Quantitative features in the computed tomography of healthy lungs

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ABSTRACT This study set out to determine whether quantitative features of lung computed tomography scans could be identified that would lead to a tightly defined normal range for use in assessing patients. Fourteen normal subjects with apparently healthy lungs were studied. A technique was developed for rapid and automatic extraction of lung field data from the computed tomography scans. The Hounsfield unit histograms were constructed and, when normalised for predicted lung volumes, shown to be consistent in shape for all the subjects. A three dimensional presentation of the data in the form of a "net plot" was devised, and from this a logarithmic relationship between the area of each lung slice and its mean density was derived (r = 0·9, n = 545, p < 0·0001). The residual density, calculated as the difference between measured density and density predicted from the relationship with area, was shown to be normally distributed with a mean of 0 and a standard deviation of 25 Hounsfield units (χ^2 test: p < 0·05). A presentation combining this residual density with the net plot is described.

Previous workers have shown that useful diagnostic and functional information about the lung can be obtained from quantitative analysis of computed tomography scans, provided that the lungs are at a known degree of inflation.[1-4] When local densities are combined with measurements of slice area they can be used to calculate regional residual and tissue volumes and vital and total gas capacities.[5] This paper describes an automated system for extracting such data and presenting it so that local characteristics are obvious.

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Methods

Observations were based on the computed tomography scans of 14 healthy men and one emphysematous patient whose anthropometric and lung function details are given in table 1. The scans were obtained with an Elscint 2002 whole body scanner (scan time 5 seconds, collimation 10 mm, 140 kV, 40 mA), and recorded on magnetic tape for later processing. The lungs were scanned at full inspiration (total lung capacity—TLC) and again at full expiration (residual volume—RV), as described previously.[5]

The magnetic tapes were used to transfer scan data to an IBM 4381 mainframe computer, linked via a Series 1 minicomputer to a Ramtek 9400 display system. Programs were written in the IAX image

Table 1 *Anthropometric and lung function data for the 14 normal subjects (mean values) and the emphysematous patient*

| | Age (y) | Height (cm) | Lung function (% predicted) | | | | | |
			FEV$_1$	FVC	TLC	RV	TLCO	KCO
Normal subjects								
Mean	35	177	103	113	112	102	102	102
SD	10	8	10	11	11	22	11	13
Emphysematous patient								
	41	165	103	136	133	131	55	49

FVC—forced vital capacity; TLC—total lung capacity; RV—residual volume; TLCO—transfer factor for carbon monoxide; KCO—transfer coefficient for carbon monoxide.

processing language developed at Winchester,[6] with subroutines written in PL/I.

COMPUTER PROCESSING

Lung regions are detected automatically. For the algorithm we have defined lung as all that material in each computed tomography slice with a Hounsfield value between −1000 and −300 inclusive, which is contiguous with some point within the obvious lung chosen by the operator. This is a single criterion version of the contiguous pixel search[7] (also called an "ink blot" routine, to describe the way it operates by spreading over the picture) and is similar to a neighbourhood search.[8] To aid this routine, the right and left lungs are separated by a single high density line, which is drawn down the centre of the screen image automatically. Air within the trachea and main bronchi is isolated by a shape finding routine that starts from other points selected by the operator.

