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Estimation of lung volumes from chest radiographs using shape information

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ABSTRACT The cross-sectional shapes of the chest and its contained structures have been assessed in post-mortem anatomical sections and from computerised tomographic scans in living subjects. These shapes are described by simple equations that can be used to increase the accuracy of measuring lung volumes from chest radiographs. Radiographic estimates of total lung capacity, using the equations, were compared with plethysmographic and single-breath helium dilution measurements in 35 normal subjects. The postures commonly used for taking chest radiographs were found, on average, to decrease total lung capacity (TLC) and to increase residual volume by about 200 ml when compared with the sitting positions used for the other two measurements (studies made in 18 of the subjects). After correction for this effect, the radiographic estimates of TLC, which measure the displacement volume of the lung, exceeded the plethysmographic estimates of contained gas volume by a mean of 720 ml, which was taken as the volume of tissue, blood, and water in the lungs. The single-breath dilution estimates of TLC fell short of the plethysmographic values by a mean of 480 ml, taken as the volume of contained gas that was inaccessible to helium in 10 seconds. The tomographic studies suggested that the radiographic technique of measuring lung displacement volumes has an accuracy of ±210 ml. The method is rapid and simple to use and has intra- and inter-observer variabilities of <1% and <5% respectively.

Radiographic methods for measuring lung volume have been known for many years. Most have been based on simple assumptions about the cross-sectional shape of the chest. Hurtado and Fray (1933) measured the area of the lungs on postero-anterior (PA) chest radiographs and multiplied this by the PA diameter of the chest measured externally. Kovach *et al* (1956) treated the chest as a paraboloid of revolution of the PA radiograph. Barnhard *et al* (1960) assumed that each lung and the heart were elliptical in cross-section and considered the diaphragm as one-eighth of an ellipsoid. All these methods are dependent for their accuracy on correlations with other methods of measuring lung volume, such as plethysmography or gas dilution. The acceptability of the plethysmograph as a standard for comparison is not entirely above suspicion, especially in patients with lung disease: recent studies by Brown *et al* (1978b) have suggested that airways obstruction may lead to inaccurate measurement. Previous studies have also neglected the effects of postural differences on static lung volumes, and have applied a single approximate magnification factor to all radiographs.

The radiographic method described herein measures the displacement volumes of the lungs as geometric structures in space, using a digitiser and computer. It was developed from determinations of the cross-sectional shape of the chest and its contained structures in post-mortem anatomical sections and from computerised tomographic (CT) scans in living subjects. It also uses individual magnification factors that are easily obtained at the time of measurement. We describe the method and compare its results with plethysmographic and helium-dilution estimates of total lung capacity (TLC), taking account of postural effects on thoracic gas volume. In principle the radiographic method estimates the displacement volume of the lung, the plethysmographic technique determines the contained gas volume, and the dilution method represents the volume of gas reached by helium in the duration of the breath (10 s). Thus the differences between these three measurements are estimates of lung tissue volume and effective gas trapping respectively.

Methods

RADIOGRAPHIC METHOD

The principles of the radiographic method can be thought of in four stages (fig 1). Firstly, the boundaries of the chest, heart, spine, and diaphragm are identified on PA and lateral radiographs and traced over using a digitiser that feeds the XY co-ordinates of successive points of each outline directly into a computer. Secondly, the computer aligns the PA and lateral views in the same vertical plane, divides them into a large number (200) of horizontal slices, and determines the PA and lateral diameters and thickness of each structure in the slice. Thirdly, the cross-sectional areas of the structures are calculated for each slice, using shape equations described below. Finally, the volumes of the whole organs are calculated by summing information from all of the slices and the results are presented in graphic and digital form.

The outlines used illustrated in fig 2 are recorded using a Summagraphics digitiser with a resolution of 100 lines per inch and a Prime 300

