STUDIES OF LUNG VOLUME. I.

Relation between Thorax Size and Lung Volume in Normal Adults.

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Plates 3 and 4.

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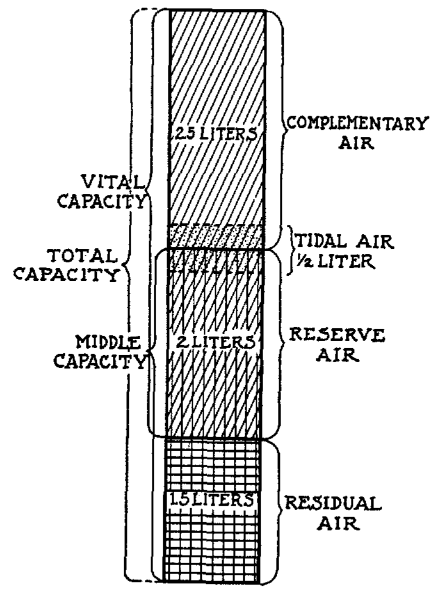
Definition of Terms.

The amount of air a person is able to expire after a maximum inspiration is called "vital capacity" (Hutchinson, 1846). The vital capacity does not, however, indicate all the air within the lungs. A certain quantity remains even after a maximum expiration; we call this "residual air" (Davy, 1800). The sum of the vital capacity and the residual air, *i.e.*, the total volume of air held by the completely filled lungs, is called the "total capacity" or "total lung volume."

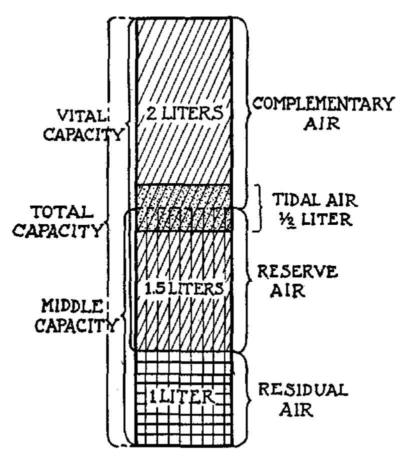
If one stops breathing half-way between a normal inspiration or a normal expiration, there will be in the lungs a certain quantity of air greater than the residual air and less than the total capacity (Text-figs. 1 and 2). We call this amount of air the "middle capacity"[1] (Panum, 1868). The difference between the middle capacity and the total capacity (all that can be breathed in after a half expiration) is called the "reserve air."[2] The difference between middle capacity and residual air (all that can be breathed out after a half expiration) is called the "complementary air."

[1] Siebeck suggested in 1910 defining the middle capacity as the amount of air in the lungs after a full normal expiration, instead of after a half expiration. In this paper the definition of Panum is used.

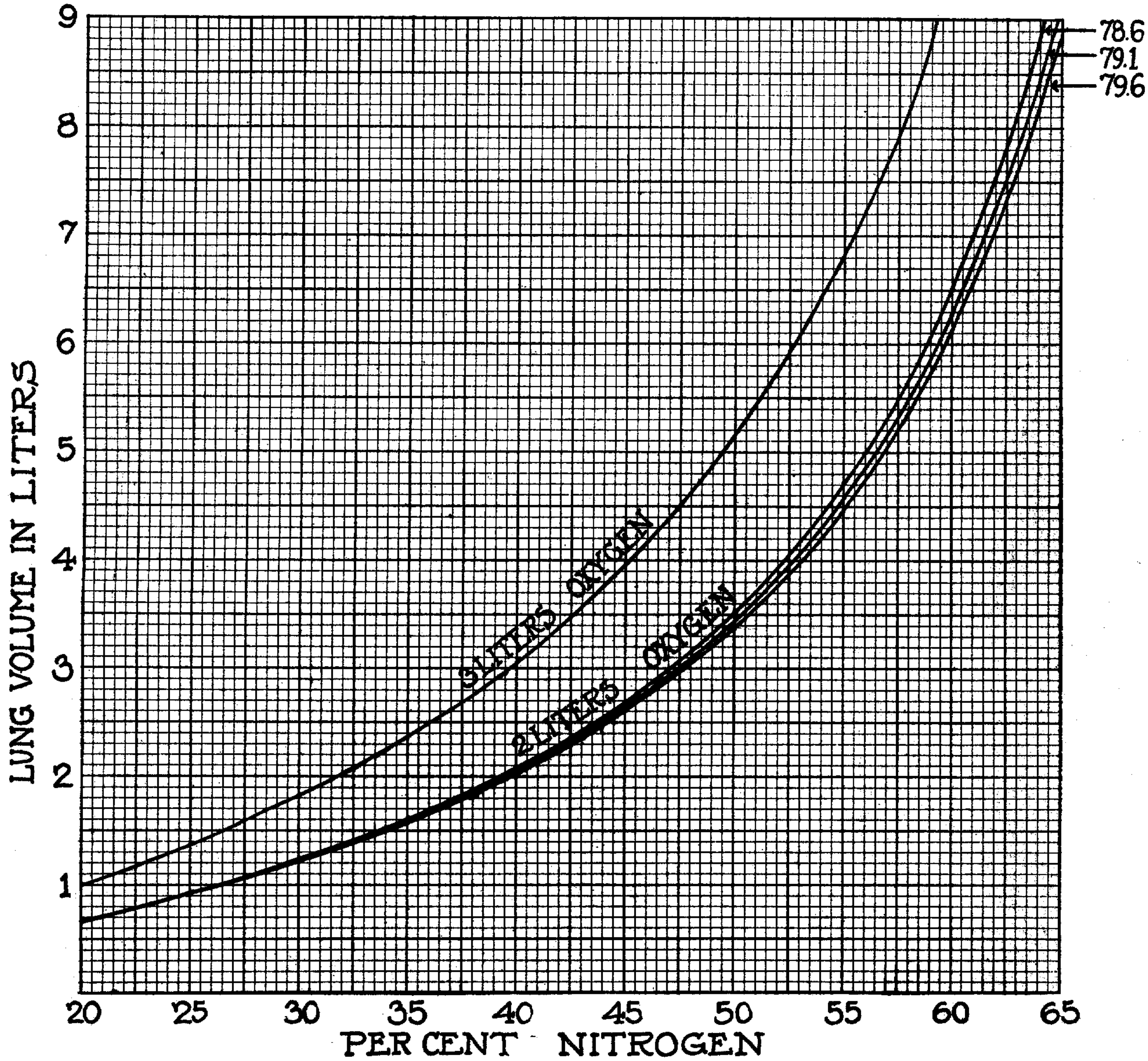
[2] Hutchinson (1846) created the terms "complementary air" and "reserve air." He used different definitions, however, defining the complementary air as the quantity of air a person can inspire after a normal inspiration, and the reserve air as the amount that can be expired after a normal expiration.



TEXT-FIG. 1. Approximate lung volumes for average normal man.



TEXT-FIG. 2. Approximate lung volumes for average normal woman.



TEXT-FIG. 3. Curves for calculation of lung volume (air content) as determined by the dilution method. The upper curve is for use when 3 liters of pure oxygen are mixed with the lung air, the lower when 2 liters of oxygen are used. The lower curve is given in three forms to indicate the range of error which may be caused by maximum variations in the nitrogen content of the alveolar air from the usual value of 79.1 per cent.

