THE LUNG VOLUME AND ITS SUBDIVISIONS

I. METHODS OF MEASUREMENT

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In perhaps no realm of physiology is there a more confusing medley of terms than in that which deals with the lung volume and its various subdivisions. Not only does the meaning of many terms vary with the user but there is an unfortunate superfluity and synonymity of the terms themselves.

Residual air as first described by Davy (1800) is the amount of air remaining in the lungs after the fullest possible expiration.

Vital capacity as described by Hutchinson (1846) is the amount of air that can be expired from the fullest inspiration to the fullest expiration.

Total lung volume or total capacity is the sum of residual air and the vital capacity.

Mid-capacity as defined by Panum (1868) is the amount of air in the lungs at a point mid-way between normal inspiration and expiration, this level being referred to as the mid-position or mid-point, or even vital respiratory level. Siebeck (1910) and others prefer to describe the mid-capacity as a quantity synonymous with the functional residual air (vide infra).

Functional residual air as described by Lundsgaard and Schierbeck (1923) is that amount of air remaining in the lungs after a normal expiration. This quantity has also been called the mid-capacity or normal capacity, and the level has been named the resting respiratory level, the expiratory level, the mid-position or mid-point.

Complemental air has been variously described as the amount of air inspired from the mid-position to maximum inflation, or from the height of a normal inspiration to maximum inflation.

Reserve air or supplemental air has been variously described as the air expired from the mid-position to maximum deflation or from the end of a normal expiration to maximum deflation.

Tidal air is the quantity of air expired by a breath of average depth.

Were it not for the confusion that already exists we would hesitate to offer any further addition to this classification but simplification necessarily involves some minor changes in definitions. The terms vital capacity and residual air have stood the test of time and we would not modify them. However, they are the product of respiratory gymnastics and surely it is important to establish some simple nomenclature with respect to the level at which we normally breathe. A glance at any

series of respiratory tracings, as taken in the routine estimation of the basal metabolic rate, shows clearly that the constant respiratory level is at the end of expiration. The inspiratory level and mid-capacity vary with the depth of inspiration, a variation which is often considerable both from breath to breath and from minute to minute. From a functional point of view also, it is the amount of air remaining in the lungs after expiration (the functional residual air) that we have to ventilate. Without entering into a discussion of the Hering Breuer reflex it can be safely said that there is much evidence that it is from the expiratory level (resting respiratory level) that the respiratory cycle has its initiation. Also it is at this level that there occurs the maximum pause during the respiratory cycle. To inflate the lungs above it one group of muscles is used, while to deflate the lungs below it an entirely different group is used. It would seem then that, from both practical and theoretical considerations, any measurements involving the amount of air normally present in the lungs should be based on the functional residual air or the resting respiratory level. On this basis we have adopted the nomenclature depicted in Figure 1. The complemental and reserve airs are
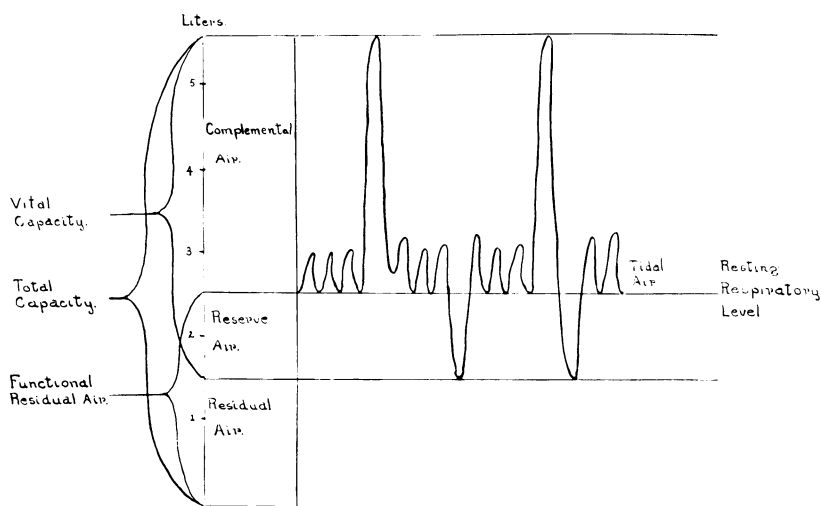

FIG. 1. THE LUNG VOLUME AND ITS SUBDIVISIONS

measured from the resting respiratory level and we agree with Anthony (1927 and 1930) that these should be measured separately, but are equally convinced that the vital capacity should also be measured independently, as in its original definition by Hutchinson. The reasons for this are obvious when we consider those cases where there is any impairment of pulmonary elasticity. Two tracings of the vital capacity in such a case are shown in Figure 2 and it is obvious that if we divide the vital capacity into complemental and reserve air we are confronted with