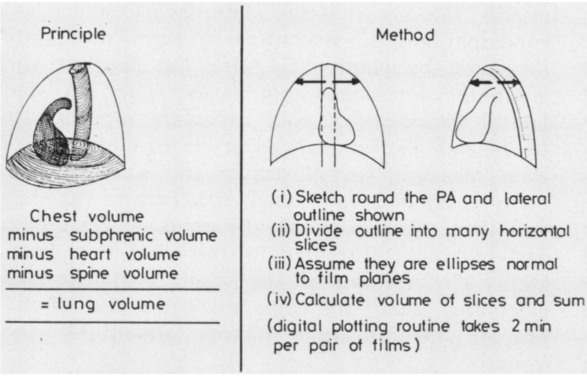


Fig 1 *General principles of radiographic method.*

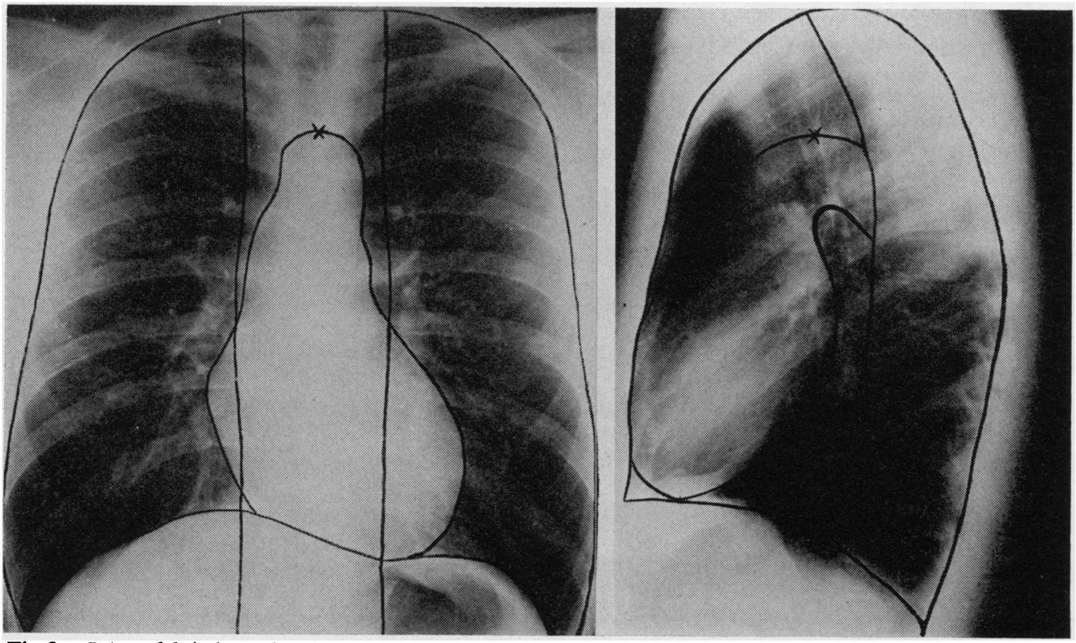


Fig 2 *PA and left lateral radiographs of a normal subject showing outlines that are digitised to estimate volumes of each of the thoracic structures.*

computer. In the PA radiograph the chest outline follows the inner rib margins, the heart boundary includes the arch of the aorta, and the spine outline follows the tips of the lateral processes of the vertebrae to take account of associated muscle masses. In the lateral view the chest boundary follows the inner border of the sternum anteriorly and the inner rib margins posteriorly. Where rotation of the chest displaces the two rib margins posteriorly a line midway between the two is taken. Similarly a line midway between the two hemidiaphragms is followed. The heart outline again includes the arch of the aorta as far posteriorly as the anterior limit of the spinal mass. This is drawn 1 cm in front of the vertebral bodies to allow for the oesophagus and descending aorta. Posteriorly the boundary of the spine follows that of the chest. We normally use the top of the aortic arch as a common point of reference for vertical alignment but any other structure that can be clearly identified in both views serves equally well.

The individual magnification factor for each radiograph was estimated from the target-film distance and half the chest diameter normal to the film in that view (fig 3). All radiographs used in this study were taken at a distance of 10 ft, but the calculation is straightforward for any circumstances in which the geometry is known. Where this is not practical the magnification factor can be obtained simply and directly by taping coins to the back, front, and sides of the chest and noting their maximum diameters as seen on the radiographs. The precise positions of the coins are not important since it is impossible to place any disc in a field of view without its true diameter being visible.

The accuracy of the method was assessed by taking PA and lateral radiographs of several containers, of known cross-sectional shape, under standard chest film conditions. The radiographic volumes were compared with the containers' water displacement volumes, which varied from 0·25 to 14·35 l and thus covered the range of chest volumes to be expected in clinical practice.

ASSESSMENT OF THE CROSS-SECTIONAL SHAPE OF THE CHEST IN MAN

The cross-sectional shapes of the chest and its contained structures were determined from anatomical and tomographic material. The anatomical data were obtained from serial frozen sections of the whole chest reported by Matsukawa *et al* (1977) and Eycleshymer and Schoemaker (1970). The areas of the chest, heart, spine, and subdiaphragmatic structures in each slice were measured by planimetry using the digitiser and computer mentioned previously. The PA and lateral diameters of each structure, appropriate to the radiological outlines described earlier, were then measured as illustrated (fig 4). The true cross-sectional area of each structure in the slice was then compared with the areas of the ellipse and rectangle generated by the same two diameters. The volume of the whole structure was calculated using the slice thickness and photographic magnification factors stated by the authors.

