were then excluded. Finally, the chest radiographs were reviewed to exclude those with abnormalities, including pneumoconiosis, by three qualified readers. Only three of 594 men and none of 583 women had any evidence of diffuse irregular opacities.[4]

*Criteria for selection of radiographs for inclusion*
Chest radiographs were made at a focal spot to film distance of 1·8 m with the focal spot aimed at the centre of a standard 35·5 × 43·2 cm film with standard upright chest *x* ray machines. Radiographs were made at full inspiration by a radiographer supervised by a pulmonary physician who asked for unsatisfactory films to be repeated. Uniform criteria were not applied for the degree of underinflation that would cause films to be repeated. Lung areas were measured by planimety from posteroanterior and lateral chest radiographs with a sound emitting stylus tracked by paired microphones as the digitiser and a computer. Lung volume was calculated by using a standard equation:[1]

$$\text{TLC (ml)} = 8{\cdot}5 \times \text{lung area} - 1200.$$

JUSTIFICATION OF METHODS
A pilot study of lung volumes in subjects with asbestosis showed that 90% of the subjects whose posteroanterior radiograph showed the diaphragm to be at or above the right ninth intercostal space posteriorly could achieve a better inspiration on their second radiograph, after further encouragement to take a deep breath. Therefore for modelling of TLC, RV and RV/TLC we excluded radiographs of 48 men and 38 women as being likely to be underinflated. In men the mean TLC was 6·15 l and 7·43 l respectively in those with a diaphragm above and below the ninth intercostal space; in women the mean values were 5·17 l and 6·05 l respectively. To test whether the low and high diaphragm groups were different we studied the 48 men with a "high diaphragm" radiograph who also had a measurement of alveolar volume from a single breath measurement of carbon monoxide transfer factor. In these men the mean radiographic TLC (5·64 l) was very close to the mean alveolar volume (5·60 l); in the model group the mean radiographic TLC (6·77 l) was 0·85 l greater than the alveolar volume (5·92 l) as expected. The near match of the dilutional alveolar volumes (5·60 l in those excluded and 5·92 l in those accepted) contrasted with a 1·03 l difference in their radiographic TLC measurement. FVC and $FEV_1$ were also similar in the two groups. The finding of similar alveolar volumes and different radiographic volumes suggests that the chest radiographs were taken at less than full inspiration in the "high diaphragm" subjects. Finally the position of the right mid diaphragm was measured (as 0·25, 0·5 or 0·75 of the distance between the ribs) from the chest radiographs of the 412 men and 359 women. (For example, a diaphragm midway between ribs 9 and 10 is position 9·5 while one positioned one quarter of the interspace distance between ribs 10 and 11 is at position 10·25.) When mean values for TLC were plotted against the position of the diaphragm from rib 8 to rib 12, TLC did not increase significantly with a diaphragm positions below 9·5. Radiographs in which the right mid diaphragm was above the mid ninth intercostal space were rejected.

Plethysmographic and radiographic measurements of TLC were similar in 46 asbestos exposed men,[5] the mean (SD) radiographic TLC being 8·11 (1·27) l and the mean plethysmographic TLC 8·09 (1·79) l. Once we had emphasised to radiology technicians that only radiographs in full inspirations were acceptable only 12 of 1000 films (1·2%) needed to be repeated, one tenth of the proportion judged unacceptable for modelling in the earlier study.

Spirometry to obtain FVC followed American Thoracic Society guidelines.[2] Subjects were tested by one physician and technician team using computerized rolling seal spirometers, which were calibrated at least twice a day with a three litre syringe. Subjects were standing, wearing a nose clip and were carefully instructed to make a maximal effort at the start and throughout expiration. Flows and FVC were calculated from the curve with the largest sum of FVC and $FEV_1$. $FEV_1$ was found by back extrapolation. All values were corrected to BTPS. Residual volume was calculated as TLC minus FVC.