the absurdity of having a negative quantity for the latter. Actually when the reserve air was measured separately in this case it amounted to some 300 cc. The significance of this type of tracing will be discussed in a subsequent communication but we believe that such a discrepancy between the sum of the complemental and reserve airs measured in this way, and the vital capacity, represents the earliest sign of impairment of pulmonary elasticity. This feature can only be brought out if the tracings are taken in the manner described.
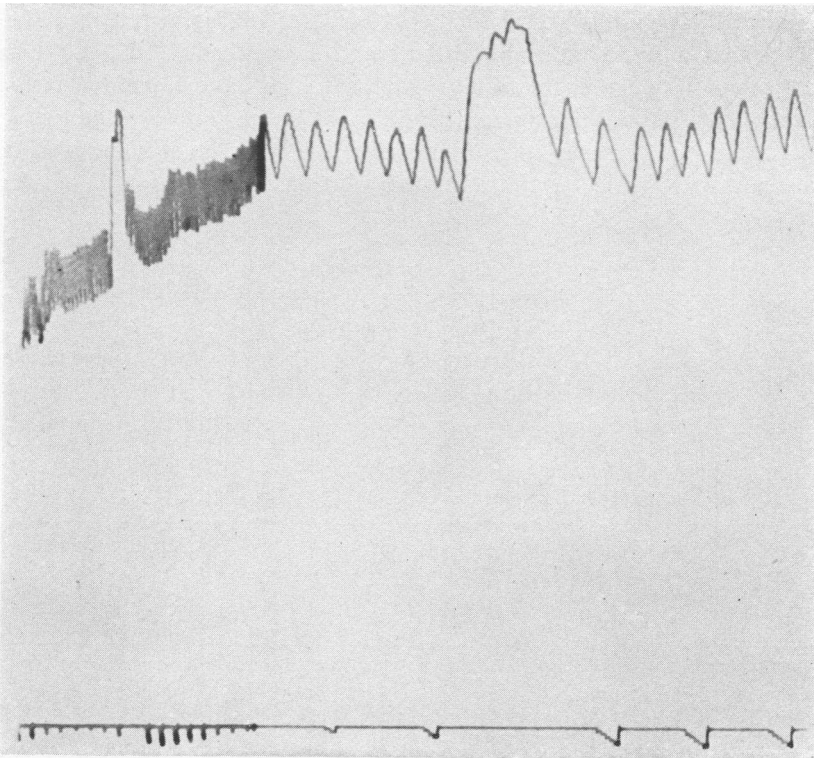

FIG. 2. THE VITAL CAPACITY IN A CASE OF ADVANCED EMPHYSEMA
Time marker 5 seconds.

By using this nomenclature a complete analysis of the lung volume and its functional and artificial subdivisions can be made, by stating only 5 quantities. (a) The complemental air, reserve air and vital capacity, (b) the tidal air, (c) the residual or functional residual air. These three groups will be considered separately.

Measurement of the complemental air, reserve air and vital capacity

It is obvious that to measure the complemental and reserve air, some method involving the graphic registration of respiration must be used

(Figure 1). By ordinary graphic spirometric methods the volume of air displaced by forced inspiration or expiration can be measured accurately to within 5 or 10 cc., and yet under even carefully controlled conditions we have found these amounts to vary by several hundred cc. in duplicate measurements on the same subject.

The expulsion of the reserve air is the result of a voluntary unnatural effort and as such can be profoundly influenced by many factors such as posture (Panum (1868), Bohr (1907), Hasselbach (1908), Wilson (1927) and Livingstone (1928)), fatigue (Peabody and Sturgis (1921)), respiratory resistance (Bittorf and Forschbach (1910), Bass (1925) and Thiel (1929)), and various external stimuli (Bittorf and Forschbach (1910)). Even when these factors were carefully excluded [1] we have found variations of over 300 cc. in both normal and pathological subjects. The same range of variation was found in measurements of the complemental air and the vital capacity (Table I), and as no correlation could be found between

TABLE 1

Variations in the vital capacity and its subdivisions

Quantity measured	Group	Number of cases	Number of observations	Average deviation from individual mean	Maximum deviation from individual mean
				cc.	*cc.*
Vital capacity	Normals	4	28	±110	314
	Emphysema	5	19	± 89	300
	Cardio-respiratory	10	33	±115	403
Reserve air	Normals	4	37	± 78	318
	Emphysema	5	27	± 76	225
	Cardio-respiratory	10	37	± 63	371
Comple-mental air	Normals	4	32	±109	316
	Emphysema	5	29	± 62	187
	Cardio-respiratory	10	40	±115	350

the variation of these three quantities and they do not permit of statistical analysis, one must conclude that they were due to fortuitous changes in muscular effort rather than changes in the resting respiratory level. Indeed this is the only possible explanation since any series of reserve and complemental air estimations made at say $\frac{1}{2}$ minute intervals show the same variations, although the resting respiratory level may remain a perfectly even base line. Such a variation in a voluntary and almost violent respiratory effort as is required for the complete expulsion of the

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[1] Subject rested for 15 minutes in recumbent position, measurements then made with arms by side, shoulders flat on bed, and one pillow supporting head.

reserve air or indraught of the complemental air is indeed to be expected from a general physiological point of view and necessarily reflects fortuitous variations in the residual air and total capacity.

Measurement of the tidal air

The measurement of the tidal air is a very simple physical problem and so many accurate methods have been described that any discussion would be pointless. The same may be said of any discussion of changes in the tidal air due to central and peripheral stimuli. It need only be emphasized that the tidal air is a quantity which varies from breath to breath and only an average over a stated period of time has any real meaning.

