Thorax (1951), 6, 103.

THE EFFECT OF POSTURE ON DIAPHRAGMATIC MOVEMENT AND VITAL CAPACITY IN NORMAL SUBJECTS WITH A NOTE ON SPIROMETRY AS AN AID IN DETERMINING RADIOLOGICAL CHEST VOLUMES

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(RECEIVED FOR PUBLICATION FEBRUARY 2, 1951)

" *What shadows we are and what shadows we pursue* "
Edmund Burke, September 9, 1780

Since earliest times the diaphragm has attracted attention from philosophers as well as anatomists and physiologists. Haller (1738) summarized the opinion of the Renaissance anatomists when he described the diaphragm as *nobilissimus post cor musculus*. Buffon, quoted by Bell (1826), reiterated a medieval superstition by describing its central tendon as a nervous centre, the place of all emotions and the seat of the soul: " in sickness and oppression, lowness and sighing, weeping and laughing, in joy or in fear, all our feelings seem to concentrate in this part."

At the beginning of the nineteenth century Bell (1826) and Astley Cooper (1839) demonstrated that life could be maintained by diaphragmatic breathing alone after injuries to the cervical spinal cord in man. Duchenne (1867) used the newly discovered faradic current to investigate the action of the diaphragm in respiration of men and animals. He stimulated the phrenic nerve in dogs, horses, and men, and found it caused the diaphragm to descend and the costal margin to rise upwards and outwards. In dead animals he made similar observations, but when he had opened the anterior abdominal wall and removed the viscera he found phrenic stimulation caused the diaphragm to descend, drawing the costal margin inwards and downwards. He believed that in life the diaphragm in its descent lifted the lower edge of the costal margin upwards and outwards by leverage against the abdominal viscera. Although the mode of action of the diaphragm was the subject of controversy among physiologists (Magendie, 1825 ; Duchenne, 1867 ; Bert, 1870), it was accepted that the diaphragm was the most important muscle of respiration.

EARLY RADIOLOGICAL OBSERVATIONS AND MEASUREMENTS OF DIAPHRAGMATIC MOVEMENTS

The introduction of radiology awakened great interest in the mechanics of respiration, and Keith (1909) expressed the view of most observers of the time that there were two mechanisms by which the lungs were expanded. The upper lobes of the lungs were expanded by movement of the upper ribs and operculum of the thoracic cage, and the lower lobes and the posterior parts of the lung, which lay in the paravertebral grooves, were expanded mainly by diaphragmatic movements.

Jamin (1906) observed changes of the level of the diaphragm with changes of posture. He gave no measurements of diaphragmatic excursion, but he described upward movement of the diaphragm during inspiration in normal subjects due to lifting and expansion of the thoracic cage.

Halls Dally (1908) made careful observations and measurements of respiratory movements of the thoracic cage, the spine, and the diaphragm in normal subjects. In measuring the excursion of the diaphragm in quiet and deep breathing he used the xiphisternal joint as the point from which he made his measurements. He found the diaphragmatic excursion in deep breathing was only 3.4 cm. on the right and 3.2 cm. on the left (mean of measurements on 15 male subjects). Both Dally (1908) and Keith (1909) found that the diaphragmatic excursion in quiet breathing was about 1.5 cm. on each side.

Since that time many observations have been made on movements of the diaphragm (Hoover, 1913 ; Butler and Dana, 1928 ; Webb, Forster, and Gilbert, 1921 ; Adams and Pillsbury, 1922 ; Middleton, 1923 ; Pryor, 1923 ; Barclay, 1930 ; Pierson and Newell, 1936). Measurements were not always made, or if made their accuracy was not stated. Sometimes the diaphragmatic excursions have been observed only during quiet breathing, and sometimes the level of the diaphragm in the thorax is not stated.

Kaltreider, Fray, and Hyde (1938) took radiographs of 10 normal male subjects in full inspiration and full expiration. They made measurements from the films and stated that the excursion of the right diaphragm during deep breathing was 6.8 cm. $\pm$ 0.23 when the subjects were standing and 5.3 cm. $\pm$ 0.32 when lying supine. The excursion of the left diaphragm was 7.0 cm. $\pm$ 0.31 when standing and 6.0 cm. $\pm$ 0.28 when supine.