Serial CT scans were obtained of the chests of four normal male subjects (aged 21–54) during breath-holding at TLC. Three further people were studied during breath-holding at functional residual capacity (FRC)—a man aged 37 with no history of lung disease, a woman of 38 with asthma, and a man of 75 with emphysema. Three normal men including two from the TLC group were studied at residual volume (RV). The same linear and planimetric measurements were made

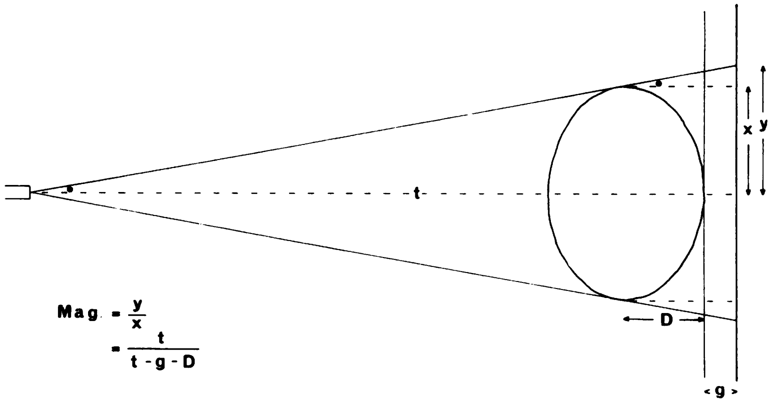
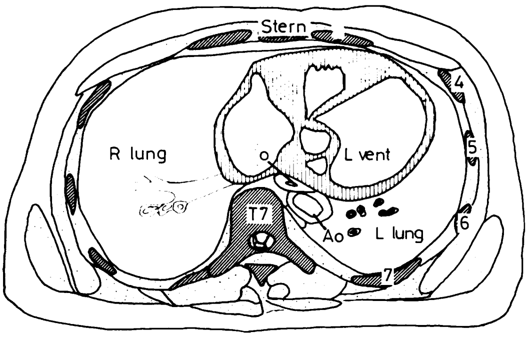


Fig 3 *Principles of estimation of magnification factors from target–film distance (t), air gap between subject and film (g), and half chest diameter measured from radiograph taken in other projection or directly from patient's chest. This magnification factor applies to plane at centre of chest.*



(Adapted from Matsukawa *et al* 1977)

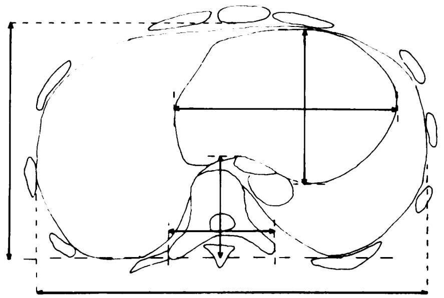


Fig 4 *Cross-sectional areas measured by planimetry and the PA and lateral linear dimensions of each structure. By determining relation between these measurements, average cross-sectional shape of each structure was established.*

on the tomographic as on the anatomical sections. Once more actual volumes were calculated from known magnifications and "slice" thicknesses. All CT scans had to be conducted with the subjects supine.

MEASUREMENTS OF LUNG VOLUMES

Lung volumes were measured in three ways: radiography, whole-body plethysmography, and single-breath helium dilution. Studies were conducted on 35 normal adults, 17 of whom were women. Their mean age was 28·9 years (range 18–52), their mean height 174·6 cm (range 152–188), and their mean weight 67·1 kg (range 45–98).

Radiographic estimates of lung volume—Standard 10 ft–150 KeV chest radiographs were taken in the PA and left lateral positions. In the PA position subjects stood with hands on hips and shoulders pressed forward on the film cassette. For the lateral view subjects stood upright with arms clasped tightly about the head and with the left side of the chest against the cassette. The subjects were told of the importance of inspiring completely to TLC and signalled when they had reached this point by pressing a toy "clicker" that was audible to the radiographer behind her screen. The cassette was fitted with a constant subject-film air gap of 5 cm in both views.