Measurement of residual or functional residual air

The number of methods described for the measurement of the residual or functional residual air approaches the number of papers published on this subject, a total of 47 having been reviewed. Although there are obvious fallacies in many of the methods and equally obvious incompatibilities in the results produced, we have been unable to find any critical review of the subject. Before describing the method which we have developed we propose to present some theoretical and experimental criticism of those methods commonly in use. These divide themselves into three main groups:

(1) The so-called pneumatometric method,
(2) Gas dilution with forced breathing,
(3) Gas dilution without forced breathing.

The principles underlying these methods will be criticised separately without entering into the minor modifications which have been proposed by almost every worker in this field.

I. PNEUMATOMETRIC METHOD

Originally described by Pflüger (1882) this method is based on Boyle's Law, which states that the volume of a gas varies in inverse proportion to the pressure to which it is subjected. The subject is placed in an air-tight cabinet, breathing through a mask or mouthpiece connected with an opening in the cabinet. The air displaced from the cabinet by the respiratory expansion and contraction of the chest is graphically recorded by means of a spirometer. Expiration is suddenly completely obstructed and the subject told to make an expiratory or inspiratory effort against this absolute resistance. The positive or negative pressure so generated in the respiratory tract is recorded by a mercury manometer and the change in the volume of air in the lungs also accurately recorded by a small spirometer attached to the cabinet. From the relationship of the volume change to the pressure change the volume of air in the lungs can

TABLE II

A comparison of methods for the measurement of the residual or functional residual air

Author	Method	Type of subject	Number of subjects	Number of observations	Maximum	Minimum	Average deviation from individual mean	Maximum deviation from individual mean
					cc.	cc.	cc.	cc.
Schenck (1894)	Pneumatometric	Normals	1	66	2065	952		726
Bass (1925)	As above	Normals	6	47	1940	930	±93	347
Bohr (1907)	H_2 dilution of residual air	Normals	5	19	2460	710	±80	190
Tobiesen (1911)	As above	Tuberculous	11	22	3650	700	±174	325
Peters and Barr (1920)	O_2 dilution of residual air	Cardiac	8	18	2320	757	±34	89
Campbell and Hill (1931)	As above	Normals	5	31	1481	710	?	184
This paper	As above	Normals	1	15	2363	2008	±83	196
Binger and Brow (1924)	H_2 dilution of functional residual air	Normals	10	27	3240	1530	±40	153
This paper	As above	Normals and tuberculous	9	21	3697	960	±72	240
This paper	O_2 dilution of functional residual air	Model lung	2 sizes	10	5120	3310	±7	10
		Cardio-respiratory	14	40	4931	948	±107	280
		Normals	3	25	2710	2292	±93	170

be calculated. Modifications of this method have been described by Neupaur (1879), Kochs (1884), Schenck (1894 (2), 1895 (2)), Bass (1925) and Wolf (1928 (3)), which give figures for the residual air ranging from 400 cc. to 19,800 cc. Bass and Schenck are the only authors who give the data necessary for an estimate of how accurately observations can be duplicated on one individual (Table II). Bass himself does not discuss the accuracy of the method from this point of view and does not deny the discarding of results which show any marked deviation from the mean. From the context of his paper and results given, we suspect this to be the case.

The fallacies and drawbacks of the method are obvious. As Schenck (1894) has shown, and as we would expect, the gases in the gastro-intestinal tract are measured with the residual air. Also, the slightest leak around the mouthpiece, while the subject is making the expiratory effort, would not be shown on the tracings and yet would completely vitiate the results. The apparatus is cumbersome and its management full of technical difficulties, while more cooperation is demanded of the subject than can be given by even the most healthy individuals (Kochs (1884)).

II. GAS DILUTION WITH FORCED BREATHING
(a) Hydrogen Dilution

Originally described by Davy (1800) and since modified on minor points of technique by Gréhant (1887), Berenstein (1891), Bohr (1907), Hasselbach (1908 (2) and 1912), Rubow (1908), Morawitz and Siebeck (1909), Bittorf and Forschbach (1910), Siebeck (1910 and 1912), Bruns (1910) and Tobiesen (1911), this method is based on the dilution of a known volume of hydrogen by the residual air in the lungs. After a forced expiration to expel the reserve air the subject takes from 5 to 7 deep and rapid breaths from a bag or spirometer containing a known volume of hydrogen. A homogeneous mixture of gases is then assumed to be present throughout the bag or spirometer and the lungs. A sample of this mixture is analysed to find the degree to which the hydrogen has been diluted. From the degree of dilution the volume of residual air can be calculated.

(b) Oxygen dilution

Exactly the same as the hydrogen dilution method in principle, the residual air is calculated from the degree to which the nitrogen in the alveolar air is diluted by a known volume of oxygen. This method was originally developed by Durig (1903) and since by Lundsgaard and Van Slyke (1918), Peters and Barr (1920), Lundsgaard and Schierbeck (1922 and 1923), Lundsgaard (1923) and Campbell and Hill (1931).