In accordance with the definition now in use, the vital capacity is equal to the sum of the reserve and complementary air. Under normal conditions the difference between the inspiration and expiration (the tidal air) is much less than the vital capacity, and can approximately be estimated at 500 cc. This means that a person only uses 250 cc. of his reserve air and 250 cc. of his complementary air in normal breathing. The rest of the vital capacity is to be considered as a reserve which can be used if necessary under abnormal conditions. There is a striking contrast, however, between the reserve air and the complementary air, the former always being within the chest and the latter always being outside the chest under normal resting conditions (Hutchinson).

Methods for Determining Lung Volumes.

The vital capacity, the tidal air, the reserve air, and the complementary air can be determined by means of a calibrated, easily movable spirometer. In determining the residual air, however, it is necessary to apply a more complicated method. It is usually determined by having the subject expire completely until only the residual air is left in the lungs. He then inspires from a bag or spirometer containing a known amount of nitrogen, oxygen, or hydrogen, which he mixes with the air in his lungs by respiring from five to seven times. Then the mixture is analyzed and the amount of residual air calculated from the degree to which the air in the chest has diluted the gas in the bag or spirometer. The total capacity and the middle capacity can be determined either directly by the bag alone, or indirectly by adding the residual air to the vital capacity and the reserve air respectively, as determining with a spirometer. We have, in our work, determined all the figures by means of the mixing method and later on checked the vital capacity by means of a spirometer.

Our technique has been the following: A 4 liter rubber bag is evacuated and filled with 2 liters of pure oxygen; in determining the residual air we sometimes use 3 liters. The bag is connected to a three-way stop-cock. The subject closes his lips air-tight around the rubber mouthpiece of the stop-cock. The nose is closed by a clamp. For a few respirations the stop-cock is held in such a position as to permit free passage between the lungs and the outside air. Then the subject brings his lungs to the desired position and retains that position long enough to have the stop-cock turned to connect the rubber bag with his lungs. Four to five fairly deep respirations are sufficient to mix the air in the lungs with the air in the bag (see below). A sample is then drawn out of the bag and analyzed for nitrogen, carbon dioxide and oxygen being absorbed simultaneously by alkaline pyrogallol. The lung volume is calculated in the following way:

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

$$x = \frac{v - y}{ay}$$

x = the lung volume in liters.

v = the percentage of nitrogen in the lung air before the experiment (usually 79.1 per cent, see page 72).

y = the percentage of nitrogen in the sample from the bag at the end of the experiment (or the percentage of nitrogen in the lungs after mixing).

a = the amount of oxygen in the bag in liters at the beginning of the experiment.

It is more convenient to calculate the lung volume by means of the curve in Text-fig. 3.

The curve and formula can only be used if the oxygen in the tank is pure or if a correction is made so that the bag will contain 2 liters of oxygen. In that case the excess nitrogen in the bag, as an impurity in the oxygen, must be subtracted from the calculated lung volume.

Our spirometer is an easily movable Krogh (1912) apparatus. The person is connected with the spirometer by means of a three-way stopcock of at least 1 sq. cm. bore. In order to determine the vital capacity, the person must fill his lungs and stop breathing for a moment. The stop-cock is then turned and a maximum expiration is made into the spirometer. This is repeated until a constant value is obtained. The determination of the vital capacity can be combined with the determination of the residual air if a three-way stop-cock is so arranged that after expiring into the spirometer the subject is instantly connected with a rubber bag containing 2 or 3 liters of oxygen, as described above. The vital capacity can also be determined by a maximum inspiration from the spirometer, but the results obtained are somewhat smaller than those obtained by expiration (Table III).

In order to determine the reserve air and the complementary air, the person must breathe normally for some time into the spirometer, which contains 3 or 4 liters of 50 per cent oxygen to prevent dyspnea. When the breathing is regular, a maximum respiration is made. This respiration must equal the previously found vital capacity.

The figures can be given directly or in values corrected for temperature, pressure, and moisture. We have not corrected them. Our figures refer to the gas volumes measured at 21° ± 3°C.

Accuracy of Methods.

Spirometry.—The spirometer method will always give the true vital capacity at that particular moment. The maximum reading error is 50 cc. Measuring the vital capacity of the same person several times, one finds that the results obtained differ by amounts usually less than 200 cc., in most cases from 3 to 6 per cent of the vital capacity. These differences are not due to the method, but to the inability of the subject to reach the same point in inspiration or expiration, or both, every time. Bohr recognized the fact that the vital capacity is not constant. He considered the maximum inspiration as a fixed point, and that the discrepancies in the determinations of the vital capacity were due to the expiration, the last part of which is done by the diaphragm. Hasselbalch showed later that it is possible to train a person to increase his total lung volume. He found, furthermore, that the total capacity and vital capacity in three normal persons decreased when they changed from the standing to the lying position. This does not exclude the fact that the maximum inspiration is a fixed point and the maximum expiration a variable point when the determinations are made within a short time and with the subject in the same position.

Dilution Method.—In the rubber bag method, or, as it may more accurately be called, the dilution method,[3] there are possibilities for several errors. The analytical error is very small because a large

[3] The volume of air in the lungs is determined in a way analogous to the determinations of the residue in the stomach in Ewald's test meal.

amount of air may be taken for analysis. In a determination where 30 cc. are taken for analysis, the error falls below 0.2 per cent, even when no special precautions are taken, such as the use of a thermobarometer. The main source of error is the difficulty in obtaining a homogeneous mixture of air in the lungs and in the bag. It is generally supposed that five to seven fairly deep respirations are sufficient to mix even pure hydrogen with the air in the lungs. A recent study by Sonne has shown that it is essential to pay more attention to that problem than was formerly considered necessary. Sonne found that it was very difficult, and in some instances almost impossible, to get a homogeneous mixture in the lungs by inhaling foreign air. He found it extremely difficult to get a proper mixture by mixing the lung air with nitrous oxide as is done in Krogh and Lindhard's (1912) method for determining the blood flow. Krogh and Lindhard themselves have later (1917) admitted this difficulty. We have, therefore, been very careful in controlling our results. We have done this in three different ways:

(1) By performing our experiments on the same person with different numbers of respirations (Table I). As seen in the table, increasing the number of respirations beyond four of at least 2 liter excursions does not change the results. The slight differences obtained

TABLE I.

Effect of Variations in the Number of Respirations on Results by the Dilution Method.

Name.	Position of chest.	Excursion of respiration.	Lung volume calculated from analyses of mixed gases after varying number of respirations.							
			1	2	3	4	5	6	7	8
		liters	*liters*	*liters*	*liters*	*liters*	*liters*	*liters*	*liters*	*liters*
Dr. F.	Maximum expiration.	2.0	1.46	1.70	2.02	1.98				
						1.84				
" A.	" inspiration.	3.5				5.75				5.58
" A.	Normal "	3.0					3.85	3.96		3.90
										4.00
										3.92
" S.	Maximum "	3.0					6.27			6.20
" P.	" expiration.	2.0	2.16	2.45	2.49	2.50	2.50			
			2.20			2.74				

are not due to an incomplete mixture, but to the previously mentioned impossibility of starting the respiration from the same point in different experiments. We have tried to overcome this difficulty in (2).

(2) By taking samples from the rubber bag after a different number of respirations in the same experiment (Table II). These experiments show that we obtained almost constant values of nitrogen in the rubber bag after four or five respirations. In all the experiments in this table the subject has started from a maximum inspiration, which probably is a more unfavorable condition for mixing than starting from a maximum expiration, because one is unable to empty

TABLE II.