ANALYSIS
Calculations were performed with the Stata statistical software package for personal computers (1987 Computing Resource Center, Los Angeles, California 90064). Equations for TLC, RV, and RV/TLC were developed with multiple regression techniques.[6] The predictive variables included sex, age, height, weight, duration of smoking, smoking status, and transformations of these variables. For TLC and RV the method of Box and Cox[7] suggested that the appropriate transformation, and thus the dependent variable for modelling, should be the square root. The age break point for TLC was identified by using a method described by Draper and Smith.[8] No transformation was needed for the RV/TLC ratio.

*Table 1 Descriptive statistics (mean (SD) values) for men (normal subjects and all subjects studied, by cigarette smoking group)*

| | *Normal group* | | | *Total group* | | |
|---|---|---|---|---|---|---|
| | *N-S (n = 77)* | *Ex-S (n = 41)* | *PS (n = 56)* | *N-S (n = 111)* | *Ex-S (n = 85)* | *PS (n = 161)* |
| Age (years) | 36·5 (16·8) | 50·0 (14·1) | 36·2 (11·1) | 41·3 (18·1) | 51·7 (15·5) | 39·5 (12·6) |
| Height (cm) | 176·2 (7·7) | 174·8 (7·0) | 176·5 (6·7) | 175·8 (7·5) | 174·5 (6·9) | 175·7 (6·8) |
| Weight (kg) | 77·4 (12·6) | 80·1 (15·2) | 78·6 (11·9) | 79·0 (14·1) | 79·2 (14·1) | 78·6 (13·0) |
| Duration of smoking (years) | 0 | 17·2 (12·5) | 17·8 (11·6) | 0 | 20·1 (14·7) | 22·6 (13·4) |
| TLC (l) | 7·33 (0·93) | 7·30 (1·01) | 7·54 (0·94) | 7·31 (0·96) | 7·21 (1·01) | 7·53 (0·95) |
| RV (l) | 2·14 (0·84) | 2·55 (0·72) | 2·36 (0·78) | 2·30 (0·95) | 2·73 (0·97) | 2·66 (1·06) |
| RV/TLC | 0·29 (0·11) | 0·34 (0·09) | 0·31 (0·08) | 0·31 (0·12) | 0·37 (0·12) | 0·35 (0·12) |
| Number of values for RV and RV/TLC | 71 | 37 | 53 | 103 | 74 | 145 |

N-S—non-smokers; Ex-S—ex-smokers; PS—present smokers; TLC—total lung capacity; RV—residual volume.

*Table 2 Descriptive statistics (mean (SD) values) for women (normal subjects and all subjects studied, by cigarette smoking group)*

| | *Normal group* | | | *Total group* | | |
|---|---|---|---|---|---|---|
| | *N-S (n = 104)* | *Ex-S (n = 30)* | *PS (n = 43)* | *N-S (n = 150)* | *Ex-S (n = 41)* | *PS (n = 124)* |
| Age (years) | 40·4 (14·4) | 40·7 (11·2) | 35·9 (13·3) | 43·5 (16·3) | 42·3 (13·2) | 39·6 (14·1) |
| Height (cm) | 162·4 (6·2) | 162·6 (5·8) | 163·4 (5·6) | 161·6 (6·2) | 161·9 (6·3) | 163·3 (6·1) |
| Weight (kg) | 65·6 (12·7) | 62·3 (13·0) | 62·4 (11·8) | 66·0 (12·8) | 65·7 (16·4) | 65·6 (14·5) |
| Duration of smoking (years) | 0 | 10·5 (7·7) | 16·5 (13·0) | 0 | 12·9 (11·8) | 20·8 (13·8) |
| TLC (l) | 6·08 (0·86) | 5·88 (0·71) | 6·06 (0·64) | 6·01 (0·81) | 5·87 (0·71) | 6·18 (0·72) |
| RV (l) | 2·53 (0·88) | 2·31 (0·51) | 2·41 (0·66) | 2·56 (0·85) | 2·44 (0·63) | 2·74 (0·82) |
| RV/TLC | 0·41 (0·10) | 0·40 (0·08) | 0·40 (0·09) | 0·42 (0·11) | 0·42 (0·10) | 0·44 (0·12) |
| Number of values for RV and RV/TLC | 91 | 28 | 41 | 134 | 39 | 112 |

For abbreviations see table 1.