To decrease the operator time needed to run the system, a display of up to 25 computed tomography slices appears at once and all the points required (up to four a slice) are marked on the one screen. A batch system allowing points from 10 such displays to be accumulated was designed, enabling the complete
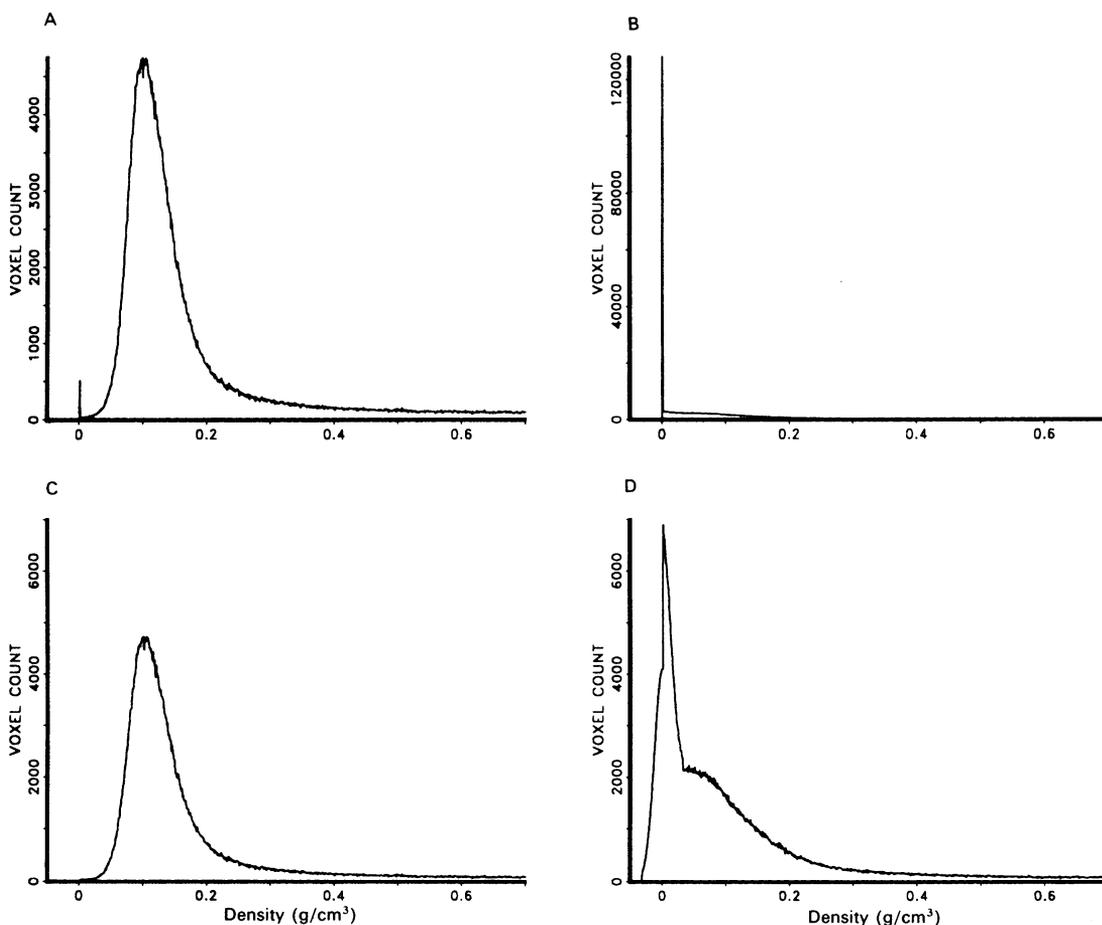

Fig 1   *Whole lung graphs, taken from the right lung at total lung capacity from one normal subject and one patient with emphysema. Each was obtained by adding together the data from individual slices. A—data from the normal subject, with a small spike at density zero; B—similar data from the patient with emphysema: the spike at zero dominates the graph and the Y axis has had to be altered to accommodate it. C and D show the same data as A and B after a Gaussian function has been applied to smooth the spike. The difference between the data from the normal and the emphysematous subject is maintained, but they can now both be plotted with the same axes. (The data from the same normal subject and patient are used in figs 2, 3, 4, and 7).*

scans from up to five patients to be processed in one session.

As the lung area is identified on each slice by the ink blot routine a Hounsfield unit histogram of the individual pixel values within it is automatically generated. A density histogram can then be derived from the linear relationship shown to exist between Hounsfield units and physical density in the range of values found within the lung.[5][9][10] Each of these histograms of individual slices, containing the data from up to 50 000 pixels apiece, can then be considered alone, or alternatively the whole data from one lung can be summed to obtain its overall characteristics. From this information air and tissue volumes can be calculated (fig 1a). Further indices, such as mean lung density, slice density, and slice area, can be readily derived.

The initial histograms always contain a spike of values at a density of zero (HU −1000, air). In the 10 mm thick slices studied here this value implies a column of air at least 1 cm long. In healthy lungs this spike represents a small fraction of all the pixels measured (1·01%). Some of these are generated by airways lying perpendicular to the slice and traversing its full thickness, but others may be artefacts of the reconstruction algorithm. As the true density gets closer to zero, the more zero values will accumulate as a unitary spike since the reconstruction algorithm does not allow densities below zero to exist. While this interferes only very slightly with the graphical presen-

Table 2 *Mean single lung volumes derived from the computed tomography data for 14 subjects (percentages express the volume of the single lung as a fraction of total lung volume)*

	Inspiration		Expiration	
	ml	%	ml	%
Right	3826	55	884	55
Left	3120	45	728	45

tation of the data from normal subjects, it completely overshadows the histograms of patients in whom unnatural air spaces actually exist (fig 1b). For purposes of display only, we have used a Gaussian distribution with a standard deviation of 10 HU to smooth this spike while preserving the total area under the curve, enabling all histograms to be plotted with the same axes and allowing for easy visual comparison of the data (figs 1c and 1d).