Observations that the diaphragm was immobile in subjects who were severely dyspnoeic with pleurisy, empyema, or emphysema led to the suggestion that excursion of the diaphragm was of much greater importance in normal respiration than movement of the chest wall (Hoover, 1917 ; Middleton, 1923 ; Pryor, 1923), and the therapeutic successes claimed in the treatment of pulmonary tuberculosis by phrenicectomy and phrenic crush seemed to support this suggestion. In recent years increasing interest in the nature and causes of post-operative pulmonary infection and atelectasis has led to studies of the position and excursion of the diaphragm after operations (Rees-Jones, 1941 ; Howkins, 1948).

Herxheimer (1949), using Verzar's thoracometer, measured and recorded simultaneously the vital capacity and the thoracic cage expansion, and, although he made no direct observations on the diaphragm, suggested that movement of the thoracic cage and of the diaphragm was of varying importance in different phases of respiration ; both played a part in the movement of the complementary air, but the diaphragm played a relatively much greater part in the movement of the reserve air.

The movement of the diaphragm and the phases of respiration do not appear to have been recorded simultaneously by any previous observers.

METHODS USED IN PRESENT INVESTIGATION

Our interest was aroused by the bizarre distortion of the diaphragm which is seen in the chest radiographs of coal-miners with advanced pneumoconiosis. We first attempted to study the movement of the diaphragm during fluoroscopy by measuring the movements of the shadows of the domes of the diaphragm on a fluorescent screen with a ruler, but we soon found that we needed a more precise method which would enable us to determine the position of the diaphragm in the thorax relative to a fixed anatomical point and to relate its movements to the phases of respiration. Radiographs give only a two-dimensional representation of the diaphragm, and the shadows of the domes of the diaphragm which are seen during anterior-posterior fluoroscopy are shadows which may be cast by different parts of the diaphragm at different phases of respiration. We have studied the relationship between the movement of these shadows and the ventilation of the lungs, and we have made the assumption that the movement of the domes of the diaphragm is closely related to the movement of the whole diaphragm. In this paper we describe observations made in normal subjects only.

Apparatus.—A standard Watson tilting *x*-ray table was used; shoulder supports could be attached to the table so that subjects could be examined lying on the table tilted at 45° head down. When the table was upright a board could be placed at right angles to the table as a seat on which subjects could sit while being screened, or on which they could lie so that they could be screened in the left or right lateral postures. The subjects breathed into an 11-litre closed circuit containing air with a CO_2 absorbing canister, and a spirometric tracing was made on a large kymograph-drum. No single tracing continued for more than two minutes and the circuit was washed out with air between tracings. While the spirometric tracing was being made, the subject was screened, and the observer followed the movements of the shadow of the dome of the diaphragm on the fluorescent screen with a tracker (Fig. 1). The tracker was mounted on a wire held in tension between two pulleys, and it was connected by a Bowden cable to a pen recording on the kymograph directly above the spirometric tracing. This cable was spring-loaded and there was no backlash. The tracking device was mounted on a Perspex carriage which was clipped on to rails on the fluorescent screen. The carriage was moved across the screen so that observations of the right and left halves of the diaphragm were made separately, or it was clipped horizontally so that observations of diaphragmatic movement with subjects in the lateral postures were easy to make. A fine cross-wire at the centre of the fluorescent screen indicated to the observer the position of the central pencil of *x* rays. This

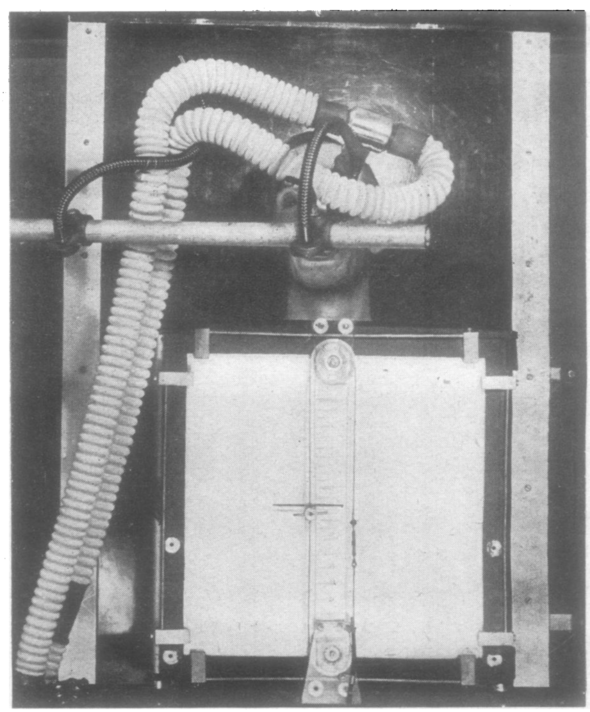


FIG. 1.—The tracking device on the fluorescent screen.

cross was centred over any anatomical structure, e.g., the iliac crest, and the distance of the structure from the foot of the table read off from a scale (Fig. 2).