In only four of the articles referred to is there sufficient data to form any estimate of the accuracy of either of these methods. With the exception of that by Peters and Barr, which will be discussed later, a

considerable range of variation in duplicate analyses on the same individual is shown amounting to an average deviation from the mean of from 80 cc. to 174 cc. and a maximum deviation from the mean of from 184 cc. to 325 cc. (See Table II.) Using the oxygen dilution method as described by Lundsgaard and Van Slyke (1918) we have performed a series of 15 estimations of the residual air on one subject. The results (Table II) show a range of from 2363 cc. to 2008 cc. with an average deviation from the mean of 83 cc. and this in spite of the fact that the subject was an intelligent, healthy technician, long accustomed to vital capacity measurements and the Haldane Priestley method of sampling alveolar air. The volume of O_2 was measured to ± 2 cc. and the O_2 analyses done in duplicate with an accuracy of $\pm .05$ per cent; a combination of sufficient accuracy to measure the volume of a model lung to within ± 10 cc. (Table II).

On analysing various points of technique in the method and some of the assumptions made, it becomes obvious that a considerable range of error is to be expected in either of these two gas dilution methods. Considering the wide use that has been made of these methods and their comparatively recent popularity, it might be well to discuss our criticisms in detail.

(a) *True but fortuitous variations in the residual air.* The inconstancy of the reserve air has already been described and it has been shown that even under carefully controlled conditions variations in this quantity may reflect changes in the residual air which are fortuitous in nature. Indeed we think it probable that this inconstancy of the reserve air is mainly responsible for the variations found in the residual air of normal individuals, as measured by this method. A comparison of Tables I and II certainly shows a very similar deviation from the mean.

(b) *Mixing of gases by forced breathing.* Owing to the popularity of gas absorption methods in the estimation of the circulation rate, the problem of gas mixing in the lungs has received considerable attention. Without going fully into the controversy it may be stated that the consensus of opinion inclines to the view that in the healthy subject 5 breaths of 2 liters depth or more from a bag containing from 2 to 3 liters of a foreign gas are sufficient to ensure homogeneity throughout the lung-bag system (Krogh and Lindhard (1917), Lundsgaard (1923), Grollman and Marshall (1928), etc.). In any pathological condition, however, where there is an impairment of alveolar ventilation or reduction of vital capacity, the evidence is entirely against complete mixing of gases or any homogeneity throughout the lung-bag system (Siebeck (1910, 1911 (2), and 1912), Bruns (1910), Weiss (1928), Anthony (1930)). In spite of these observations, both these H_2 and O_2 dilution methods for the measurement of residual air have been used on patients with all types of pulmonary impairment, in some of which the vital capacity was admit-

tedly below a liter. One such is the publication by Peters and Barr, whose duplicate analyses are summarised in Table II. All the criticisms we have to make regarding these gas dilution methods apply both to the methods and to the patients they used. It must be added that they make no statement as to the accuracy of the method and on that score may have discarded results showing any marked deviation from the mean, in which case our tabulation of their results in Table II is meaningless. In any case it is yet to be shown that measurements of this type on patients with such a low vital capacity have any real relationship to the residual air.

(c) *Inconstancy of percentage of nitrogen in alveolar air.* In the oxygen dilution method it is necessary either to measure or to assume some constant for the percentage of nitrogen in alveolar air since it is this that is being diluted with the O_2 (even the respiratory dead space will contain alveolar air after expulsion of the reserve air). Various constants have been assumed for this value but actually the alveolar nitrogen shows considerable variation among different groups of patients and in individuals of the same group. In fifty-three observations on four normal individuals we have found an average of 80.28 per cent N_2 in the alveolar air, in thirty-eight observations on eighteen cases with cardiorespiratory disease an average of 79.98 per cent N_2, and in fourteen observations on six cases with emphysema an average of 81.21 per cent N_2. Even these average values show considerable variations between the different groups but when we take the extremes we find a maximum of 82.33 per cent N_2 in the alveolar air of a case of emphysema with extreme cyanosis and a minimum of 79.42 per cent N_2 in a case of congenital stenosis of the pulmonary artery. In both these cases the pCO_2 as calculated from analysis of the arterial blood closely agreed with that found in the alveolar air, so we can accept these extreme variations as being real and not due to faulty sampling.

(d) *Gas absorbed by blood.* It is known that hyperventilation produces very definite changes on the circulatory system and on haemorespiratory exchange (Marshall and Grollman (1928), Schneider (1930), Herxheimer and Kost (1931)). Any change in the circulation rate through the lungs must obviously be associated with changes in O_2 consumption and also in the amount of a foreign gas which will enter into solution in the blood. To estimate the significance of these factors we have performed some experiments on a subject on whom we had made 15 determinations of the residual air by the O_2 dilution method of Lundsgaard and Van Slyke (Table II). We found that during a 20 second period of hyperventilation, with 5 breaths of between 3.3 and 3.6 liters, the circulation rate ranged from 6.5 to 9.8 liters a minute, with an average of 7.8 liters in 4 observations, representing an increase of 90 per cent over his resting circulation rate. (Details of the method used have not yet been pub-

