REGIONAL LUNG VOLUME MEASUREMENT BY TRANSMISSION SCINTIGRAPHY

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A technique for the absolute measurement of regional lung volume using transmission scintigraphy is described. A gamma camera placed behind the patient detects radiation passing through the chest from a uniform source containing ^{99m}Tc placed in front. The regional distribution of counts transmitted through the chest is recorded on a data handling unit linked to the camera. The regional distribution of anteroposterior chest thickness is also measured. From these two distributions it is possible, using a digital computer, to calculate the regional variation of lung volume. Total lung volumes measured in this way correlate very well with spirometer measurements. This technique overcomes the errors of regional lung volume measurement using ^{133}Xe gas where chest thickness variation, blood background, and nonuniform labeling of gas in poorly ventilating areas give false values. The technique is useful for measuring distributions of lung volume at different levels of respiration.

Quantitative studies of lung volume, with the exception of divided bronchospirometry, have been generally limited to the measurement of parameters relating to total function of both lungs. Fluoroscopic and radiographic techniques have been used to provide much useful regional information on the lungs and the former have also been applied to obtain regional ventilation assessment both qualitatively and quantitatively (*1,2*). The introduction of radioisotope techniques has broadened the scope of measurement of regional lung function. Perfusion can be assessed using labeled macroaggregates and ventilation by means of radioactive gases. Assessment of regional lung density changes has also been possible using monochromatic gamma-ray sources. Both multidetector systems (*3*) and gamma cameras (*4,5*) have been used to observe the change in transmitted counting rate from a monochromatic radiation source over the lung area between different levels of respiration.

The ^{133}Xe gas inhalation technique has been applied to measure regional lung volume (*6*). However, this procedure is subject to large errors due to the solubility of xenon in blood (*7*) and to the variation of chest thickness over the lung area. In an attempt to overcome these errors we have been investigating a technique for regional lung volume measurement using transmission scintigraphy.

METHODS

Patient procedure. The arrangement of equipment for the investigation is illustrated in Fig. 1. The patient lies on his back with a gamma camera placed below a low-attenuation couch. A high-energy diverging collimator is used to ensure that both lungs are included in the field of view. A uniform planar source containing a known amount of ^{99m}Tc-pertechnetate in the range 5–10 mCi is placed at a distance of 35 cm above the couch and centrally over the lung field. The source was chosen to be 14-in. square

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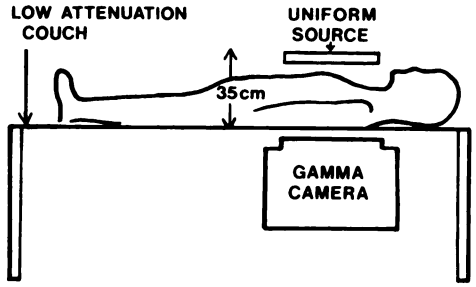

FIG. 1. Diagram showing arrangement of patient and apparatus for investigation.

so as to cover patients with large lungs while minimizing transmission at the edge of the chest of small patients. The collimator on the camera insures that only photons passing approximately perpendicularly through the chest will be detected. Different areas of the chest will absorb different amounts of radiation depending on the mean density and thickness of the chest below the area. The patient is instructed to hold his breath for either 10 or 20 sec at the selected level of respiration, e.g., total lung capacity (TLC) or residual volume (RV). The regional distribution of transmitted counts is accumulated in a 64 × 64 channel memory unit and stored on magnetic tape for computer processing later.

In the initial study the purpose has been to correlate total lung volume changes evaluated by the transmission technique with standard spirometer measurements and the latter were performed simultaneously with the aforementioned procedure in most cases.

The regional distribution of chest thickness is measured by assuming a simple model. It is taken to be constant across the thorax and to vary in the superoinferior direction as shown in Fig. 2. For males the thickness is constant just superior to the xyphisternum and then decreases linearly to the sternal notch. Measurement of the chest thickness at the sternal notch and the xyphisternum together with the position of gradient change are then sufficient to define regional chest thickness. For females the model is slightly different and three measurements of chest thickness are necessary. The measurements are made either just before or just after the regional transmission procedure with the patient supine and at the same level of respiration. The mean of three readings is taken for each thickness measurement.