Fifteen minutes of screening were sufficient to allow tracings to be made of one subject in seven different postures.

Geometrical Distortion.—The *x*-ray tube was only three feet behind the fluorescent screen and there was distortion of the shadows cast by all rays except those of the central pencil (Fig. 2, inset). Care was taken to centre this pencil of rays over the

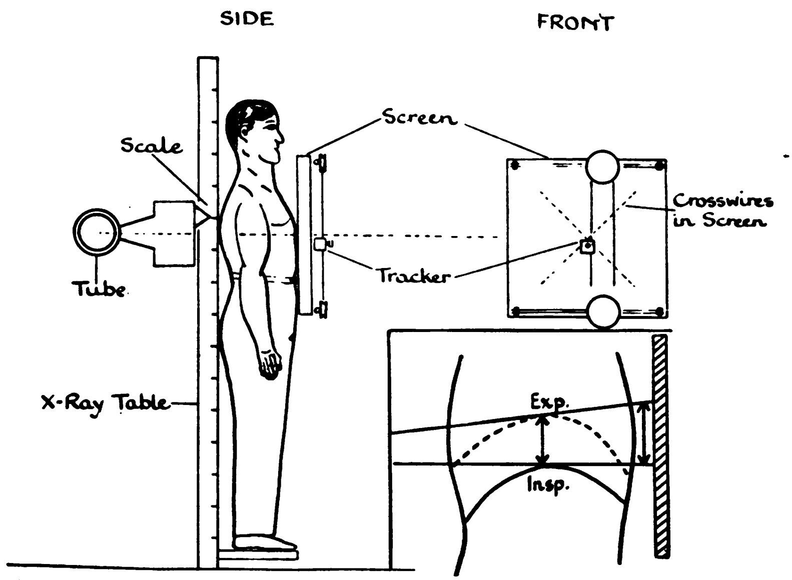


FIG. 2.—Diagram of the apparatus, showing method of measuring the level of anatomical structures. Inset diagram illustrates the geometric distortion for which corrections were made.

resting level of the diaphragm, and, although all movements of the diaphragm away from this level were exaggerated on the screen, the extent of this exaggeration was determined geometrically and experimentally, and corrections were made for it (Table I). Unless otherwise stated, all measurements of diaphragm movement given in this paper have been corrected in this way.

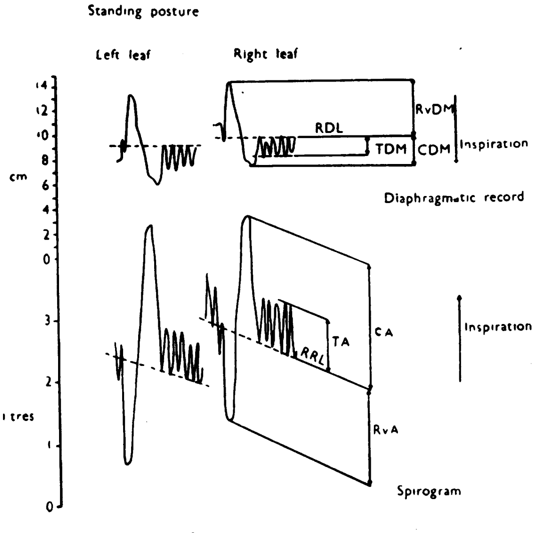
TABLE I

CORRECTIONS FOR GEOMETRICAL DISTORTION OF MEASUREMENTS FROM RECORDS OF DIAPHRAGM MOVEMENT

Extent of Movement of Diaphragm away from Resting Level (measured to nearest 0.5 cm.)	Correction
0–1.5	None
2–3.5	Subtract 0.5 cm.
4–5.5	,, 0.75 ,,
6–10	,, 1.00 ,,
Over 10	,, 1.30 ,,

Records.—Fig. 3 is a tracing of a record of the movement of the mid-point of the right and left leaves of the diaphragm and of a spirogram from a subject in the erect posture.