Analyses of Mixed Gases in the Bag after Varying Numbers of Successive Respirations.

Name.	Position of chest.	Amount of pure oxygen in bag.	Excursion of respirations.	Sample 1.		Sample 2.	
				No. of respirations.	Nitrogen.	No. of respiration.	Nitrogen.
		liters	*liters*		*per cent*		*per cent*
Dr. V.	Maximum inspiration.	2 (approximately)	3½	4–6	60.5	7	60.0
							60.1
" V.	" "	2	3½	4–6	59.1	8	59.4
" L.	" "	2 (approximately)	3	4–5	58.2	7	58.5
" S.	" "	2	3½	4–6	57.4	8	57.5
" S.	" "	2 (approximately)	3½	4–6	58.3	7	58.5

the rubber bag each time. The respiratory excursions in these experiments have been from 3 to 3½ liters.

(3) By determining the vital capacity as the difference between the total lung volume and the residual air, determined by the dilution method, and checking this by determining the vital capacity with the spirometer. We have done this in all but two of our subjects. The results are shown in Table III.

The values for the vital capacities determined by expiration into the spirometer are, with few exceptions, from 1 to 5 per cent greater than the values obtained by the dilution method. The reason for this is undoubtedly that we have given as our spirometer values the highest figures obtainable with the spirometer, whereas the dilution method figures are the average of all determinations. The values for the vital capacities determined by inspiration from the spirometer are always slightly smaller than the values obtained by expiration. This is probably accounted for by the greater power of the expiratory muscles and by the resistance of the spirometer. Another reason may be the difference in temperature and moisture content of the expiratory air.

Inconstancy of the Nitrogen Percentage in the Lung Air.—Another possible error is due to the inconstancy of the nitrogen in the lung air and the impossibility of determining it in relation to the determination of the lung volume. We determined the nitrogen percentage in a sample from the total amount of expired air in six normal people. Six determinations were done on each person, three on the expired air after an ordinary expiration and three after a maximum inspiration. The values fell between 78.7 and 79.5 per cent in 27 cases; in 9 cases the values fell outside these limits but within 78.4 and 79.6 per cent. The variations in the same person are usually as great as from person to person. We have used 79.1 per cent in all our calculations. The curves in Text-fig. 3 show the limits of the possible errors. The constancy of the figures in Tables I and II shows that the actual errors due to increased absorption of oxygen in blood plasma and tissues from the oxygen-rich mixture breathed during the 10 to 15 seconds of the experiment, to the excretion of nitrogen from blood, and to the deviation of the respiratory quotient from 1.0 are negligible.

Standard Procedure for the Determination of Lung Volumes.

The determinations of the lung volume in Subject 2 (Table III) were done in a way which we considered the best and most reliable. It is given in detail as follows:

(1) *Determination of Vital Capacity by Means of Expiration in the Spirometer.*—

Expiration.	Volume. *liters*	Temperature. °C.	Pressure. *mm.*
First	5.75	24	762
Second	5.80		
Third	5.95		
Fourth	5.95		

Vital capacity = 5.95 uncorrected.

(2) *Determination of Residual Air by the Dilution Method.*—The subject breathed through a three-way stop-cock by means of which he could be connected with either the spirometer or a rubber bag containing 3 liters of oxygen. He filled his lungs with room air and breathed repeatedly into and out of the spirometer. When the volume of expiration equalled the previously determined maximum vital capacity (5.95 liters), the stop-cock was turned in such a manner that the next inspiration was made from the bag. The oxygen drawn in from the bag was rebreathed seven times in 15 seconds. The nitrogen content of the mixed gases was 32.6 per cent, indicating a residual air volume of 2.1 liters.

(3) *Total Capacity.*—The total capacity was then determined with the bag, which contained 2 liters of oxygen. The subject respired eight times. The nitrogen content of the mixture was 63.4 per cent, indicating a total capacity of 8.05 liters.

Vital capacity determined by spirometer = 5.95 liters.
Vital capacity determined by bag = 8.05 − 2.1 = 5.95 liters.

(4) *Middle Capacity.*—While breathing quietly the subject was connected with a spirometer containing about 4 liters of air with 50 per cent oxygen. He continued regular breathing from the spirometer, which registered as follows:

Readings of the Spirometer Dial.

	After inspiration. *liters*	After expiration. *liters*	Mean. *liters*	Vital capacity. *liters*
Normal respiration.....	3.2	3.9	3.55	
	3.1	3.9	3.50	
	3.15	3.85	3.50	
Maximum "	0.4	6.1	—	5.7

Reserve air = 6.1 − 3.5 = 2.6 liters.
Complementary air = 3.5 − 0.4 = 3.1 liters.

The value for the vital capacity obtained in this experiment is 6.1 − 0.4 = 5.7, instead of 5.95. The reason for this is that the maximum inspiration was made from the spirometer, a condition which, as mentioned before, regularly gives a smaller vital capacity than that registered when the lungs are filled from the free air (Table III). For this reason we increase the value of the complementary part of the total air by 0.25 to 3.35 liters.

Immediately afterwards the chest measures of the subject were taken.

Lung Volumes in Eighteen Normal Individuals.

The results of our experiments on eighteen normal persons between 20 and 38 years of age are tabulated in Table III, and diagrams of the

TABLE III.

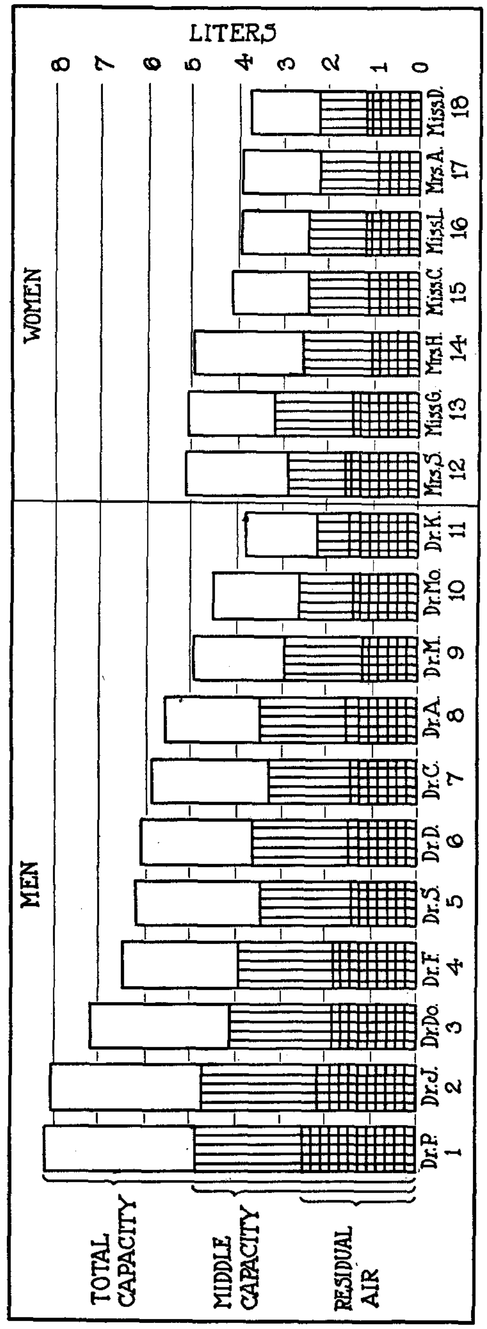
Summary of Lung Volume Determinations on Normal Individuals.