The equations for TLC and RV took the form of $\sqrt{TLC}$ = −constant + height − weight; $\sqrt{RV}$ = −constant + height − weight + age. Backward elimination was used to determine the predictor variables to be retained in the equation. The influence of each observation on the estimates of the coefficients was determined by using Cook's D statistic. The residuals were normally distributed. There was no relation between the residuals and the predicted values or between the residuals and any of the possible predictor variables.

*Table 3 Predictive equations for total lung capacity, residual volume and the RV/TLC ratio in men*

| | $\sqrt{TLC}$ *(l)* | $\sqrt{RV}$ *(l)* | | *RV/TLC* | |
|---|---|---|---|---|---|
| | *N-S, Ex-S+PS* | *N-S+Ex-S* | *PS* | *N-S+Ex-S* | *PS* |
| *Normal group* | | | | | |
| Constant | −0·0282* | −0·2096 | −0·7569 | 0·2573 | 0·2573 |
| Height (cm) | 0·0162 | 0·0088 | 0·0104 | NS | NS |
| Weight (kg) | −0·0013 | −0·0028 | −0·0028 | −0·0007 | −0·0007 |
| Age (years) | NS | 0·0092 | 0·0043 | 0·0008 | 0·0008 |
| Age (years$^2$) | | | | 0·000035 | 0·000035 |
| Duration of smoking (years) | NS | NS | 0·0143 | NS | 0·0012 |
| *Total group* | *N-S, Ex-S+PS* | *N-S* | *Ex-S+PS* | *N-S+PS* | *Ex-S* |
| Constant | 0·0971* | −0·2989 | −0·2989 | 0·2377 | 0·2179 |
| Height (cm) | 0·0156 | 0·0098 | 0·0098 | NS | NS |
| Weight (kg) | −0·0017 | −0·0038 | −0·0038 | −0·0006 | −0·0006 |
| Age (years) | † | 0·0094 | 0·0094 | 0·0012 | 0·0012 |
| Age (years$^2$) | | | | 0·000035 | 0·000035 |
| Duration of smoking (years) | 0·0014‡ | 0 | 0·0046 | 0·0020‡ | 0·0020 |

*−0·0982 if under 29 years of age.
†0·0079 if under 29 years of age.
‡PS only.
For abbreviations see table 1.

## Results

The descriptive statistics for the 174 normal men and for all 357 men are shown as mean values for age, height, weight, and volume in table 1. The same indices for the 177 normal women and all 315 women are in table 2. Data were incomplete for six women and seven men and are not considered further. In normal men and all men of 29 years of age or more predictive equations for TLC showed that height and duration of smoking were the significant positive independent variables. Weight had a significant negative coefficient but age was not significant (table 3). The models in women 29 years of age or more were similar (table 4). There was an age break at 29 years in the models for TLC in men and women which required different equations. For normal subjects under 29 years of age there was a slightly smaller constant for TLC. The constant was considerably larger in women, which was offset somewhat by an age coefficient (tables 3 and 4). For men there was an age coefficient only for those under 29 years of age in the total group. In women there was an age coefficient for those aged under 29 years in both the normal group and the total population. More than half the variance in TLC was explained by the model in the normal men and women ($r^2$ = 0·65) and in all men and women ($r^2$ = 0·61) (table 5).