Whole-body plethysmography—For these measurements subjects sat upright in a constant-volume whole-body plethysmograph (Fenyves-Gut, Basle). Thoracic gas volumes were determined from inspiratory efforts against a shutter closed at FRC. TLC was obtained from the maximal inspiration that followed release of the shutter. The mean of at least three reproducible measurements was obtained in each subject. Calculated volumes were reduced by 130 ml in all cases to allow for abdominal gas compression (Brown *et al*, 1978a; Habib and Engel, 1978).

Single-breath helium dilution—For this manoeuvre subjects sat upright, exactly as in the plethysmograph, expired to RV, rapidly inspired a helium-rich mixture to TLC, held their breath for 10 seconds, and then expired quickly back to RV precisely as in the standard single-breath DLCO procedure. The helium concentration of the mid-expirate (750–1250 ml expired volume) was measured with a P K Morgan Mk IV respara-meter. The mean of at least two reproducible measurements was obtained in each subject. The single-breath, plethysmographic, and radiographic estimates of TLC were made within a one-hour period in each person.

Postural changes in TLC and RV—The changes in TLC and RV between the standing posture of the radiographic procedure and the sitting position of the other two were determined in 18 of the 35 subjects. This was done by connecting a water-filled spirometer to the subject, who was in the position adopted for the PA radiograph, and asking him to perform a vital capacity manoeuvre in that posture and then to repeat the manoeuvre in the normal sitting position, without coming off the mouthpiece. This procedure was repeated using the lateral radiograph position. Duplicate measurements were obtained in reverse order on each subject and the main effects of posture upon TLC and RV calculated. A typical record illustrating the procedure is shown in fig 5.

Observer error—To assess the accuracy with which lung volumes can be measured from a given pair of radiographs one observer measured 18 sets of radiographs in triplicate and three observers measured five sets of films in triplicate. Two of the three had no previous experience of the method.

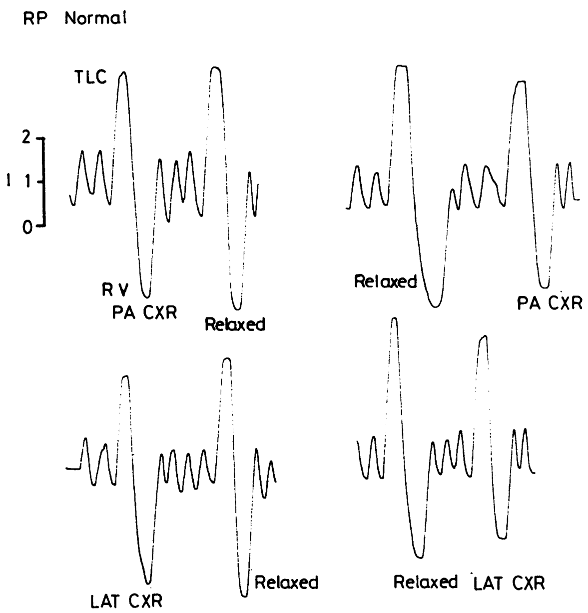


Fig 5 *A typical spirographic record showing effect of radiographic postures in reducing TLC and increasing RV.*

Results

CROSS-SECTIONAL SHAPE ASSESSMENT

The average cross-sectional shape of the chest in the anatomical studies exceeded that of the ellipse, but was smaller than that of the rectangle generated by the PA and lateral linear dimensions. The area was found to be one-third of the way between the elliptical and rectangular shapes (fig 6),

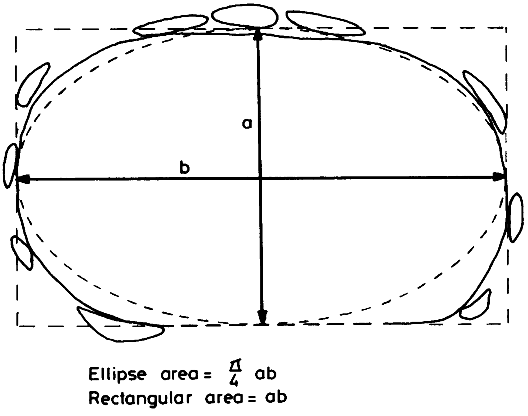


Fig 6 *Diagramatic representation showing average cross-sectional area of chest (solid line follows pleural margin). Area of chest was found to be greater than that of ellipse based on PA and lateral linear dimensions (inner broken line) by one-third of difference between area of ellipse and that of enclosing rectangle (outer broken line).*

and is described by the equation:

$$A = \frac{\pi ab}{4} + (ab - \frac{\pi ab}{4})/3,$$

which simplifies to 0·857 ab, where a and b are the linear dimensions. Table 1 shows the error in estimating the actual volume of the chest from its PA and lateral diameters using this cross-sectional shape for both the anatomical sections and the CT scans. The mean error for the 10 CT