No. of individual.	Name.	Age.	Height.	Weight.	Bag. Residual air.	Bag. Middle capacity.	Bag. Total capacity.	Bag. Vital capacity.	Bag. Reserve air.	Bag. Complementary air.	Spirometer. Vital capacity. Expiration.	Spirometer. Vital capacity. Inspiration.
		yrs.	*cm.*	*kg.*	*liters*	*liters*	*liters*	*liters*	*liters*	*liters*	*liters*	*liters*
1	Dr. P.	34	185	90	2.48	4.80	8.22	5.74	2.32	3.42	5.90	5.70
2	" J.	31	179	76	2.10	4.70	8.05	5.95	2.60	3.35	5.95	5.70
3	" Do.	29	186	86	1.86	—	7.20	5.34	—	—	—	—
4	" F.	32	178	68	1.87	3.89	6.51	4.64	2.02	2.62	4.90	4.85
5	" S.	32	178	91	1.47	3.45	6.24	4.77	1.98	2.79	4.87	4.80
6	" D.	34	178	69.5	1.52	3.66	6.13	4.61	2.14	2.47	4.65	4.60
7	" C.	29	172.5	65	1.46	3.31	5.88	4.42	1.85	2.57	4.63	4.55
8	" A.	38	165	67	1.61	3.50	5.58	3.97	1.89	2.08	3.87	3.77
9	" M.	32	167.5	63	1.25	2.99	4.95	3.70	1.74	1.96	3.97	3.93
10	" Mo.	29	162.5	51	1.41	2.60	4.56	3.15	1.19	1.94	3.40	3.35
11	" K.	28	152	52	1.53	2.23	3.84	2.31	0.70	1.61	2.40	2.35
12	Mrs. S.	34	175	88	1.64	2.88	5.10	3.46	1.24	2.22	—	—
13	Miss G.	26	173	63	1.42	3.17	5.05	3.63	1.75	1.88	3.75	3.70
14	Mrs. H.	24	162	59	1.07	2.69	4.91	3.84	1.62	2.22	3.90	3.85
15	Miss C.	23	169	65	1.10	2.40	4.12	3.02	1.30	1.85	3.15	3.10
16	" L.	29	156	43	1.15	2.45	3.93	2.78	1.30	1.48	2.75	2.70
17	Mrs. A.	28	158	52	0.97	2.28	3.93	2.96	1.31	1.65	3.10	2.95
18	Miss D.	21	160	53	1.15	2.35	3.72	2.57	1.20	1.40	2.65	2.60

same determinations are shown in Text-fig. 4. The values for the different lung volumes in these determinations agree with what other investigators have found.

From his determinations on eight normal men and four normal women, Bohr derived a standard for the different lung volumes which is usually accepted.

We have divided our results into two groups according to the



TEXT-FIG. 4. Chart showing the lung volumes in eleven normal men and seven normal women.

TABLE IV.

Average Lung Volumes for Normal Men and Women in Standing Position.

Sex.	Residual air.	Reserve air.	Mean.	Complementary air.	Total capacity.
	liters	*liters*	*liters*	*liters*	*liters*
Men............	1.5	2.0	3.5	2.5	6.0
Women.........	1.0	1.5	2.5	2.0	4.5

sexes and believe that the figures given in Table IV and Text-figs. 1 and 2 represent the approximate average somewhat more closely than the approximations used by Bohr; namely, 1 liter of residual, 2 liters of reserve, and 2 liters of complementary air.

Previous Investigations to Find a Relationship between the Vital Capacity and Other Body Figures.

Pulmometry has never played an important part in clinical medicine, chiefly on account of the great variations in the lung volumes of different persons. For that reason we have been unable to tell whether the lung volume in a pathologic case is normal or not for the individual examined unless the deviation from the usual values is great. The variations in the values of the lung volume[4] in different individuals have been recognized by even the earliest investigators.

Borelli (1679) was the first who tried to determine the air in the lungs. He found that from 300 to 600 cc. are taken in by a single inspiration. Jurin (1718) says about Borelli's figures: "But this quantity is different not only in different persons, but even at different times in one and the same person." Hales (1728) determined the air in the lungs to be 4 liters. Goodwyn (1788) says after reporting his own experiments: "These experiments are sufficient to show that the lungs contain a considerable quantity of air, even after complete expiration, but this quantity must vary in different subjects in proportion to the capacity of the thorax. It is, therefore, extremely difficult to establish a medium. However, we shall for the present adopt the medium quantity of these latter experiments and say that the lungs of the human subject contain 109 cubic inches (1,800 cc.)[5] of air after complete expiration."

[4] It took a considerable time before the differences between vital capacity, residual air, and so forth were recognized.

[5] Determined post mortem by filling the pleural cavities with water, in this way compressing the lungs (the diaphragm was fixed).

Davy (1800), who invented the dilution principle in determination of the residual air, gives the figures for his own lungs: "So that making the corrections for temperature, it would appear, that my lungs in a state of voluntary inspiration, contained about 254 cubic inches (4,160 cc.); in a state of natural inspiration, about 135 (2,210 cc.); in a state of natural expiration, about 118 (1,190 cc.); and in a state of forced expiration 41 (670 cc.)." He also remarks: "This capacity is most probably below medium; my chest is narrow, measuring in circumference but 29 inches." Hutchinson, by the invention of the spirometer, made the easily determinable vital capacity the central point in the pulmometry until the time of Bohr, half a century later. Hutchinson realized that, should the vital capacity be of any importance in clinical medicine, it was necessary to find some relationship to other body figures. For that purpose he examined 1,012 normal men and women and found that there was a certain relationship between the height and the vital capacity. He worked out the figures by means of which it should be possible to calculate the normal vital capacity from the height of the person. He showed that the weight, age, and sex might modify these figures to a slight extent. Between the vital capacity and the circumference of the chest he could not find any proportion at all. Simon (1848) confirmed Hutchinson's results as far as height was concerned, but he found that if only lean persons were used, there was some relation between the vital capacity and the circumference of the chest. Fabius (1853) found a rather close relation between the vital capacity and the volume of the trunk, which he calculated from the circumference of the chest and the distance from the neck (eminentia occipitalis) to the tip of the os coccygis. His first idea was to compare the vital capacity with the "chest volume"; he gave that up because he was unable to obtain any figures for the chest volume. Apparently without knowing Fabius' publication, Müller (1868) and Schönfeld (1882) found the same thing. The idea of Fabius (Müller and Schönfeld) did not attract much attention and was never used by others in clinical medicine. Hutchinson's old idea of calculating the vital capacity from the height prevailed and was generally used, sometimes with a slight modification of the constant and sometimes in combination with a correction for weight or age (Schneevoogt, 1854).

Wintrich (1854), Arnold (1855), von Ziemssen (1888), Cornet (1907), and Peabody (1917) have all adopted the principle laid down by Hutchinson, even if they have used it in a somewhat different way. Von Ziemssen, for instance, used a quotient (1: 20 in men and 1: 17 in women) to express the ratio between vital capacity and height. This quotient (Ziemssen's quotient) has been used in several papers, particularly in papers dealing with the vital capacity in people suffering from tuberculosis. Peabody divides his patients (heart patients) into four groups, according to the height.

A relationship between the residual air and other body factors has not been worked out. Only some rather rough estimates have been adopted (Schenck, 1894).