The model for RV had the same form as that

*Table 4 Predictive equations for total lung capacity, residual volume and the RV/TLC ratio in women*

| | $\sqrt{\text{TLC}}$ (l) | $\sqrt{RV}$ (l) | | RV/TLC | |
|---|---|---|---|---|---|
| | *N-S, Ex-S+PS* | *N-S+Ex-S* | *PS* | *N-S+Ex-S* | *PS* |
| *Normal group* | | | | | |
| Constant | −0·0934* | −0·0732 | 0·0732 | 0·3468 | 0·3468 |
| Height (cm) | 0·0162 | 0·0088 | 0·0104 | NS | NS |
| Weight (kg) | −0·0013 | −0·0028 | −0·0028 | −0·0007 | −0·0007 |
| Age (years) | † | 0·0092 | 0·0043 | 0·0008 | 0·0008 |
| Age (years²) | | | | 0·000035 | 0·000035 |
| Duration of smoking (years) | | NS | 0·0143 | NS | 0·0012 |
| *−0·3211 if under 29 years of age | | | | | |
| †0·0070 if under 29 years of age | | | | | |
| *Total group* | *N-S, Ex-S+PS* | *N-S* | *Ex-S+PS* | *N-S+PS* | *Ex-S* |
| Constant | 0·0228* | −0·2989 | −0·0574 | 0·3286 | 0·3089 |
| Height (cm) | 0·0156 | 0·0098 | 0·0098 | NS | NS |
| Weight (kg) | −0·0017 | −0·0019 | −0·0019 | −0·0006 | −0·0006 |
| Age (years) | † | 0·0094 | 0·0094 | 0·0012 | 0·0012 |
| Age (years²) | | | | 0·000035 | 0·000035 |
| Duration of smoking (years) | 0·0014‡ | | 0·0046 | 0·0020‡ | 0·0020 |

*−0·1725 if under 29 years of age.
†0·0070 if under 29 years of age.
‡PS only.
For abbreviations see table 1.

*Table 5 Regression summary statistics*

| *Group* | *Variable* | $r^2$ | *Standard error* | *Number* |
|---|---|---|---|---|
| Normal | TLC | 0·65 | 0·12 | 342 |
| Normal | RV | 0·34 | 0·20 | 313 |
| Normal | RV/TLC | 0·55 | 0·07 | 312 |
| All | TLC | 0·61 | 0·13 | 663 |
| All | RV | 0·43 | 0·20 | 597 |
| All | RV/TLC | 0·59 | 0·08 | 603 |

The coefficients were the same for both sexes, only the constants differed. The regressions were summarised for the entire group of normals and all subjects studied.
For abbreviations see table 1.

*Table 6 Comparison of mean values predicted for TLC, RV, and RV/TLC for normal men and women with height, weight and age standardised derived from three sets of predictions*

| | *O'Brien and Drizd[10]* | *Difference from present series* | *Peterson and Hodous[11]* | *Difference from present series* | *Present series* |
|---|---|---|---|---|---|
| *Men* | | | | | |
| TLC (l) | 6·51 | 0·82 | 6·72 | 0·61 | 7·33 |
| RV (l) | 1·58 | 0·56 | 1·72 | 0·42 | 2·14 |
| RV/TLC | 0·23 | 0·06 | 0·26 | 0·03 | 0·29 |
| *Women* | | | | | |
| TLC (l) | 5·22 | 0·86 | 5·19 | 0·89 | 6·08 |
| RV (l) | 1·31 | 1·22 | 1·65 | 0·88 | 2·53 |
| RV/TLC | 0·31 | 0·10 | 0·33 | 0·08 | 0·41 |

For abbreviations see table 1.

for TLC except that age increased RV in both men and women and the coefficients were identical, though the constants differed. For the normal subjects $r^2 = 0·34$ and for the total population $r^2 = 0·43$. For both TLC and RV the sum calculated from the linear equation is squared. Thus for a normal man aged 35 years, height 177·8 cm and weight 72·7 kg, $\sqrt{\text{TLC}}$ = −0·0282 (constant) + 0·0162 × 177·8 (height) − 0·0013 × 72·7 (weight) = 2·758, which squared equals 7·60 l.