In a previous paper we used a manual technique similar to that described here to measure lung volumes from computed tomography scans,[11] and found a good correlation between the lung air volume derived by the computed tomography and the conventionally measured TLC, even in patients with enlarged, abnormal air spaces. In those patients we found many pixels with a zero density value, and included them in the calculations. We have therefore ensured for this study that a similar algorithm was used, and carried out all
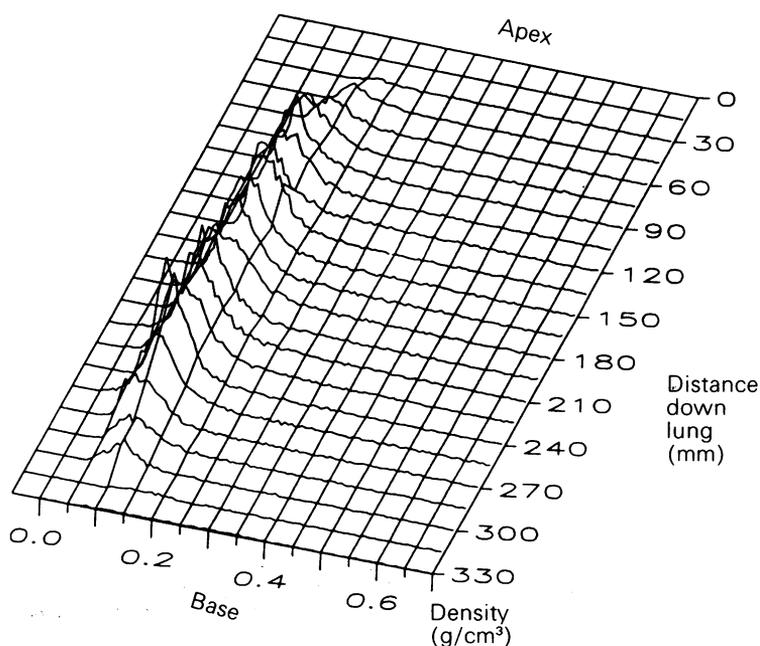

Fig 2 *"Net plot" taken from the right lung at total lung capacity in a normal subject. Each horizontal line corresponds to a histogram, taken from a single slice, at the marked distance down the lung. The similar shapes of adjacent lines indicates that they have similar pixel distributions. The varying heights of the lines shows the different proportions of the lung on each slice.*
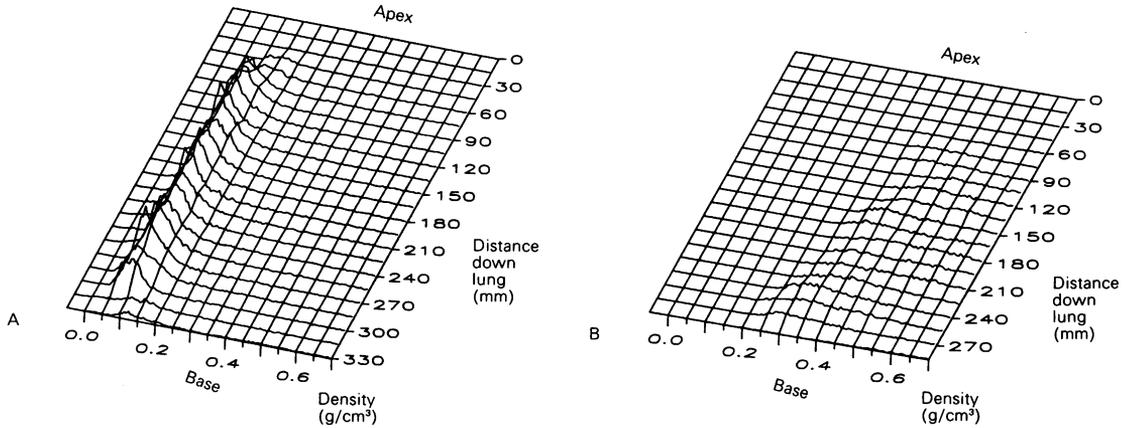
Fig 3 *Two net plots derived from one normal subject showing the left lung at total lung capacity (A) and residual volume (B).*

calculations on the initial histogram data before performing the smoothing for display.