Table 1 *Comparison of estimated with actual volume of the whole chest*

	Actual chest volume (l)	*Estimated* chest volume (l)*	*Error of estimate (%)*
Anatomical sections			
Matsukawa *et al* (1977)	4·69	4·68	−0·2
Eycleshymer and Schoemaker (1970)	6·56	6·49	−1·0
CT scans			
TLC—normal subjects			
1	10·67	10·46	−2·0
2	8·55	8·53	−0·3
3	12·64	13·04	+3·1
4	11·61	11·14	−4·1
FRC—patients			
5 Normal chest	7·88	8·01	+1·6
6 Asthma	6·83	6·92	+0·5
7 Emphysema	9·24	9·29	+0·5
RV—normal subjects			
3	7·69	7·68	−0·01
4	5·63	5·42	−3·7
8	6·34	6·27	−1·1

Mean error for the 10 CT scans = −0·5% (SD 2·2%).

*Estimate based on: Cross-sectional area $= \frac{\pi ab}{4} + (ab - \frac{\pi ab}{4})/3$

where a and b are PA and lateral diameters of the chest.

scans was −0·5% of a mean chest volume of 8·71 l (ie 45 ml), and the SD of the error was 2·2% (190 ml).

The average cross-sectional areas of the heart, spine, and subdiaphragmatic region were found to be very close to those of the ellipses generated by their PA and lateral diameters. The errors inherent in the estimation of these volumes from anatomical and tomographic data, by making this assumption, are shown in table 2. The means and standard deviations of these errors are all small (<50 ml). By compiling the mean errors for the chest, heart, spine, and subphrenic volumes from the CT scan data, the total lung volume was found to be underestimated by 125 ml. Combining the variances yields an overall accuracy for the estimation of lung volume of ±210 ml. Lung volume is calculated from the other volumes so:

$$\text{Lung vol} = \text{vols chest} - (\text{heart} + \text{spine} + \text{subphrenum}) + 125 \text{ ml}$$

Only two subjects had CT scans at both TLC and RV. In both there was little change in the shape of the chest between the two volumes. This suggests that the expansion of the chest is relatively isotropic over the vital capacity range. The cross-sectional shape of the heart, subdiaphragmatic structures and, more predictably, the spine also showed little change between TLC and RV.

The results of the comparison of radiological volume and water displacement volume of the containers are shown (fig 7). Agreement between the two measurements is extremely close.

The study of the effects of posture on lung volumes showed that TLC was reduced by a mean of 0·71 l (SD 0·16 l) in the PA radiographic position when compared to the sitting relaxed position, and by 0·18 l (SD 0·12 l) in the lateral radiographic position. Residual volume, on the other hand, was increased by 0·20 l (SD 0·13 l) in

Table 2 *Elliptical estimation of heart, spine, and subdiaphragmatic volumes*

	Actual volume (l)	*Error of estimate (%)*
Anatomical sources (n=2)		
Heart	0·77±0·13	−0·6±5·9
Spine	0·62±0·12	−3·0±0·1
Subdiaphragmatic volume	1·33±0·49	+0·4±2·9
CT scans (n=10)		
Heart	1·01±0·34	+2·8±4·7
Spine	0·88±0·15	+0·6±5·5
Subdiaphragmatic volume	1·76±1·06	+2·8±2·3

Estimates based on: Cross-sectional area $=\pi ab/4$ where a and b are PA and lateral linear dimensions of each structure. Figures are mean ± 1 SD.

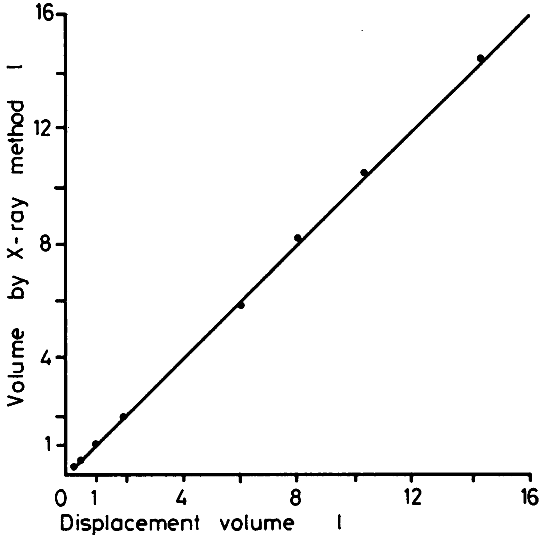


Fig 7 *Correlation of radiographically determined and water displacement volumes for series of containers used to evaluate accuracy of radiographic method. Line is line of identity (slope=1·0).*

the PA position, and by 0·21 l (SD 0·14 l) in the lateral position. Accordingly, in the comparison between radiological TLC and the other volume estimates described below, 0·18 l has been added to the radiological volume, to correct for the postural differences.