RV/TLC predictive equations for men and women were linear and not transformed. Age, age squared, and weight in non-smokers and ex-smokers and duration of smoking in current and ex-smokers were the significant independent variables. They accounted for more than half the variance in the normal subjects ($r^2 = 0·55$) and in the total population ($r^2 = 0·59$). The only sex difference was that RV/TLC was consistently larger in women, who had a smaller TLC than men but a similar RV.

When the final models were examined the residuals had a normal distribution. No relationships were found between residuals and the predicted values for TLC, RV, or RV/TLC or between the residuals and possible predictor variables.

## Discussion

In this study TLC was measured from lung areas traced by planimetry of chest radiographs and predictive equations were modelled to provide a profile of reference pulmonary function values in a probability population sample of Michigan.[2 3] The similarity of the predictive equations from the total population and the normal subset (the model group) makes an age adjusted population comparison possible. The two groups had virtually identical TLC and RV measurements. Duration of smoking affected TLC in current smokers both in the normal group and in the total populations but not in ex-smokers. TLC increased with age in the total population. Residual volume showed the same pattern in men and women, being increased by height and age and decreased by weight in the normal and total populations. RV/TLC increased with age and age squared and with duration of smoking in current smokers and ex-smokers and decreased with weight in non-smokers. There was an age break (a change in inflection) in the age coefficient at 29 years in both sexes for TLC. FVC and $FEV_1$ reach their developmental peaks at 25 years of age and then become age related.[2]

These prediction equations should provide suitable reference data for detecting an increase in TLC from airways obstruction in asthma and emphysema, as was seen with cigarette smoking in this study. The values derived from the equations are comparable to reference standards for TLC measured by body plethysmography in that they include the total residual volume (including air not communicating with airways and thus not measured by helium or nitrogen dilution methods).[9]

Our study produced larger TLC and RV volumes than did two recent population studies which used radiographic methods. One was the national survey of O'Brien and Drizol,[10] who used the same planimetry method to measure chest radiographic lung volumes, but films with a high diaphragm were not rejected. On the basis of their equations, the mean TLC in our male non-smokers was 0·82 l (11·2%) lower than the measurements we obtained and those calculated with our prediction equations. Residual volume estimated from their equations was lower by 0·56 l (26·2%) and estimated RV/TLC by 0·06 (20·7%). The differences for women were of similar magnitude (table 6). The other study using radiographic methods was of a normal blue collar population from North Carolina.[11] It used geometrical sections to measure radiographic volume[12] and also did not reject underinflated radiographs, although their films were said to have met International Labour Organization standards for pneumoconiosis (which advise full inspiration). Their published regression equations are further complicated by the introduction of a factor for educational attainment for RV in all groups and for TLC in their normal group. When this coefficient was replaced by age in their model equation, the age slope of TLC had a significant coefficient.[11] The values predicted from the North Carolina study of blue collar workers for our normal men were only slightly higher than those obtained with the national sample equations.[10] When the North Carolina study was used to predict values for our population TLC was 0·61 l (8·3%) lower, RV was 19·6% lower and RV/TLC was 0·03 (10·3%) less. Similarly, the estimate from their equations of TLC in their normal women was 14·6% less than our value, RV was 34·8% less and RV/TLC was 0·08 (19·5%) less. If 12% of radiographs (as in the present study) had been taken at 1–2 l below TLC with all others at full inspiration, the average difference in TLC would have been only 0·075–0·13 l. Since the differences were 7–10 times larger, it appears likely that in both cohorts a considerable proportion of the chest radiographs on men and women were taken at less than full inspiration, according to our criteria.

We concluded from earlier comparisons,[1] as do others,[13] that both radiographic methods of measuring TLC work well provided that chest radiographs are taken at "full inspiration," defined in normal subjects as the right mid diaphragm at or below the ninth posterior intercostal space. Because TLC and RV measured on our "underinspired" chest radiographs (removed from the population for modelling) and the mean values for TLC and RV in published series[10 11] are similar, we conclude that previous equations were based on populations in which many of the radiographs were made with less than full inspiration. The planimetry method is simple, requires only a planimeter and calculator, and is easily computerised for greater speed.

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