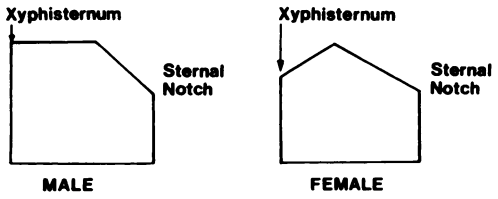

FIG. 2. Approximate model of chest thickness variation in superoinferior direction for males and females.

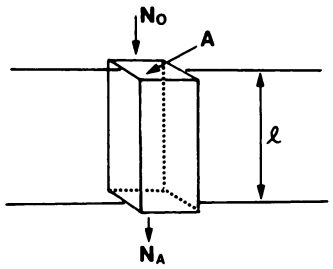

FIG. 3. Diagram illustrating variables used in theory of volume measurement.

Regional lung volume calculation. The regional lung volume is then calculated from the regional distribution of transmitted counts and regional variation of chest thickness using a 12k byte computer on line to the memory unit. It is first necessary to correct the regional distribution of transmitted counts for the nonuniform response of the gamma camera. Statistical smoothing of the data can also be applied if required. The counting rate N_A at the small area A of the lung is given by

$$N_A = N_0 \exp[-(u/\rho)\rho_A l]$$

where N_0 is the counting rate from the corresponding area of the source with no attenuation, ρ_A the mean density through the chest, l the chest thickness, and u/ρ the mass attenuation coefficient for tissue (Fig. 3). Attenuation by the air in the lung can be ignored. The mass attenuation coefficient and N_0 are determined in a calibration experiment described below. N_A and l are found during the examination leaving ρ_A, the mean density of the chest, the only unknown in the equation. The volume of air below area A of the chest is then given by

$$V_A = l\,A(\rho_C - \rho_A)/\rho_C$$

where ρ_C is the mean density of tissue and bone through the chest. An approximate calculation based on the relative amounts of tissue and bone in the chest shows this value to be about 1.04.

The computer is used to calculate these equations for each area of the chest. Correction is made for the variation of the area A represented by each channel of the memory unit due to the use of a diverging collimator. The calculated regional lung volume is then displayed on the memory unit. The total lung volume or the volume in any particular region can be found using a light pen.

Determination of mass attenuation coefficient. The mass attenuation coefficient was determined experimentally for tissue-equivalent material using the same arrangement of source and gamma camera as for patients. With a known activity of ^{99m}Tc in the source, the variation of counting rate on the memory unit with thickness of tissue-equivalent material was determined. This enabled calculation of the mass attenuation coefficient and, by extrapolation to zero thickness, the value of N_0. In general, the activity used for the patient examination is different from that used in the calibration experiment and N_0 has to be suitably corrected.

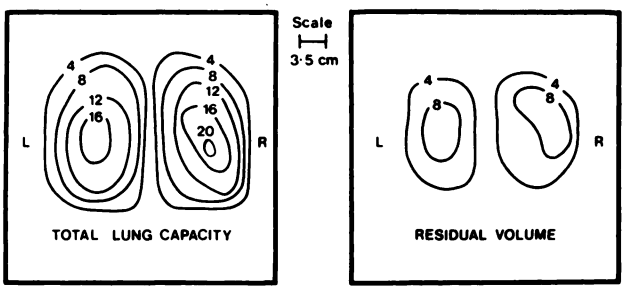

FIG. 4. Regional distribution of lung volume as contour plot for normal volunteer at total lung capacity and residual volume. Units are volume (milliliters) per square centimeter of surface area.