lished.) With this was found an increase of from 59 per cent to 98 per
cent in the oxygen consumption with an average of 73 per cent. The
average basal oxygen consumption was 270 cc. per minute and from these
figures we can calculate that the respiratory gymnastics associated with
this method of measuring the residual air was accompanied by an oxygen
consumption of approximately 160 cc. in 20 seconds, the actual amount
varying somewhat within the degree of hyperventilation. If we add to
this 10 cc. as representing the amount of O_2 taken up in physical solution
at $\frac{1}{2}$ an atmosphere pressure of O_2, we have a total of 170 cc. of O_2 which
has passed into the blood during 20 seconds of hyperventilation. If an
equal amount of CO_2 be excreted during this period, no error in the
estimation of lung volume will result. Unfortunately this is not the case.
The percentage of oxygen in the bag is sufficient to ensure complete
saturation of the blood but since the percentage of carbon dioxide in the
inspired air is continuously rising, some impairment of CO_2 excretion
must occur which would tend to lower the respiratory quotient. The
hyperaeration of the alveoli on the other hand would tend to raise the
respiratory quotient. The exact balance of these two factors is difficult
to estimate when breathing high oxygen mixtures. When room air is
rebreathed under the same conditions we have found the R.Q. to average
0.92 on 5 estimations and we can only say that with high oxygen mixtures
it must be considerably lower. Even an R.Q. of 0.8 would lead to an
error of 34 cc. in the estimated lung volume under the circumstances
described.

   With the H_2 dilution method the error involved by gas absorption is
small but is still present. If we assume that 2000 cc. of blood passes
through the lungs during the period of hyperventilation approximately
15 cc. of H_2 will be absorbed at a pressure of $\frac{1}{2}$ an atmosphere representing
an error of less than 20 cc., with a final dilution to 50 per cent H_2.

   (e) *Nitrogen excretion from the blood.* In the H_2 dilution method, the
N_2 excreted is of no moment but in the O_2 method, where dilution of the
alveolar air is the basis of calculation, all N_2 excreted will be measured
as if it were originally present in the alveolar air. From the figures of
Hill, Long and Lupton (1924), and of Campbell and Hill (1931), the N_2
excreted in 20 seconds with hyperventilation and $\frac{1}{2}$ an atmosphere of O_2
would only amount to some 10 or 12 cc., which would result in an error of
less than 20 cc. in the residual air estimation.

III. GAS DILUTION WITHOUT FORCED BREATHING
(a) *Hydrogen dilution*

   A very definite advance in the technique of lung volume measurement
was made when Van Slyke and Binger (1923) described their method for
the estimation of the residual air, or functional residual air, without
forced breathing, and it is remarkable how few have availed themselves

of this excellent method or its modification by Binger and Brow (1924). The method is based on the mixing of a known volume of hydrogen with the nitrogen in the lungs, mixing being accomplished by quiet respirations from a spirometer for from 5 to 7 minutes.   The volume of air in the lungs at the moment the patient is switched to the spirometer is calculated from the volume of hydrogen originally added to the spirometer and the ratio of the percentage of hydrogen after mixing has been accomplished. Those who have worked with the method have found it entirely satis- factory (Binger (1923), Binger and Brow (1924), Meakins and Christie (1929), and Anthony (1930)), but unfortunately only one of these papers contains the data necessary for an estimate of the accuracy of the method when applied to the human subject.   Meakins and Christie have used this method on a limited number of subjects with satisfactory but less im- pressive results than those obtained by Binger and Brow (Table II).   It must be stated, however, that our own figures were obtained with the use of a Haldane gas analysis machine, using the micro method, and part at least of the variation found by us may have been caused by errors in an- alysis.   Anthony (1930), although no protocols are published, finds with this method a maximum variation of 100 cc. and an average variation from the mean of 50 cc.

From a technical point of view the only criticisms of this method we can offer are the errors from absorption of hydrogen and excretion of nitrogen by the blood, but with similar technique it seems improbable that these factors should vary greatly from time to time in the same sub- ject.   With a final mixture of 30 per cent N_2 it can be estimated from the figures of Hill, Long and Lupton (1924) and Campbell and Hill (1931) that at least 65 cc. of N_2 are excreted into the lungs in 5 minutes.   No figures for the absorption of hydrogen are available but if we take the absorption coefficient of hydrogen as 0.01644 and the final percentage as 30, and assume gaseous equilibrium to have been established between the alveolar air and 10 liters of body fluids (an amount which is probably too low), it can be calculated that approximately 50 cc. of hydrogen have been absorbed from the lungs.   If 1500 cc. of H_2 were originally added to the spirometer and 1500 cc. of N_2 were present in the alveolar air, this haemo- respiratory exchange would result in a measured $\frac{N_2}{H_2}$ ratio of 1.07 instead of the true ratio of 1.00.   The resultant error in the lung volume estimation would amount to 105 cc., a figure very close to that assumed by Anthony (1930) but a figure which, in our opinion, is minimal, 150 cc. or 200 cc. being equally probable.   Again a figure for the percentage of nitrogen in the alveolar air has to be assumed and a certain error will result.   In the extreme case of emphysema quoted above with an alveolar N_2 of 82.33 per cent this error would amount to some 60 cc. even if the residual air were normal and not increased, as was the case.   Mixing of gases through- out the lung-spirometer system, on the other hand, has been shown to be

complete, both in normals and in those with cardiovascular disease (Van Slyke and Binger (1923)).