LUNG VOLUME COMPARISONS

The mean values for the three lung volumes and the differences between them are shown in table 3. The correlations between radiographic and plethysmographic and helium dilution TLC are shown in figs 8, 9, and 10 respectively. The correlation coefficients were 0·96, 0·95, and 0·97 respectively and were all highly significant statistically ($p<0·01$, method of least squares). The mean difference between radiographic and plethysmographic TLC was +0·72 l (SD 0·37 l) and is attributable to lung tissue, water, and blood volumes. The mean difference between radiographic TLC and helium dilution volume was +1·19 l (SD 0·42 l) and this exceeds the above difference by a

Table 3 *TLC estimation in 35 normal subjects by three methods**

Chest radiograph (posture corrected)	6·93±1·32	0·72±0·37	1·19±0·42
Body plethysmograph	6·22±1·18		
Helium volume (single breath)	5·74±1·20	0·48±0·29	

*Results are mean ± 1 SD litres.

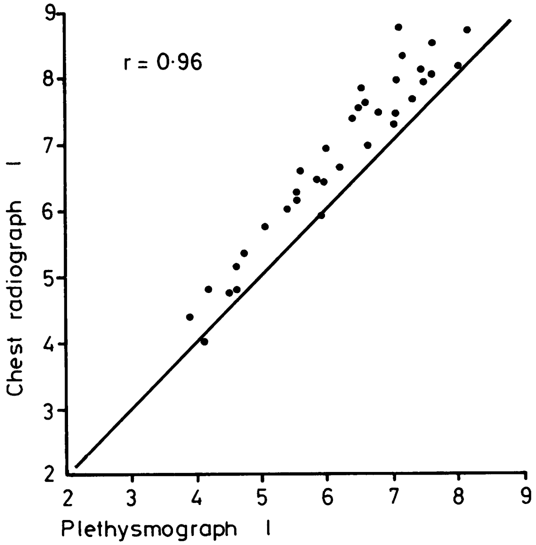


Fig 8 *Correlation between radiographic (posture corrected) and plethysmographic estimates of TLC in 35 normal subjects. Line is line of identity.*

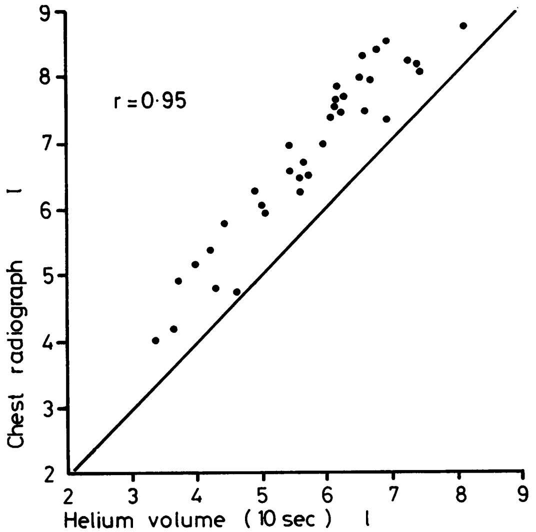


Fig 9 *Correlation between radiographic and single breath helium estimates of TLC in 35 normal subjects.*

volume of 0·48 l (SD 0·29 l) which we attribute to the volume of gas in the lungs that cannot be reached by a single breath of helium in 10 seconds. This can be thought of as the effective trapped gas volume. The coefficient of intraobserver variation was 0·56% (SD of the differences was 37·8 ml). Interobserver variability among the three separate observers gave a coefficient of variation of 4·9% (SD of the differences was 0·32 l).