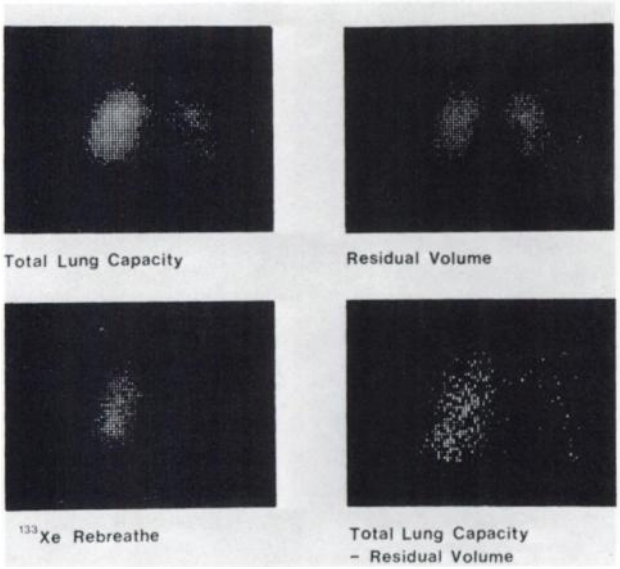

FIG. 5. Regional lung volume distribution of patient with poorly ventilating right lung at total lung capacity (top left) and residual volume (top right). Regional lung ventilation is displayed by xenon rebreathing technique (bottom left) and by subtracting transmitted counts at residual volume from those at total lung capacity (bottom right).

RESULTS

Regional lung volume distributions have been studied in a series of ten subjects including normal volunteers and patients with a variety of lung diseases. A typical normal distribution of regional lung volume at total lung capacity and residual volume displayed as a contour plot is shown in Fig. 4. Figure 5 shows the total lung capacity and residual volume distributions for a patient with a poorly functioning right lung. The total residual volume was normal (1.45 liters) and the distribution showed approximately equal volumes in the left and right lungs. However on inspiration to total lung capacity the increase in volume of the right lung is only 130 ml, showing the ventilation in this lung to be extremely poor.

The accuracy of the technique has been assessed by measuring total lung volume changes and correlating the values obtained with spirometer readings. The results are illustrated in Fig. 6 which shows good agreement between the techniques. The root mean square percentage difference between the paired measurements relative to the spirometer values was ±6%.

DISCUSSION

The principal cause of error in the technique is that encountered in measuring the regional variation of chest thickness. This is due to the approximations involved in assuming the models and to the fact that measurements are made at a different time from the regional transmission procedure. The assumption that chest thickness is constant across the thorax over the lung field is generally valid (*8*). Deviations from this occur at the edge of the lungs where chest thickness decreases and also in females. The models chosen for the superoinferior variation of chest thickness were considered to provide the best simple method of regional chest thickness determination. Over the series of patients studied, which covered a wide range of age and body build, the models were generally found to be accurate to within a maximum error of ±2 cm at any particular point. The reproducibility of the individual chest thickness measurements were nearly always within ±0.5 cm of a mean value. An error of 1 cm in the measurement of chest thickness at any particular area gives typically an error of 7% in the estimate of lung volume there. When total lung volumes are being calculated, there is an additional error due to the uncertainty in estimating the extent of the lung

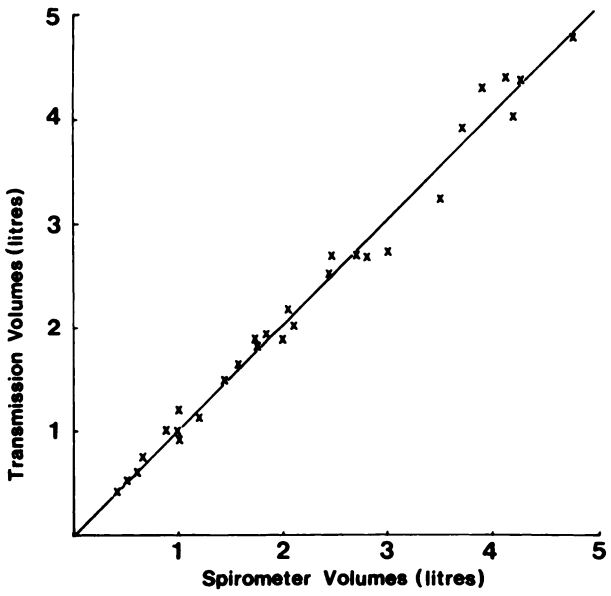

FIG. 6. Graph showing correlation of total lung volume changes measured by spirometer and transmission techniques.

field. With the collimator used, the counting statistics were adequate, a 20-sec breath hold being sufficient to obtain a total count of about 150,000. The spatial resolution of the lung volume distribution is limited by the high-energy collimator being used. Use of a low-energy diverging collimator would improve both counting rate and resolution.