The main drawback of this method is one that appeals perhaps to the less scientific and more imaginative members of the medical profession. The routine use of an explosive mixture in respiratory experiments is considered by some to be unsafe and to my knowledge has frightened several investigators from the method. The possibility of arsenical poisoning must also be excluded. In a laboratory with careful workers we do not see that there is any danger, but have also found it difficult to convince both the laity and some of the medical profession. It was mainly for this reason, but also in the hope that we might be able to simplify the technique of lung volume measurement, that we have developed a method which requires little but what is available in every well-equipped hospital laboratory.

(b) Oxygen dilution without forced breathing

The principle underlying the method is again the dilution of the nitrogen in the lungs with a known volume of oxygen, but complete mixing is ensured by adopting the technique of Van Slyke and Binger. At the same time some of the drawbacks of their method are avoided.

DETAILS OF THE APPARATUS

The spirometer is of the standard type as commonly used in the estimation of the basal metabolic rate, with a capacity of from 6.5 to 8 liters (preferably the latter) and equipped with the usual ink recording attachment and thermometer. The counterpoise is adjusted so that balance is perfect with the bell at half capacity. The soda lime scrubber should be removed from the body of the spirometer and this space filled with solid paraffin to form a solid central core pierced by the inspiratory and expiratory tubes. The spirometer dead space is then reduced to a minimum, as when the bell is lowered its interior is almost completely occupied by the solid centre core, the thermometer projecting into either the inspiratory or expiratory tube. The inspiratory and expiratory valves are placed outside the spirometer and as near to the mouthpiece as is convenient. Between each valve and the spirometer is placed a 3-way tap so that in the one position the subject breathes to and from the room, and in the other, to and from the spirometer. A soda lime scrubber is inserted on the expiratory side of the circuit between the 3-way tap and the spirometer. Between the scrubber and the spirometer is the usual side tap for the collection of samples. With the bell fully lowered the volume of air in the whole circuit, from mouthpiece to spirometer and spirometer to mouthpiece, should not exceed 3,000 cc. or at the most 3,500 cc. (see measurement of spirometer dead space) and this quantity should be kept absolutely constant. All tubing connecting the mouthpiece with the spirometer should be of such rigidity and so arranged that the volume of its lumen will remain constant. We have found short lengths of glass tubing connected with rubber tubing very satisfactory. The volume of soda lime in the scrubber is kept constant by weighing. It is also important that there should be no variation of the level of water in the water seal. This is easily avoided by the use of a small syphon manometer so placed that it will not interfere with movements of the spirometer bell.

Gas analysis may be accomplished by any of the many methods capable of analysing up to 50 per cent oxygen mixtures with an accuracy of ±0.1 per cent or less. A Haldane gas analysis machine graduated to the 5 cc. mark has been found satisfactory although the absorption of oxygen is somewhat tedious. We have collected the samples over mercury in a Haldane sampling tube, and analyses have always been done in duplicate.

Measurement of spirometer dead space

With such a complicated system it is impossible to obtain any accurate calculation of the volume of air in the spirometer dead space (i.e., the volume of air in the spirometer and tubing with the bell empty) by simple linear measurements. Much more accurate is its measurement by gas dilution, which serves the double purpose of giving a figure for this quantity, and also of standardizing the accuracy of the gas analysis and other points of technique. We have found the following technique for the measurement of the dead space simple, and surprisingly accurate. A rubber bag of from 2 to 6 liters capacity and with an air opening at both ends (such as is commonly used in the administration of gas anesthetics) is equipped with two glass stopcocks, one at either opening. One of these taps (Tap A) is connected to the mouthpiece by a short piece of rubber tubing, so that when open, the bag is in direct communication with the spirometer. The other tap (Tap B) leaves the bag open or closed to the atmosphere. With Tap A closed and the spirometer empty (having been previously thoroughly flushed through with room air), the 3-way taps are so turned that the airways are open from mouthpiece to spirometer. The rubber bag is completely evacuated by suction and Tap B closed. A carefully measured volume of oxygen is then run into the spirometer, Tap A opened, and by using the spirometer bell as a pump the gases in the circuit are thoroughly mixed. A sample is then taken from the spirometer and the oxygen percentage determined. The volume of the spirometer dead space is then calculated as follows:

$$x \frac{79.1}{100} = (x + a) \frac{y}{100}$$

or

$$x = \frac{ay}{79.1 - y}, \tag{1}$$

where x = the volume of the dead space in cc.,
  y = the percentage of nitrogen in the sample taken after mixing is complete,
  a = the amount of oxygen introduced into the spirometer in cc.

Duplicate measurements show a very close agreement. Five measurements made on the spirometer circuit described above, and 5 on a standard basal metabolic rate machine, gave an average deviation from the mean of 7 cc. and a maximum deviation of 10 cc. (Table II, "Model Lung").