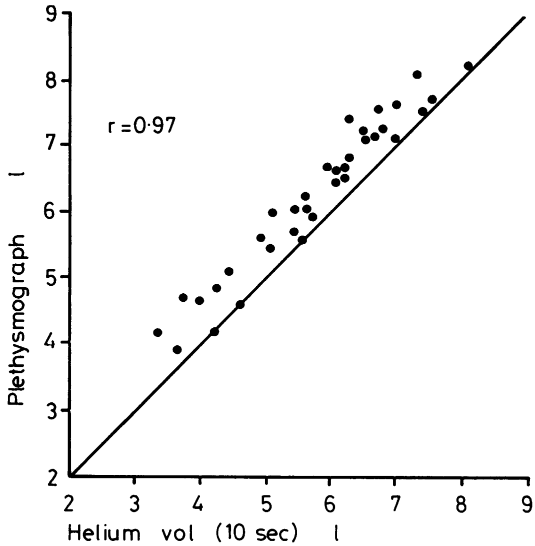


Fig 10 *Correlation between plethysmographic and single breath helium estimates of TLC in 35 normal subjects.*

Discussion

This radiographic method is both rapid and simple to use. Estimation of lung volume from a pair of radiographs takes less than two minutes. The use of computers to reduce the time and tedium of the older manual methods has also been described by others (Paul *et al*, 1974; Glenn and Greene, 1975; Barrett *et al*, 1976). A scanning device and microprocessor are being developed to read the films and do the relatively simple sums, obviating the need for a computer. This will permit wider use of the method. The main advantage of this method is that it uses geometric cross-sectional shape information derived from the chests of living subjects to arrive at a completely independent measurement of the displacement volume of the lungs. The estimates of lung volume that it produces correlate closely with those of the other independent methods used when the differences between what each method measures, and postural effects, are taken into account.

Magnification factors can be simply and accurately measured even under non-standard radiographic conditions. Although it is possible to use individual factors for each of the thoracic structures, the errors introduced by assuming that the heart and spine lie at the true centre of the chest in both PA and lateral projections and using a single magnification factor applicable to this central plane are small, and are minimised by using a long target-film distance that reduces all factors towards unity. Minimising the distance between the patient and the x-ray film is also important in this regard.

Close co-operation between the radiographer and the subject in ensuring that the subject inspires to TLC is essential, and the advantage of letting the subject signal the radiographer to expose the radiograph when he has inspired fully may be of considerable importance in patients with disease of the airways who have a long inspiratory time.

A mean posture correction was applied to the radiological TLC estimates of all subjects in this study for comparison with the estimates by the other methods. This was done because the time and effort spent in measuring postural effects for every patient on a routine basis would be considerable.

The mean value for the difference between radiographic and plethysmographic volumes in the 35 normal subjects was +0·72 l (SD 0·37 l). This difference should be accountable for by pulmonary blood and tissue volumes, and in fact is very close to the combined values for these volumes measured by other methods. The mean pulmonary blood volume for subjects of the height and weight of those in this study measured by the dye dilution method of McGaff *et al* (1963) is about 420 ml. Their tissue volume by the method of Sackner *et al* (1975) using an acetylene rebreathing technique is about 280 ml. The combination of these other estimates gives a volume of blood and tissue of about 700 ml for our subjects. The agreement with our estimate is quite close, although the data of Peterson *et al* (1978) and Petrini *et al* (1978) suggest that the acetylene method may slightly overestimate tissue volume in normal lungs.

The standard deviation of the difference between radiographic and plethysmographic volumes was rather large and the problem with estimation of lung tissue and blood volume in this way is that of obtaining a relatively small number from the difference between two large ones, each of which has its own appreciable error. For this reason, although the mean value for the whole group is a reasonable one, less reliance can be placed on that for any individual subject. In this regard it should be noted that the soluble gas techniques of estimating lung water are good at estimating small volumes of quickly accessible fluid but greatly underestimate larger, more slowly available pools of water (Denison *et al* in preparation). Thus the two techniques are strictly complementary.

The mean difference between plethysmographic and single breath helium dilution volume in this group of normal subjects was +0·48 l (SD 0·29 l), and that between radiographic and helium dilution volumes was +1·19 l (SD 0·42 l). These differences may provide a useful index of inhomogeneity of ventilation or gas "trapping" in subjects with airways obstruction, and the combination of radiographic and gas dilution techniques permits such measurements to be made without a body plethysmograph.

The assessment of cross-sectional shape of the heart from CT scans in this study was complicated by the fact that since the scanner did not have the facility for gating with respect to the cardiac cycle, the cardiac image seen on the scans is a composite of the movements of the heart within the chest as well as its size and shape. This accounts for the rather large mean cardiac volume (1·01 l) obtained from the CT scans. In the anatomical sections, however, shape of the heart was even more accurately approximated by the elliptical estimate and the mean volume was a more realistic 0·77 l. In practice the chance that the heart should be in exactly the same position and state of contraction during the two instants at which the PA and lateral radiographs are taken is small. Mean radiological volume for the heart in the 35 normal subjects was 0·80 l (SD 0·145 l). Since this volume is relatively small compared with those of the whole chest and lungs, small errors due to slightly inaccurate shape assessment are unimportant in lung volume estimation. The method can be used to measure cardiac volume from radiographs and thus may be of use in the study of patients with cardiac disease.