FIG. 3.—Tracing of a typical record of movement of the right and left leaf of the diaphragm and of spirogram. R.D.L. = resting diaphragm level. RvD.M. = reserve diaphragmatic movement. T.D.M. = tidal diaphragmatic movement. C.D.M. = complementary diaphragmatic movement. R.R.L. = resting respiratory level. RvA. = reserve air. T.A. = tidal air. C.A. = complementary air.



Corresponding to the tidal air (TA) there is a tidal diaphragmatic movement (TDM). The resting diaphragmatic level (RDL) corresponds to the resting respiratory level (RRL) (Christie, 1932). Corresponding to the inspiration of complementary air (CA) there is a downward movement of the diaphragm below its resting level, the complementary diaphragmatic movement (CDM), and corresponding to the expiration of reserve air (RvA) there is an upward movement of the diaphragm above its resting level, the reserve diaphragmatic movement (RvDM).

Measurements from Records of Diaphragmatic Movement.—Measurements of tidal movement of the diaphragm and of complementary and reserve diaphragmatic movement are all made from the resting diaphragmatic level; these measurements are corrected (Table I). "The total diaphragmatic excursion" is the term used for the sum of the corrected complementary and reserve diaphragmatic movements.

Accuracy of the Method.—(1) Measurements of the level of the iliac crest were made in normal subjects by centring the wire cross, and therefore the central pencil of x rays, over the iliac crest, and reading the distance from the foot of the table off the centimetre scale at the side of the table (Fig. 2). These measurements were made in the erect and supine postures (Table II). The standard error of a single observation is 0.53 cm., and this compares favourably with the accuracy of anthropometric measurements of stature (Morant and Gilson, 1945).

TABLE II

HEIGHT OF ILIAC CREST MEASURED RADIOLOGICALLY IN 48 NORMAL SUBJECTS

Mean level of iliac crest (supine)	105.750 cm.
Mean level of iliac crest (standing)	105.385 ,,
Standard deviation of iliac crest level	5.34 ,,
Standard error of single measurement of level	0.53 ,,
Difference of mean level standing and supine	0.365 ,,
Standard error of difference	·0.075 ,,

(2) To estimate the repeatability of this method of recording diaphragmatic movement, duplicate records of the left diaphragmatic movement were made in 17 subjects. From

each record the "total diaphragmatic excursion" (the sum of corrected RvDM and CDM) was obtained and is given in Table III. In the erect posture the standard error

TABLE III
DUPLICATE READINGS OF TOTAL LEFT DIAPHRAGMATIC EXCURSION

Subject	Standing		Supine	
	1st Measurement (cm.)	2nd Measurement (cm.)	1st Measurement (cm.)	2nd Measurement (cm.)
O	6.75	7.5	6.25	6.5
L	8.0	7.25		
C	7.0	6.25	5.75*	8.0
CC	4.75	6.0	5.75	6.25
Ri	8.75	7.5	8.5	7.0
K	5.0	5.75	4.75	6.5
B	9.0	7.5	6.25	7.25
Re	6.25	7.0	6.75	6.5
E.80	6.25	5.75		
E.94			7.0	7.75
E.100			6.75	6.25
E.96	3.75	4.25		
E.112	4.25	4.5	6.75	6.25
E.119			6.75	6.25
E.124	8.0	8.5	8.0	7.5
E.107	6.75	7.0		
E.108			4.25	5.0

* Unreliable reading: spirometer bell emptied during inspiration.

of a single measurement is 0.59 cm. and 95% confidence limits of a single measurement are ± 1.27 cm. In the supine posture the standard error of a single measurement is 0.61 cm. and the 95% confidence limits of a single measurement are ± 1.33 cm.

(3) If chest radiographs of a subject are taken in full inspiration and full expiration they can be superimposed so that the images of the cervical transverse processes lie over each other and the change in level of the diaphragm can be measured. Provided certain precautions are taken, measurements obtained in this way, where the diaphragmatic movement is measured relative to the spine, agree closely with measurements taken from the fluoroscopic records, where the diaphragmatic movement is measured relative to the iliac crest or to a fixed point outside the body. This subject is discussed later. Measurements made from records and from radiographs in a group of subjects are given in Table IX.