In these histograms the area under the curve is equal to the total number of voxels scanned and is related to total lung volume (including air and tissue) by slice interval and voxel size. To group together or compare histograms from subjects with different lung volumes, who may have been scanned at various slice intervals, the data need to be normalised. There are several standards that could be used to do this. We prefer to use predicted total lung capacity, derived from a subject's height, age, and sex,[12] as the reference because it allows abnormalities of both size and density to be seen at the same time. The predicted capacity is first increased to include a tissue component, calculated from the measured mean computed tomography density of the lung, and then divided between the right and the left lungs, in the proportions 55% and 45%, to give the individual lung predictions and allow data from each lung to be viewed separately. The mean difference in volume between the two lungs is taken from the data in this study (table 2), and is similar to previously reported values.[13] The histograms of individual slices can also be combined graphically to obtain a three-dimensional "net plot." We have chosen to present this information as if the physician
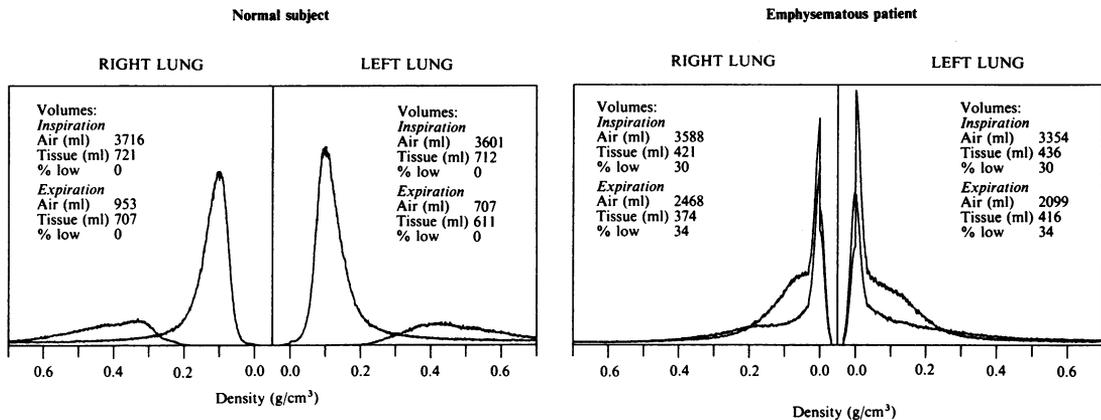

Fig 4 *Composite plot from one normal subject (above) and the emphysematous patient (below), showing graphs for the right and left lung total lung capacity and residual volume. The lung air and tissue volumes were derived from the initial data before smoothing (see text). The percentage of pixels with a Hounsfield unit value below −990 (density below 0·01 g/cm³) (% low) is also derived from the initial data as an index of abnormal air space content. The tissue volumes correspond to overall mean lung densities of 0·16 g/cm³ in the normal subject and 0·11 g/cm³ in the emphysematous patient.*

were looking towards the supine patient from the foot of the bed. Distance down the lung is on one axis, lung density on another, and normalised volume on the third (fig 2). Four such plots are obtained from each subject, representing the right and left lungs in inspiration and expiration (fig 3). These net plots allow easy visualisation of slice to slice density variations, and also provide quality control feedback on the initial scan, as any slice taken at the wrong phase of respiration will show an appreciably different density profile from that of its neighbours. Comparison of the inspiratory and expiratory plots shows the uniformity of ventilation as the density profiles change.

Results

The individual lung histograms give a simple visual summary of lung density and relative volumes. The percentages of pixels with densities below -990 HU are also calculated, as such measurements have been shown to be useful quantitative indices of emphysema in computed tomography scans (fig 4). Whilst the density values derived from computed tomography reconstructions are specific to each machine, we are prepared to accept these as actual densities on the basis of phantom studies conducted on this machine previously.[5] The inspiratory histograms for all 14

subjects are similar in outline, and when overlaid occupy a narrow range of possible shapes (fig 5). These data could be used to provide a standard with which any patient's histogram might be compared; but the net plot, because it preserves the information from individual slices, presents the possibility of raising a standard that could be used on a slice by slice basis. The inspiratory net plots are similar in shape in all subjects. The individual lines within them, however, show a systematic variation, the extreme apical and basal slices having smaller fractional volumes and higher densities. Allowing for this change of density with area in individual slices would provide a tight normal range of densities for each level of the scan.