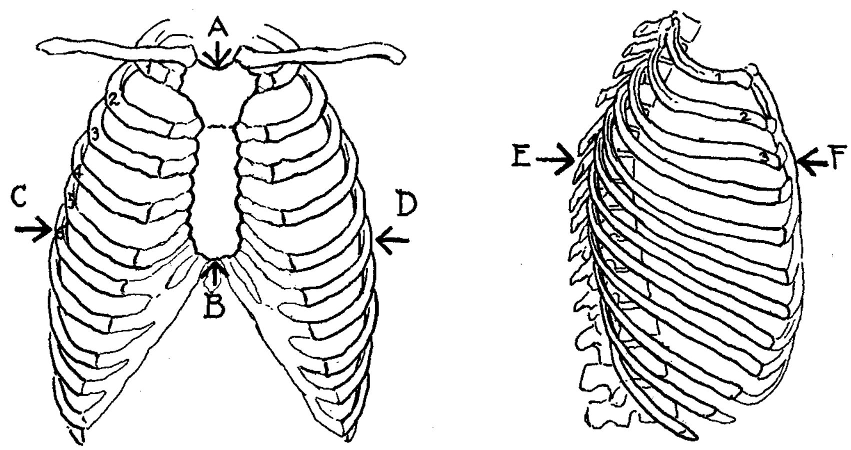
Bohr was the creator of a new era in pulmometry. He objected to the use of Hutchinson's figures for estimating the normal vital capacity from the height because the individual variations are too great. He furthermore objected to exclusive use of the vital capacity, because it does not take the total or residual air into consideration. He and his pupils (Hasselbalch, Rubow, Siebeck, and Bie and Maar) in several publications investigated the relation between the total lung volume, the middle capacity, and the residual air under normal and pathologic conditions, and put less stress on the absolute figures than on their relationships. The problems raised by these investigators have attracted attention for a good many years.

Determination of the "Chest Volume" and Calculations of a Ratio between Chest Volume and Lung Volume in Different Positions of the Chest (Full Inspiration, Rest, and Full Expiration).

The problem of finding an accurate relationship between the lung volume and chest or body size remained unsolved. It seemed to us, however, that it might be possible to approach the solution by using the chest volume as the constant and the lung volume as the variable. The reason for this seems obvious when we consider the chest wall as a sort of spirometer. When a person is respiring from a spirometer, it is a natural thing to look upon the chest wall as another spirometer connected with the first one and moving inversely to the latter. And if we take different individuals it is natural to regard their chests as spirometers containing different amounts of air.

The x-ray pictures (Figs. 1 and 2) illustrate fairly well what we mean. Fig. 1 (No. 7, Table III) is from the same person with the chest in full inspiration and expiration. Fig. 2 is from two different persons (Nos. 1 and 11) and shows the possibilities of individual variation. Our problem was to find measurements which could be used in calculating the chest volume, which alone seemed a logical basis for calculation of lung capacity. The old idea of using the chest circumference must be given up because the muscles, fat, and breasts give room for a considerable error. It seems obvious that the best way is to consider the chest as a geometrical figure and take three dimensions, the product of which will represent a volume proportional to the chest volume. We have then to measure the height, depth, and breadth of the chest and to do it in such a way that (1) the fat and muscles play as small a part as possible, (2) the different diameters represent parts of the chest wall which move in fair accordance to the respiration.

After some consideration and experiments we came to the following procedure which has been used in all our cases. The height of the chest is taken as the length of the sternum from incisio intraclavicularis to a point just below articulatio sterno-xiphoidea. The depth is then taken as the horizontal distance from the middle of the sternum at the insertion of the third rib to the spinal column, and the breadth is the distance across the sixth ribs in the midaxillary line. The points between which the measures are taken are almost without any muscular covering. The transverse points are in the axilla between



TEXT-FIG. 5. Points on the thorax where the chest measurements are taken. *AB* is the height of the chest, *CD* the breadth, and *EF* the depth.

musculus pectoralis major and musculus latissimus dorsi. The distances representing the depth and breadth vary with the phases of inspiration; the height is constant (Text-fig. 5).

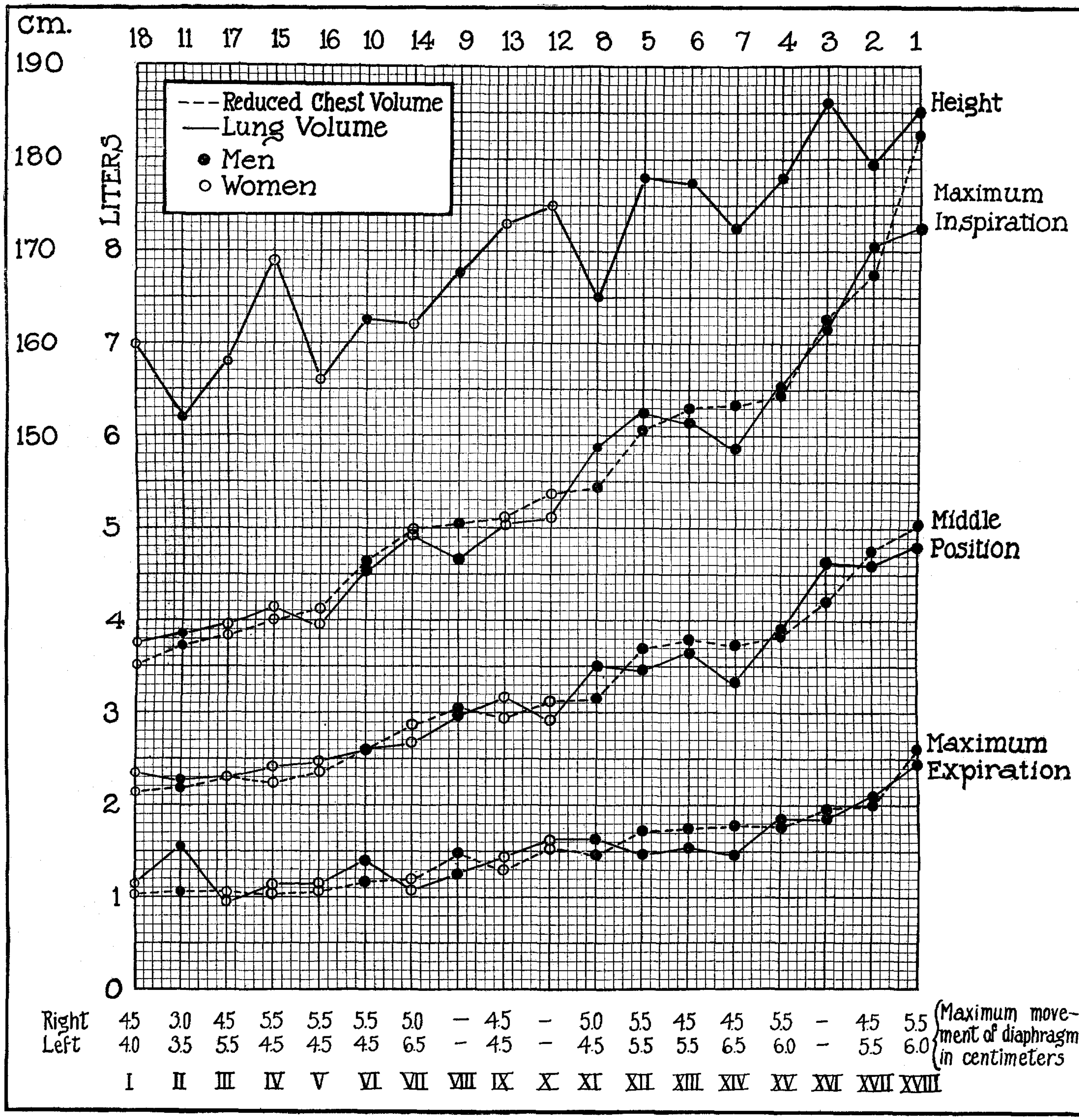
The measuring requires some practice and a good deal of care. We do it in the following way: The person stands in a natural position. The points are found and marked. The point on the upper part of the sternum is rather easy to find; it is just above the edge of the bone. The lower point is sometimes very difficult to locate. We do it as follows: The curvature is found and lines are drawn to indicate it. Then we try to find the joint between the sternum and processus xiphoideus. It is usually slightly prominent. The point from which we measure is just below that prominent ridge. Locating the tip of the processus xiphoideus sometimes helps, but it cannot always be done. The lateral points are easy to find by counting the ribs. In taking the measure it is necessary to put the nodes of the pelvimeter tight to the chest wall in order to get as close to the bone as possible. It is particularly necessary to take care that the ends of the pelvimeter do not slip and go into the intercostal spaces. The first measures are taken in rest (half-way between normal expiration and inspiration, position of middle capacity). The pelvimeter is kept on and the person is requested to take a maximum inspiration and stop a second while the measures are taken. Then he is asked to expire to the residual air and stop for another measurement. The product of the figures obtained does not, of course, represent the real chest volume, but a volume approximately proportional to it.