The accuracy of the tracking method is such that its use for our present purposes is justified.

THE RELATIONSHIP OF DIAPHRAGMATIC MOVEMENTS TO RESPIRATION AND THE EFFECT OF POSTURE

Hutchinson (1849) showed that the vital capacity decreased with the change from the erect to the supine posture. Wilson (1927) found that, while the vital capacity decreased from 2.6 litres to 2.3 litres with this change of posture, the reserve air decreased considerably from about 1,150 c.cm. to about 700 c.cm. He suggested that the total lung volume also changed with this change of posture. Hamilton and

Morgan (1932) concluded that the reduction of vital capacity was due to pulmonary vascular congestion. Hurtado and Fray (1933) believed the reduction in vital capacity to be due to raising the diaphragm and to the decrease of the volume of the thoracic cavity. McMichael and McGibbon (1939) believed the decrease in vital capacity and functional residual air, which they found with this change of posture, to be due to pulmonary congestion. They also observed that the resting level of the diaphragm rose in the thorax when subjects were supine and thought this change due to displacement of the weight of the abdominal viscera.

Experimental Results.—We have investigated the effect of posture on diaphragmatic movement in 12 normal male subjects (Table IV). Each subject was

TABLE IV

AGE AND ANTHROPOMETRIC MEASUREMENTS OF 12 NORMAL SUBJECTS

Measurement	Mean Value for Group	Standard Deviation
Age (years)	31.5	4.27
Height (cm.)	171.0	6.8
Stem height (cm.)	90.6	2.6
Weight (kg.)	67.2	7.9

examined erect, lying tilted 45° head up, and supine; 11 were examined in the sitting posture, and 10 were observed lying tilted 45° head down. All except three of the subjects were examined on two occasions. On the first occasion only the left diaphragmatic movement was recorded in each posture; on the second occasion the movement of both diaphragmatic leaves was recorded in each posture.

Table V gives the mean measurements of the position and movement of the diaphragm and vital capacity for the whole group, and Fig. 4 shows tracings of the record of diaphragmatic movement and of the spirogram in one of these subjects in four postures, erect, lying tilted at 45° head up, supine, and lying tilted at 45° head down.

Reserve Air and Reserve Diaphragmatic Movement.—Fig. 5 is a scatter diagram of the measurements of reserve air and reserve diaphragmatic movements made on

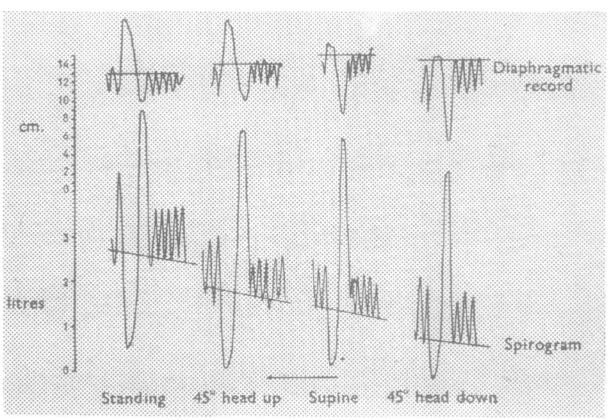


FIG. 4.—Tracings of the spirogram and the record of movement of the left diaphragm of one subject in four postures. The resting level of the diaphragm in cm. from the iliac crest was 16.5 cm. erect, 17.0 cm. tilted 45° head up, 20 cm. supine, and 22 cm. tilted 45° head down.