Since the radiographic method is extremely accurate for structures of known geometric shape, its accuracy for estimating lung volume is dependent on that with which the actual volumes of each of the thoracic structures can be estimated from the appropriate PA and lateral dimensions. Combination of the error standard deviations for the chest, heart, spine, and subdiaphragmatic volumes yields an overall accuracy for the measurement of lung volume of ±210 ml. This is comparable with the accuracy of the body plethysmograph in the estimation of TLC which has been assessed by Barrett *et al* (1976) as ±250 ml, consisting of components of ±170 ml each for the thoracic gas volume at FRC (DuBois *et al*, 1956) and the inspiratory capacity components of the plethysmographic method. The reproducibility of the radiographic method is dependent on that of a pair of radiographs taken at TLC and that with which a given set of radiographs can be digitised. The former is difficult to assess because of the radiation exposure required for multiple pairs of radiographs in the same subject. The latter is <1% for a trained observer.

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References

Barnhard, H J, Pierce, J A, Joyce, J W, and Bates, J H (1960). Roentgenographic determination of TLC. A new method evaluated in health, emphysema and congestive heart failure. *American Journal of Medicine*, **28**, 51–60.

Barrett, W A, Clayton, P D, Lambson, C R, and Morris, A H (1976). Computerized roentgenographic determination of total lung capacity. *American Review of Respiratory Disease*, **113**, 239–244.

Brown, R, Hoppin, F G, jun, Igram, R H, jun, Saunders, N A, and McFadden, E R, jun (1978a). Influence of abdominal gas on the Boyle's law determination of thoracic gas volume. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, **44**, 469–473.

Brown, R, Ingram, R H, and McFadden, E R, jun (1978b). Problems in plethysmographic assessment of total lung capacity in asthma. *American Review of Respiratory Disease*, **118**, 685–692.

Dubois, A B, Botelho, S Y, Bedell, G N, Marshall, R, and Comroe, J H (1956). A rapid plethysmographic method for measuring thoracic gas volume: A comparison with a nitrogen washout method for measuring functional residual capacity in normal subjects. *Journal of Clinical Investigation*, **35**, 322–326.

Eycleschymer, A C, and Schoemaker, D M (1970). *A Cross-section Anatomy*. Butterworths, London.

Glenn, W V, jun, and Greene, R (1975). Rapid computer-aided radiographic calculation of total lung capacity (TLC). *Radiology*, **117**, 269–273.

Habib, M P, and Engel, L A (1978). Influence of the panting technique on the measurement of thoracic gas volume. *American Review of Respiratory Disease*, **117**, 265–271.

Hurtado, A, and Fray, W H (1933). Studies of total pulmonary capacity and its subdivisions. II Correlation with physical and radiological measurements. *Journal of Clinical Investigation*, **12**, 807–823.

Kovach, J C, Avedian, V, Morales, G, and Poulos, P (1956). Lung compartment determination. *Journal of Thoracic Surgery*, **31**, 452–457.

Matsukawa, A, Ito, T, and Kimura, K (1977). *Cross-section Anatomy and Computed Tomography: Trunk*. Igakutosho Shuppan, Tokyo.

McGaff, C J, Roveti, G C, Glassman, E, and Milnor, W R (1963). The pulmonary blood volume in rheumatic heart disease and its alteration by isoproterenol. *Circulation*, **27**, 77–84.

Paul, J L, Levine, M D, Fraser, R G, and Laszlo, C A (1974). The measurement of total lung capacity based on a computer analysis of anterior and lateral radiographic chest images. *IEEE Transactions on Biomedical Engineering*, **21**, 444–451.

Peterson, B T, Petrini, M F, Hyde, R W, and Schreiner, B F (1978). Pulmonary tissue volume in dogs during pulmonary edema. *Journal of Applied Physiology*, **44**, 782–794.

Petrini, M F, Peterson, B T, and Hyde, R W (1978). Lung tissue volume and blood flow by rebreathing: Theory. *Journal of Applied Physiology*, **44**, 795–802.

Sackner, M A, Greeneltch, D, Heiman, M S, Epstein, S, and Atkins, N (1975). Diffusing capacity, membrane diffusing capacity, capillary blood volume, pulmonary tissue volume and cardiac output measured by a rebreathing technique. *American Review of Respiratory Disease*, **111**, 157–165.

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