In Table V are given the data on different normal individuals. The product of the measurements in the three dimensions is given as the chest volume and the ratio between the chest volume and lung volume calculated as

$$\frac{100 \times \text{lung volume}}{\text{chest volume}}$$

The average ratio for the total lung capacity is 55, for the middle capacity 37, and for the residual air 19.

The curves of Text-fig. 6 show the different chest volumes multiplied by these factors (reduced chest volume). It will be seen that there is a close agreement between the reduced chest volumes and the actual lung capacities. We have plotted the height on the upper part of the chart to show that the relations between the different lung volumes and the height are much more variable than the relations between the lung and chest volumes. The relationship between height and vital capacity (Hutchinson) is equally variable. The vital capacity, on the other hand, bears nearly as constant a ratio to the reduced chest volume as do the total or middle capacities. The average ratio between the vital capacity and the middle chest volume is 45 (Table VI).



TEXT-FIG. 6. Chart showing air contents of lungs (lung volumes) in normal subjects as determined in the three respiratory positions by the dilution method (solid lines) and as calculated from the thoracic measurements (broken lines). The subjects are arranged in order according to chest volumes measured at maximum inspiration. The numbers above the chart are those by which the same subjects are designated in Text-fig. 4. The numbers below indicate the maximum excursion of the right and left diaphragm in centimeters, as calculated from fluoroscopic tracings.

TABLE V.

Summary of Thorax Measurements in the Three Positions of Respiration, Namely, Expiration, Rest, and Inspiration, and Ratios of Chest Volumes Calculated from These Measurements to Lung Volumes.

No. of individual.	Name.	Position of chest.	Sternum.	Diameter. Ant.-Post.	Diameter. Transverse.	Chest volume.	Lung volume.	Ratio $\frac{100 \times \text{lung volume}}{\text{chest volume}}$
			cm.	*cm.*	*cm.*	*liters*	*liters*	
1	Dr. P.	Expiration.	22.0	21.0	29.5	13.63	2.48	18.2
		Rest.	22.0	22.0	31.0	15.00	4.88	32.0
		Inspiration.	22.0	24.0	32.5	17.15	8.22	48.0
2	Dr. J.	Expiration.	21.0	17.5	29.0	10.65	2.10	19.7
		Rest.	21.0	19.5	30.5	12.49	4.70	37.6
		Inspiration.	21.0	21.0	32.0	14.08	8.05	57.2
3	Dr. Do.	Expiration.	20.5	17.0	29.5	10.28	1.86	18.1
		Rest.	20.5	18.5	30.0	11.36	4.63	—
		Inspiration.	20.5	20.0	32.0	13.12	7.20	54.8
4	Dr. F.	Expiration.	19.5	18.5	26.0	9.38	1.87	19.9
		Rest.	19.5	19.0	28.0	10.38	3.89	37.5
		Inspiration.	19.5	20.0	30.0	11.70	6.51	55.6
5	Dr. S.	Expiration.	18.0	18.5	27.5	9.15	1.47	16.1
		Rest.	18.0	19.5	28.5	10.00	3.45	34.5
		Inspiration.	18.0	20.0	30.5	11.00	6.24	56.7
6	Dr. D.	Expiration.	20.5	18.5	24.5	9.30	1.52	16.4
		Rest.	20.5	19.5	25.5	10.20	3.56	35.9
		Inspiration.	20.5	21.5	26.5	11.45	6.13	53.6
7	Dr. C.	Expiration.	19.5	17.5	27.5	9.39	1.46	15.6
		Rest.	.19.5	18.5	28.0	10.10	3.31	32.6
		Inspiration.	19.5	20.0	29.5	11.50	5.88	51.1
8	Dr. A.	Expiration.	20.0	16.0	24.5	7.83	1.61	20.6
		Rest.	20.0	17.0	25.0	8.50	3.50	41.2
		Inspiration.	20.0	18.0	27.5	9.90	5.88	56.4
9	Dr. M.	Expiration.	19.5	15.5	26.0	7.86	1.25	16.4
		Rest.	19.5	16.0	26.5	8.26	2.99	36.4
		Inspiration.	19.5	17.0	27.5	9.11	4.64	51.0
10	Dr. Mo.	Expiration.	19.0	15.0	22.0	6.27	1.41	22.5
		Rest.	19.0	16.0	23.0	6.99	2.60	37.4
		Inspiration.	19.0	18.0	24.5	8.38	4.56	54.6

TABLE V—*Concluded.*

No. of individual.	Name.	Position of chest.	Sternum.	Diameter. Ant.-Post.	Diameter. Transverse.	Chest volume.	Lung volume.	Ratio $\frac{100 \times \text{lung volume}}{\text{chest volume}}$
			cm.	*cm.*	*cm.*	*liters*	*liters*	
11	Dr. K.	Expiration.	16.0	14.5	24.0	5.57	1.53	27.5
		Rest.	16.0	15.0	24.5	5.88	2.23	37.9
		Inspiration.	16.0	17.0	25.0	6.80	3.84	56.4
12	Mrs. S.	Expiration.	17.5	18.5	24.5	7.93	1.64	20.7
		Rest.	17.5	19.0	25.2	8.38	2.88	34.3
		Inspiration.	17.5	20.2	27.5	9.72	5.10	52.4
13	Miss G.	Expiration.	18.3	14.8	25.3	6.85	1.42	20.7
		Rest.	18.3	16.5	26.1	7.88	3.17	40.3
		Inspiration.	18.3	18.5	27.3	9.29	5.05	54.2
14	Mrs. H.	Expiration.	17.2	16.0	24.8	6.83	1.07	15.7
		Rest.	17.2	17.1	25.8	7.77	2.69	34.6
		Inspiration.	17.2	18.3	28.3	8.91	4.91	55.1
15	Miss C.	Expiration.	17.9	13.9	22.2	5.52	1.10	19.9
		Rest.	17.9	14.9	22.6	6.03	2.40	39.7
		Inspiration.	17.9	15.7	25.8	7.25	4.12	55.8
16	Miss L.	Expiration.	17.1	14.9	22.5	5.73	1.15	20.0
		Rest.	17.1	16.0	23.4	6.40	2.45	38.3
		Inspiration.	17.1	17.3	25.3	7.49	3.93	52.4
17	Mrs. A.	Expiration.	16.2	14.0	23.5	5.32	0.97	18.2
		Rest.	16.2	15.5	24.5	6.15	2.28	37.1
		Inspiration.	16.2	17.1	25.4	7.04	3.93	55.4
18	Miss D.	Expiration.	17.1	14.0	22.1	5.30	1.15	21.7
		Rest.	17.1	15.0	22.2	5.79	2.35	40.3
		Inspiration.	17.1	16.5	23.2	6.55	3.72	57.8

Excursions of the Diaphragm.