The measurement of the functional residual air

The spirometer circuit is thoroughly flushed with room air using the bell as a pump. Our routine has been 3 series of 4 to 5 liter excursions of the bell with an interval of 2 to 3 minutes between each to allow for diffusion of oxygen from the soda lime and other parts of the circuit. The spirometer bell is then emptied and the two 3-way taps turned so that the mouthpiece leads to the

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room air.   A carefully measured volume of O_2 is run into the spirometer (we have found it more accurate to measure this volume of oxygen from a tracing taken with the pen attachment than from direct observation of the scale), three minutes being allowed for temperature equilibrium to be reached, and a thermometer reading is taken.   The subject who has been lying in the dorsal decubitus with the arms by the side, shoulders resting on the bed, and one pillow supporting the head, for at least 15 minutes, is then attached to the apparatus by means of the usual rubber mouthpiece and nose-clip.   He breathes room air for 2 minutes, the drum is started and the subject is then suddenly switched to the spirometer by turning both 3-way taps simultaneously, preferably at some point during the respiratory cycle near the height of inspiration.   After a period of seven minutes' quiet breathing, the 3-way taps are again turned, disconnecting the patient from the spirometer.   A weight is placed on the bell of the spirometer, and left for three minutes during which time any leak will show itself.   The small tap for the collection of samples is opened and from 2 to 3 liters of gas allowed to escape.   A sample of the air in the spirometer can then be collected for analysis.   The following practical details are essential if accurate results are to be expected.   If the subject is unaccustomed to breathing from a spirometer practice should be given prior to the experiment.   The subject should be unaware of the purpose of the experiment, as any conscious effort to maintain an even resting respiratory level usually results in hopeless irregularities.   It has been our custom to inform the subject that it is just a "breathing test," that he will feel nothing, need only breathe quietly and can go to sleep if he wants to.   Leaks around the mouthpiece should be carefully avoided.   It has been our custom to moisten the mouthpiece with water or dilute glycerin and observe the mouth throughout the experiment.   Resistance to respiration should be minimal and any change in resistance, such as is easily produced by sticking of the rubber valves, should be carefully avoided.   The influence of resistance on the resting respiratory level has already been mentioned.   In one of our normal subjects we have found that a slight increase in the expiratory resistance, although insufficient to affect the respiratory rhythm, raised the functional residual air from an average of 2425 cc. in 15 estimations to an average of 2750 cc. in 5 estimations. For these reasons the respiratory valves should be examined daily for any stickiness of the valve flaps.   The efficiency of the soda lime scrubber should be checked at regular intervals by analysing the spirometer air for CO_2; if this rises above 0.2 per cent the soda lime should be changed.

CALCULATION

The actual volume measured by this method is obviously the amount of air in the lungs at the moment the patient is switched to the spirometer.   The nitrogen in the lungs at this moment is diluted by a known volume of oxygen, and from the degree of dilution the lung volume can be calculated from the equation,

$$x \frac{v}{100} + d \frac{79.1}{100} = (x + d + a - b) \frac{y}{100} ,$$

where x = the lung volume in cc.,
v = percentage of N_2 in lungs at beginning of experiment,
y = percentage of N_2 in the circuit at end of experiment,
a = oxygen in spirometer at beginning of experiment in cc.,
b = oxygen absorbed during experiment in cc.,
d = dead space in spirometer circuit in cc.

Unfortunately for the utility of this equation the value of v has been shown to be by no means a constant and is not measured in each subject. Also, there is no justification for the assumption that at the end of the experiment there is any homogeneity throughout the lung spirometer system. Indeed it is only reasonable to suppose that, at the time the sample is taken, the nitrogen in the inspired air (i.e., the nitrogen in the spirometer) is of lower percentage than the nitrogen in the alveoli, since more oxygen is being absorbed than CO_2 excreted, and therefore a process of N_2 concentration is continuously taking place in the lungs. However, the rise in the percentage of N_2, which takes place when air is inhaled from the spirometer, must be equivalent to the rise which takes place when air is inhaled from the room, since in both the lungs are performing the same process of N_2 concentration. Applying these theoretical considerations to our technique of lung volume measurement, it is clear that if we use v (the alveolar N_2 percentage at the beginning of the experiment) to represent the amount of N_2 being diluted, the sample y (the percentage of N_2 in the circuit after mixing is complete) must also be taken from the alveolar air. But since the difference between v and the room air nitrogen is equivalent to the difference between y taken from the alveoli and y taken from the spirometer, we are perfectly justified in substituting the room air nitrogen (79.1 per cent) for v, if the sample from which y is estimated is taken from the spirometer.

Our equation will then simplify itself to

$$x\frac{79.1}{100} + d\frac{79.1}{100} = (x + d + a - b)\frac{y}{100}$$

or

$$x = \frac{y(a - b)}{79.1 - y} - d, \tag{2}$$

the meaning of x, a, b and d remaining unchanged but y signifying the percentage of nitrogen in the spirometer at the end of the experiment. In this way those errors accruing from the inconstancy of the alveolar nitrogen are made to compensate for the lack of homogeneity throughout the lung spirometer system after so-called mixing has been completed. Actually it can be shown that compensation for these errors is not quite complete. If room air be inspired and 7 cc. per cent of O_2 are absorbed, and 6 cc. per cent of CO_2 excreted, then the percentage of N_2 will rise from 79.1 in the inspired air to 79.9 in the expired air, a rise of 0.8 per cent. If the oxygen of the inspired air be raised to 45 per cent, then with the same metabolic factors the percentage of N_2 will be raised from 55 to 55.6, a rise of 0.6 per cent. Since the respiratory dead space is a constant factor throughout, these differences between the inspired and expired nitrogen are exactly proportional to the differences between inspired and alveolar nitrogen. As shown, this difference does vary somewhat with the percentage of nitrogen inspired, the change when breathing 55 per cent N_2 amounting to only 75 per cent of that when breathing room air. This discrepancy has to be disregarded in our calculations, but the error involved is a small one, amounting to some 10 to 20 cc. in the functional residual air of an average subject.