To do this we have standardised the area of each slice against the predicted lung volume as previously, and plotted mean slice density against the logarithm of that area (fig 6). The relation between the two quantities is very nearly linear ($p < 0.0001$). When the equation derived from the correlation line is used to predict density from measured area, a residual value can be obtained that is equal to the difference between the predicted and the observed densities. Analysis of these residual values shows them to be normally distributed (χ^2 squared test, 11 degrees freedom; $p < 0.05$), with a mean value of Hounsfield units (95% confidence limits $+2.5$ to -2.5) and standard devia-
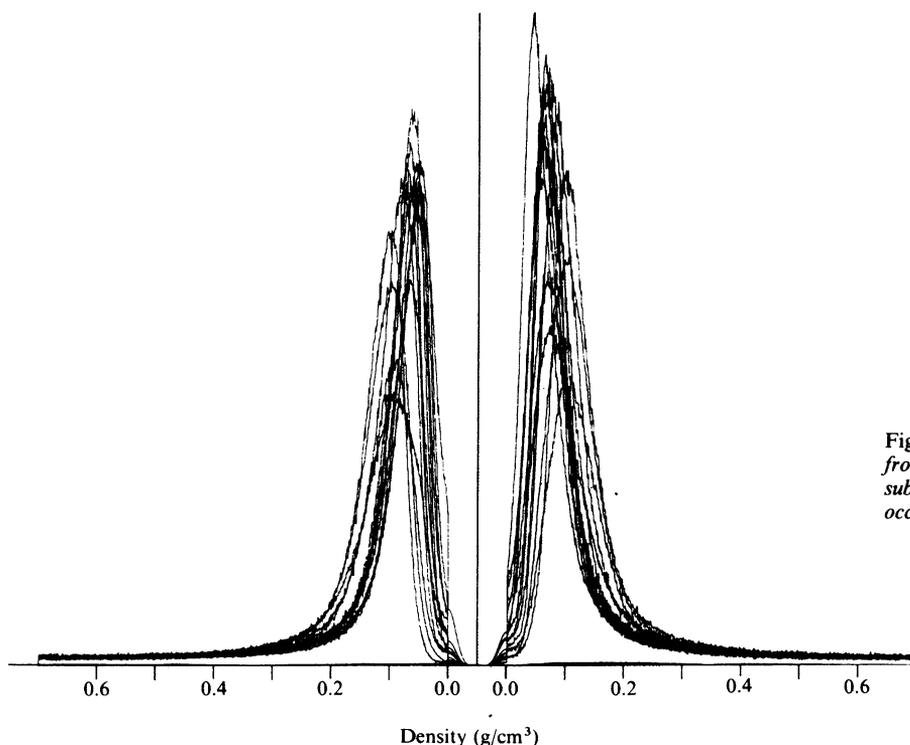

Fig 5 *Normalised curves from both lungs for all 14 subjects, showing them to occupy a narrow range.*

Density (g/cm^3)
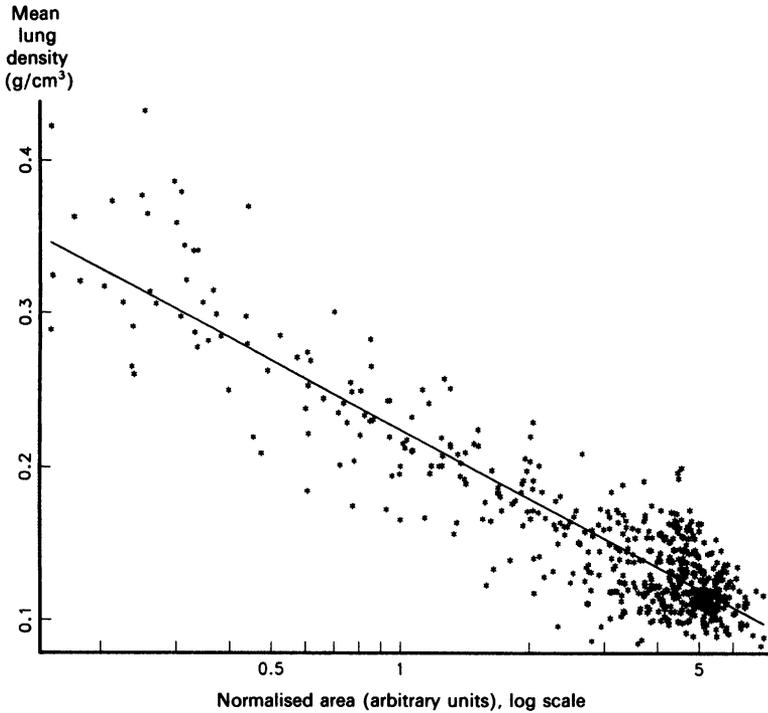
Mean
lung
density
(g/cm³)