Realizing that the measurement of the chest wall does not give us the variations in the height of the thoracic cavity, we have made a particular study of the movement of the diaphragm by means of x-rays.[6] The figures are given in Table VI. It will be seen that there is one man

TABLE VI.

Maximum Excursions of the Right and Left Diaphragm.

No. of individual.	Name.	Greatest possible movement of diaphragm. Right.	Left.	Right + left.	100 × residual air / chest volume at expiration	100 × vital capacity / chest volume at rest
					Men.	
		cm.	*cm.*	*cm.*		
1	Dr. P.	5.5	6.0	11.5	18.2	38.3
2	" J.	4.5	5.5	10.0	19.7	47.7
3	" Do.	—	—	—	18.1	47.0
4	" F.	5.5	6.0	11.5	19.9	43.0
5	" S.	5.5	5.5	11.0	16.1	47.7
6	" D.	4.5	5.5	10.0	16.4	45.2
7	" C.	4.5	6.5	11.0	15.6	43.7
8	" A.	5.0	4.5	9.5	20.6	46.7
9	" M.	—	—	—	16.4	44.8
10	" Mo.	5.5	4.5	10.0	22.5	45.1
11	" K.	3.0	3.5	6.5	27.5	39.2
					Women.	
12	Mrs. S.	—	—	—	20.7	41.3
13	Miss G.	4.5	4.5	9.0	20.7	46.1
14	Mrs. H.	5.0	6.5	11.5	15.7	49.4
15	Miss C.	5.5	4.5	10.0	19.9	50.1
16	" L.	5.5	4.5	10.0	20.0	43.5
17	Mrs. A.	4.5	5.5	10.0	18.2	48.1
18	Miss D.	4.5	4.0	8.5	21.7	44.4

[6] We used fluoroscopy. Being unable to use parallel light we worked out a correction for the parallax by measuring the distance from the light to the screen (50 cm.) and the distance from the light to the middle part of the diaphragm (35 cm.). The correction is very close to 0.7 in all instances; for that reason all our directly found values have been multiplied by that factor.

with a very small movement of his diaphragm. His residual air is unusually great (Text-figs. 4 and 6). He apparently expired naturally as far as the thoracic movement was concerned, but was unable to press his diaphragm up at the end of the expiration. He was a physically untrained man, with rather undeveloped abdominal musculature. A too small movement of the diaphragm might, of course, indicate that he was unable to lower it during inspiration. The normal figures for his total capacity and the abnormally high figure for his residual air prove that this was not the case. One of the women (No. 14, Table V and Text-fig. 4) had a particularly small residual ratio, 15.7. It will be seen that the movement of her diaphragm is very extensive. She had been trained in college to breathe very deeply and had powerful abdominal muscles. She wore, like all the other women, a rather loose corset during the determination. The importance of the movements of the diaphragm will be discussed more in a later paper.

SUMMARY.

1. The total capacity, middle capacity, and residual air have been determined on 11 normal men and 7 normal women. All the determinations have been done on subjects in standing position and at least 2 hours after a meal.

2. The figures for the total and middle capacities agree with those of previous investigators, particularly with Bohr's. The values for the residual air seem to be a little higher than those previously published.

3. A procedure has been devised by means of which it has been possible to find a numerical relationship between external chest measurements and lung capacity.

4. With the aid of the relationship thus ascertained the lung capacity normal for a chest of given measurements can be estimated.

5. The excursions of the diaphragm have been studied.

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EXPLANATION OF PLATES.

PLATE 3.

FIG. 1. Two x-ray pictures from a normal man, No. 7, taken after maximum expiration (*a*) and maximum inspiration (*b*). The outline of *a* is superimposed on *b*.

PLATE 4.

FIG. 2. Two x-ray pictures from No. 11 (*a*) and No. 1 (*b*). They are both taken in maximum inspiratory position. *a* is superimposed on *b*.

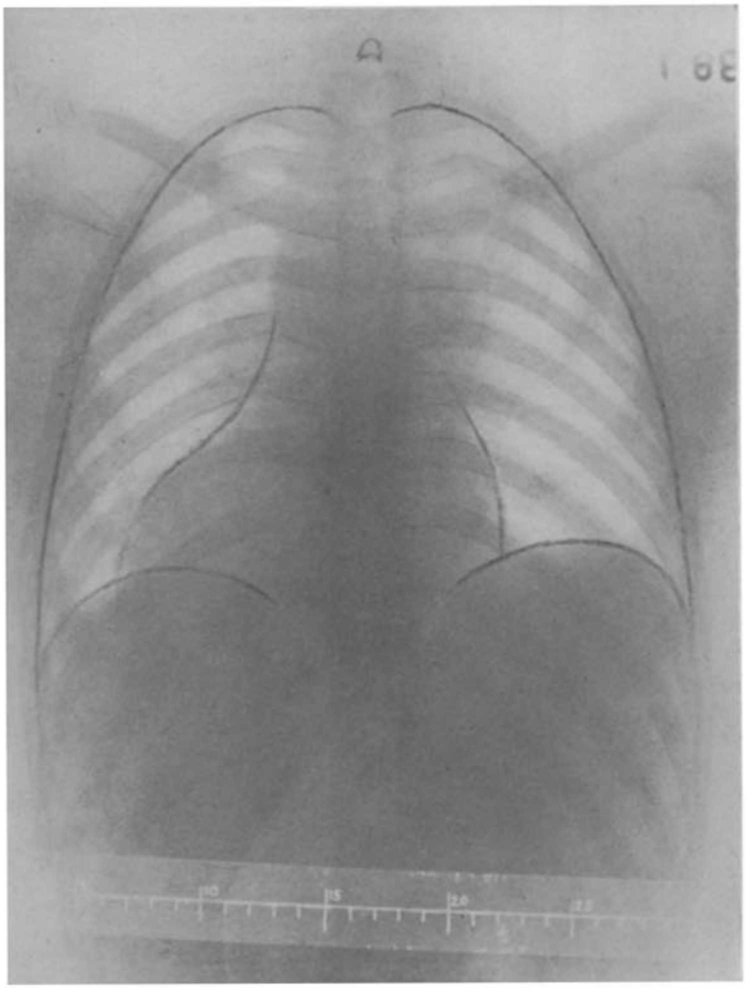

FIG. 1a.