The errors involved in the transmission technique are a considerable improvement on the alternative method of regional lung volume measurement using ^{133}Xe. In this technique the subject rebreathes oxygen labeled with ^{133}Xe from a spirometer until it appears that equilibration between the gas in the lung and the spirometer has been reached. Counts are then accumulated at the level of respiration of interest and taken to be proportional to lung volume over the lung field. Calibration is made by comparing total lung volume changes measured on the spirometer with total lung counting rate changes. Xenon, however, is appreciably soluble in blood and is also accumulated by tissue so that there is contribution to the counts obtained over the lung area from the blood perfusing the lungs and the blood and tissue in the chest wall. In addition, it has been shown that there is nonuniform labeling of the air in the lungs due to the different equilibration rates at the apex and the base (*7*). The more rapid equilibration at the apex gives rise to overestimates of the volume there with respect to the base of the lung of about 12% in normal subjects. The errors associated with patients with poorly ventilating regions of the lung are considerably greater. Each of the errors mentioned here can be reduced by the use of ^{13}N which is less soluble in blood than ^{133}Xe. However ^{13}N is cyclotron-produced and has a short half-life (10 min) so that it is not generally available. Also the energy of ^{13}N is higher than for ^{133}Xe and this results in decreased counting efficiency and more difficult collimation of the photons. A further error in the ^{133}Xe technique is introduced by the variation of chest thickness over the lung area and the corresponding differing amounts of attenuation. Since the chest is thicker at the base than at the apex, volumes at the base are underestimated. Using a gamma camera placed posteriorly with ^{133}Xe gas, underestimates of base volume with respect to apex volume due to chest thickness variation are typically as high as 15%.

Gamma-ray densigraphy using monochromatic gamma-ray sources has been used to study density changes between levels of respiration using single- and multidetector systems (*3,9*). The principle has also been applied in gamma camera studies of lung ventilation using the differential transmission of the 140 keV gamma rays from a ^{99m}Tc source (*4,5*). Use of the gamma camera enables a more detailed assessment of density changes than the probe system. These techniques, however, have only been used to detect differences in transmitted counting rate through the chest at different levels of respiration. The method described in this paper extends this principle by correcting the counts for the regional variation of chest thickness to obtain a true distribution of lung volume.

The ability to measure regional lung volume should prove to be particularly useful when used in conjunction with the xenon gas inhalation techniques for measuring regional ventilation. In some cases there are parts of the lung which are ventilating so poorly that no xenon is able to get into them in a 3-min rebreathing period. Figure 5 illustrates an example of this. The xenon rebreathe picture does not show up the right lung at all, revealing the lack of ventilation there. The transmission procedure provides the additional information that there is a volume of 670 ml of air trapped in that lung. The lack of function can also be demonstrated by subtracting the residual volume counts from the total lung capacity counts (*5*).

By using higher source activities it should be possible to investigate dynamically the variation of regional lung volume between different levels of respiration. We are currently investigating the measurement of regional closing volumes by taking frames of 1-sec duration while the patient breathes out from total lung capacity to residual volume over a period of about 15 sec. It may also be possible to measure regional forced expiratory volumes (FEV_1). However the counting rate required to produce adequate counting statistics would probably saturate an Anger camera system and deadtime corrections would have to be made.

The investigation is not unpleasant for the patient and takes only about 4 min to obtain the data for each lung volume distribution. No rebreathing with a gas from a spirometer is required as with the ^{133}Xe technique. The dose rate is very low (0.1 mrad/mCi/min) so that there is no restriction in the use of the test in children and in cases where followup examinations are necessary.

In conclusion, this technique makes possible regional measurement of a number of lung function parameters which could only be determined previously for the whole lung.

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