As already stated, we have found that a more accurate measurement of the amount of oxygen added to the spirometer is obtained by graphic registration than by a direct reading on the scale. The oxygen absorbed is measured in the usual way by a line drawn through the resting respiratory level. Difficulties in the measurement of this quantity are discussed below.

The actual volume measured by the above technique and by the use of

formula (2) is the amount of air in the lungs at the moment the subject was switched from breathing room air to the spirometer. The height of this point above the resting respiratory level is measured from the respiratory tracing. To obtain the value of the functional residual air, this amount is subtracted from x. The quantity so obtained represents the volume of the residual air at the temperature of the spirometer air. This must be corrected to 37° C. saturated with water vapor. It has been the custom of some to correct also for the barometric pressure but it has yet to be shown that the barometric pressure has any influence on lung volume.

To allow for nitrogen excretion we have estimated from the figures of Hill, Long and Lupton (1924) and Campbell and Hill (1931) that approximately 65 cc. of nitrogen will be excreted in 7 minutes when breathing an atmosphere of 44 per cent oxygen. We have therefore subtracted 80 cc. in all cases from the measured functional residual air. Obviously no correction need be made for oxygen passing into solution, as this will be registered as oxygen consumption

From the functional residual air, the total capacity and residual air can be calculated by adding the complemental and subtracting the reserve air respectively. It has been our custom to measure these immediately after the lung volume estimation and with the subject in the same carefully controlled position.[2]

<p align="center">CRITICISM</p>

In our opinion the main drawback to this method is the difficulty in obtaining an accurate estimation of the oxygen consumption on some subjects. However, one can always tell from a 7 minute respiratory tracing approximately how much room there is for error. Our routine has been to draw the base line, which we think represents the oxygen consumption, and if one has to admit the possibility of more than a 50 cc. error in the total oxygen consumed the experiment is discarded or, if a better tracing is not procurable, the possible range of error is noted. With a final mixture of 45 per cent oxygen, an error of 50 cc. in the oxygen consumption will lead to an error of 93 cc. in the lung volume. The only other criterion for the discarding of an experiment has been the possibility of a leak as shown by the spirometer tracing.

Nitrogen excretion probably varies somewhat from patient to patient

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[2] Sendroy, Hiller and Van Slyke (1932) have recently published a method for the determination of lung volume by respiration of oxygen without forced breathing. In their method it is essential that "at the end of the period the subject brings his lungs to the same position as at the beginning." They have only used this method for the estimation of the residual air but when we consider the fluctuation of the reserve air described above it becomes evident that expert cooperation is necessary, and accurate results can hardly be expected from patients with any impairment of respiratory function. The authors do not describe any measurements of the functional residual air, and we hardly think that this would be feasible with their method. We have always found that any such voluntary control of the resting respiratory level even in trained individuals leads to marked irregularities.

but we cannot believe that with similar experimental technique this quantity can vary by more than 10 or 20 cc. representing a final error of from 15 to 25 cc.

The question of mixing throughout the lung-spirometer circuit cannot be so satisfactorily approached by this method as by the method of Van Slyke and Binger (1923), since the nitrogen percentage is falling at an increasing rate throughout the experiment, and since the sample taken must represent the air in the spirometer bell. Van Slyke and Binger have conclusively shown that both in cardiacs and in normal subjects the technique we have used is sufficient to ensure mixing in 5 minutes. To make doubly sure we have extended this time to 7 minutes.

In 25 measurements of the functional residual air in 3 normal subjects we have found an average deviation from the mean of each subject of 93 cc., and a maximum deviation of 170 cc. In 40 measurements on 14 subjects with cardio-respiratory disease, ranging from advanced emphysema to spontaneous pneumothorax, we have found an average deviation from the mean of each subject of 107 cc. and a maximum deviation of 280 cc. When these results are compared with those by other methods (Table II) it must be remembered that at least in some instances in this group results showing marked deviation from the mean have been discarded. Moreover, only this method and the method of Van Slyke and Binger can be used with any justification in those cases where there is any marked impairment of vital capacity or pulmonary ventilation. In this type of case our method may or may not be as accurate as the method of Van Slyke and Binger, but in its simplicity and applicability to clinical use it certainly presents some advantages.

SUMMARY AND CONCLUSION

(*a*) A simple classification of the subdivisions of the total lung volume is proposed.

(*b*) The complemental, reserve and residual airs can show considerable variations which are purely fortuitous in nature, even under carefully controlled conditions on one individual. Similar variations could not be demonstrated in the functional residual air.

(*c*) The methods for the determination of the residual and functional residual air are reviewed, and experimental evidence given to show that most of these will give fallacious results in both normal and abnormal individuals.

(*d*) A simple method is described for the measurement of the functional residual air.

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