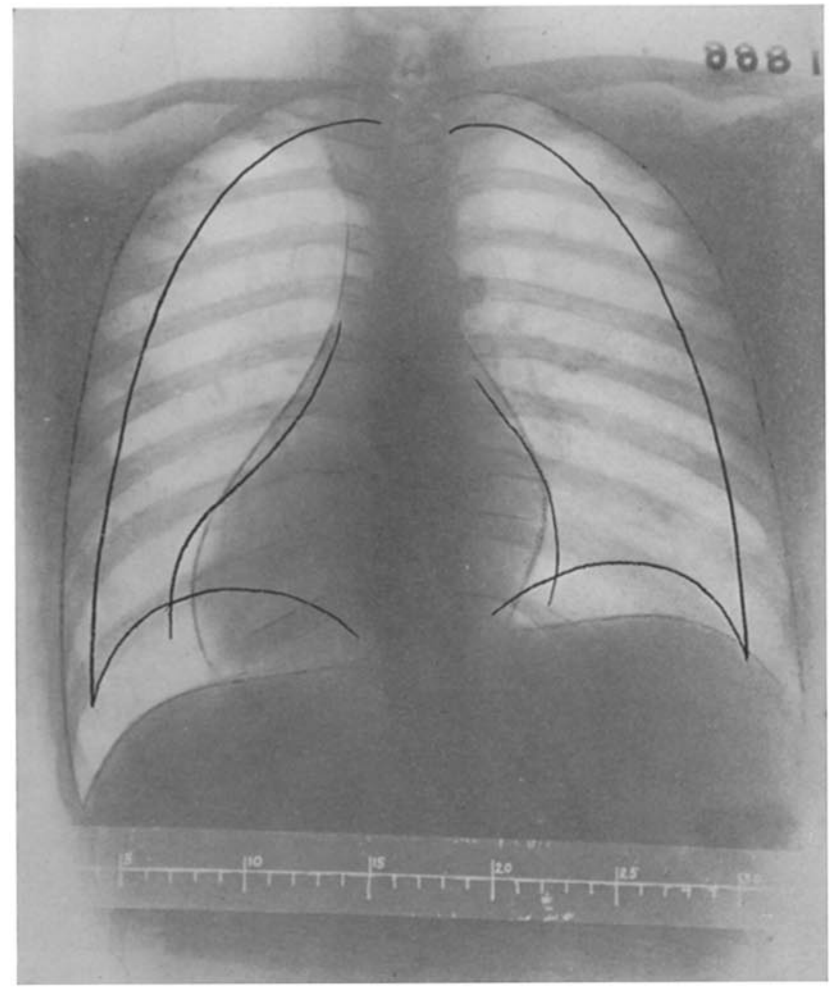

FIG. 1b.

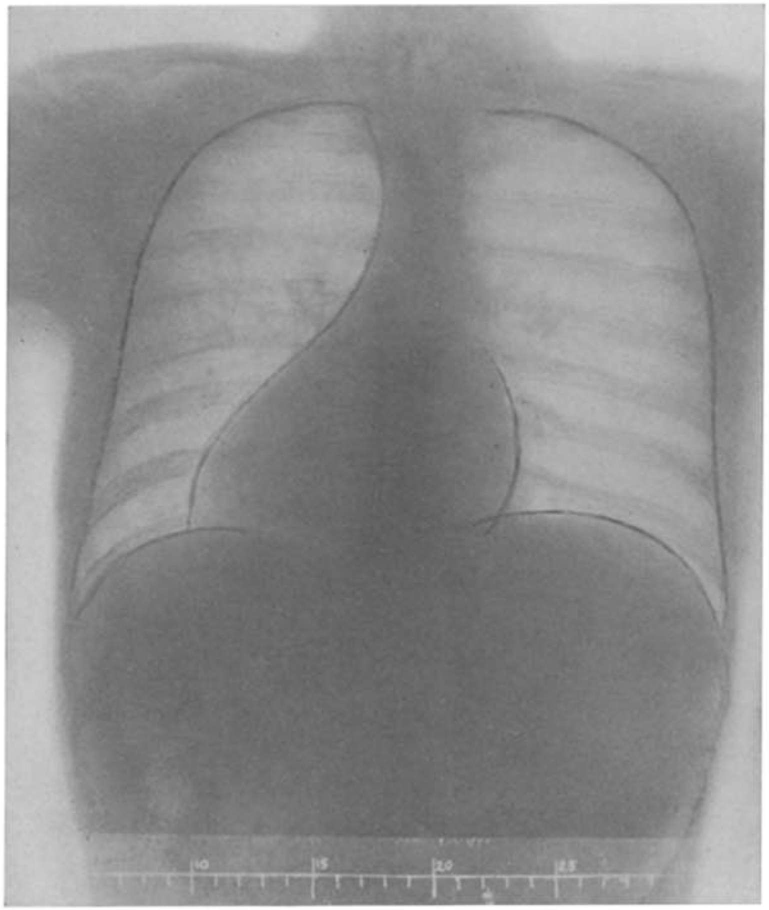

Fig. 2a.

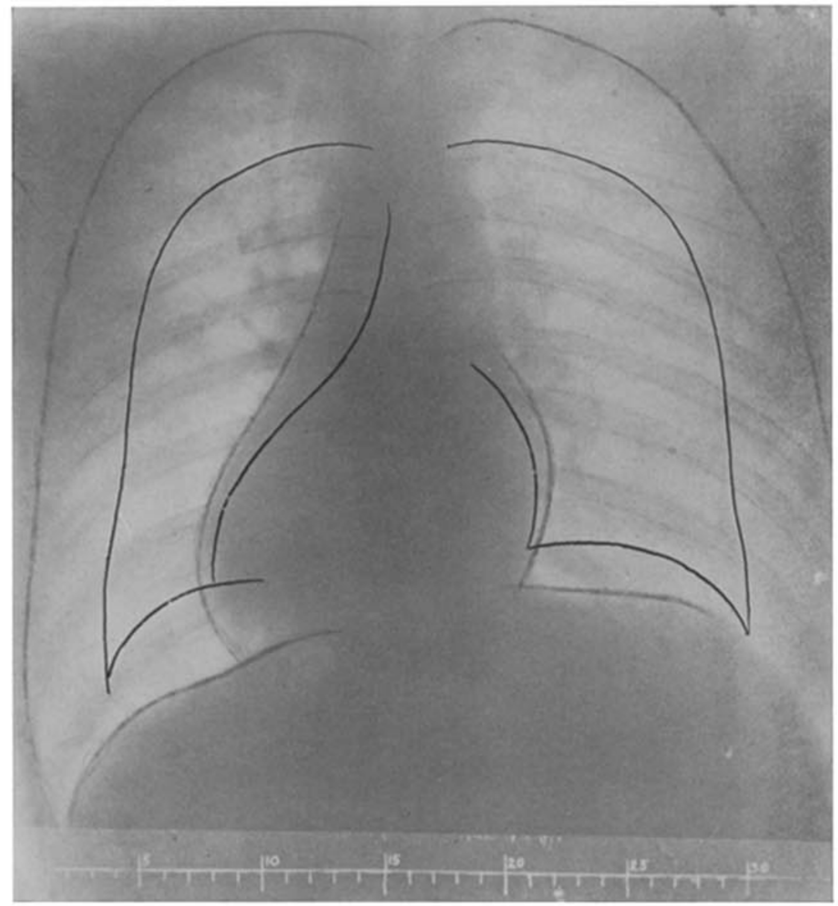

Fig. 2b.

(Lundsgaard and Van Slyke: Studies of lung volume. I.)