Fig 6 *Measured mean densities of individual slices plotted against the natural logarithms of their normalised areas. The data are derived from the slices taken at total lung capacity only, and very small slices (those accounting for less than 1% of the total lung volume) have been excluded. The correlation line is highly significant (r = 0·9, n = 545, p < 0·0001) and is given by the equation y = 223 − 64 x.*

Normalised area (arbitrary units), log scale

tion of 25 (95% limits + 3 to − 3). Using this as a test slice density allows abnormal slices to be highlighted on the net plot as shown in figure 7.

Discussion

Previously we and others have defined the range of

Hounsfield units observed in normal lungs, and described the shape of their HU histograms from single slices. Differences in the histograms of normal, emphysematous, and fibrotic lungs have been described qualitatively, and the use of quantitative data to diagnose emphysema has been suggested.[1-5]

The present paper describes new information in the

LEFT LUNG—inspiration volumes:
Air   3354 ml
Tissue 436 ml

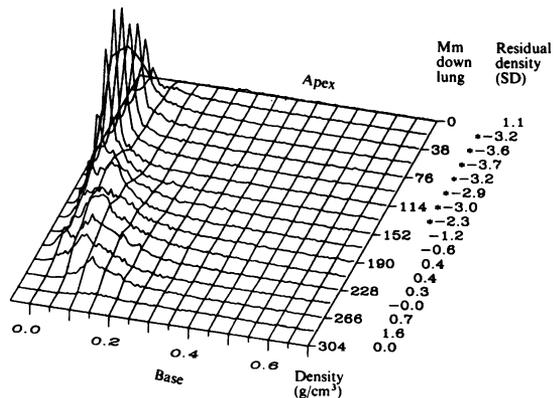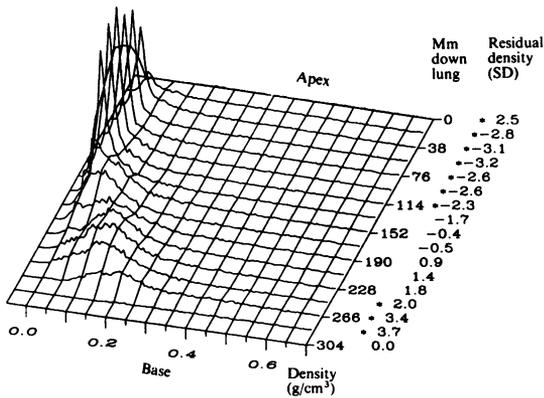RIGHT LUNG—inspiration volumes:
Air   3588 ml
Tissue 421 ml

Fig 7 *Net plots at total lung capacity from both lungs of an emphysematous patient. The lung volumes and residual densities, expressed in standard deviations, have been added for ease of interpretation.*

following senses. Firstly, it defines HU histograms for whole lungs. Secondly, it defines normal standards of density for computed tomography scans of the lung on a slice by slice basis, showing how these can be corrected for variations in mean density that are associated with slice area. It also suggests a new method for presenting complex slice by slice information in a way that can be rapidly appreciated by eye.

We believe that the relationship between mean lung density and normalised area is due to partial volume effects, which, being proportional to the circumference of the lung area, have a greater effect on smaller slices. Moreover, there is known to be a ventrodorsal density gradient within the lung on computed tomography scans due to gravity[10] and, because many of the small area slices consist of small crescents posterior to the diaphragm at the lung base, these will have a higher mean density than the larger slices.

We wish to draw attention to the limitations of the standards proposed here as they are derived from one scanner and are based on only 14 people. Subjects must be selected retrospectively after they have had scans for valid clinical reasons. In our case we see professional divers referred for "fitness to dive" examinations after pulmonary barotrauma at sea. We plan to revise the standards suggested here once substantially more data become available. We think that the density values obtained with our scanner are correct, as a result of previous phantom studies.[5] The standards may have to be modified before being used on data from other scanners.

The ventrodorsal density gradient present on each slice of the scan has not been investigated in this paper. Refining the technique used to include this would give more precise information on the distribution of density throughout the lung in normal subjects, and so enable more precise standards to be derived. This in turn could lead to easier detection of abnormal density areas within the lung by an automated system. Clearly this is an area where further research is required.

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