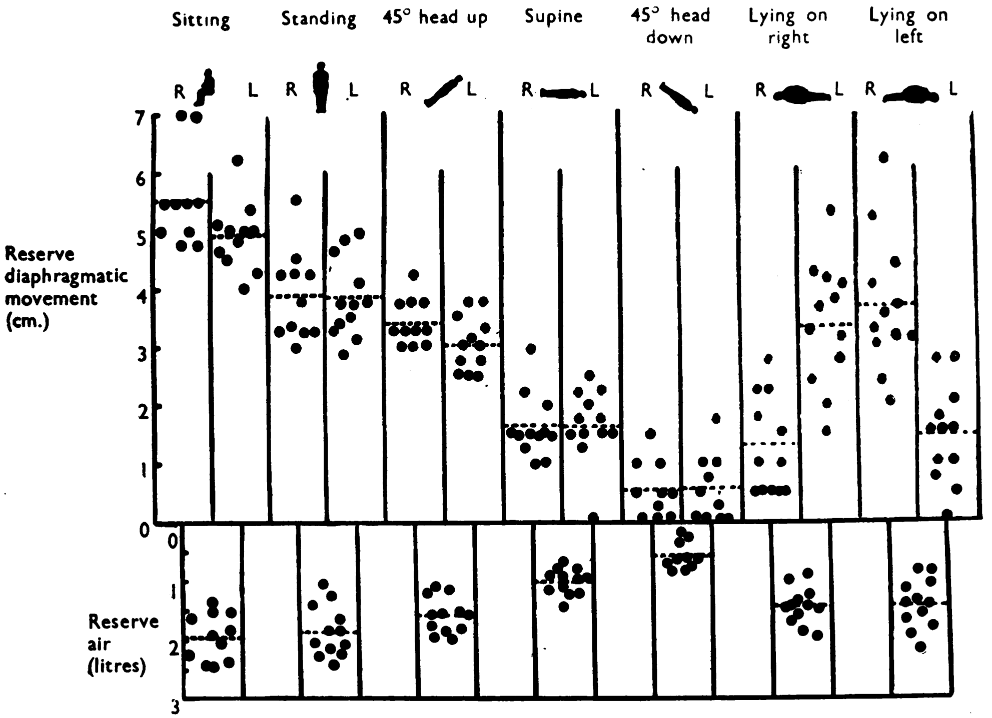


FIG. 5.—Scatter diagram of measurements of reserve diaphragmatic movement and reserve air of 12 subjects in seven postures. The dotted lines indicate the mean value in each column.

the subjects of this group in seven postures and it shows that with changes of posture the reserve air and reserve diaphragmatic movement both change and tend to be closely related to each other.

In Table VI are given the measurements of reserve air and reserve diaphragmatic movements of 10 subjects of this group in four postures, erect, lying 45° head up, supine, and lying tilted 45° head down. Only measurements of the left diaphragm are used here for simplicity of analysis. The behaviour of the right diaphragmatic movement was in no way different from that of the left.

The relationship between these measurements has been investigated and it has been found that in each posture the measurements are significantly related but that the relationship changes slightly from posture to posture and can be expressed by the following regression equations.

Erect posture	RvA = 0.362RvDM + 0.556
Lying 45° head up	RvA = 0.180RvDM + 1.037
Supine	RvA = 0.123RvDM + 0.821
Lying 45° head down	RvA = 0.136RvDM + 0.507

where RvA = reserve air; RvDM = reserve diaphragmatic movement.

The regression equations were obtained by a method devised by Carter (1949) which makes allowance for intercorrelation between results because the same men were examined in each posture.

MEASUREMENTS OF DIAPHRAGMATIC LEVEL AND MOVEMENT AND VITAL CAPACITY IN SEVEN POSTURES

Posture	Resting Diaphragmatic Level (cm. above iliac crest)		Total Diaphragmatic Excursion (cm.)		Reserve Diaphragmatic Movement (cm.)		Tidal Diaphragmatic Movement (cm.)		Vital Capacity (litres)	Reserve Air (litres)	Complementary Diaphragmatic Movement (cm.)	Complementary Air (litres)
	Right	Left	Right	Left	Right	Left	Right	Left			Left	
Sitting	17.4* *2.8*	16.7 *2.8*	7.6 *0.8*	7.8 *0.8*	5.6 *0.8*	4.9 *0.6*	1.3 *0.2*	1.5 *0.4*	4.8 *0.7*	1.9 *0.4*		
Standing	19.5 *2.5*	18.2 *2.5*	6.0 *0.7*	6.7 *1.2*	3.9 *0.7*	3.8 *0.7*	1.5 *0.3*	1.5 *0.2*	4.7 *0.7*	1.8 *0.4*	2.8 *1.08*	2.9 *0.49*
45° head up ..	19.1 *2.2*	18.2 *1.8*	6.3 *0.7*	6.6 *1.1*	3.4 *0.3*	3.0 *0.5*	1.5 *0.3*	1.6 *0.3*	4.7 *0.6*	1.6 *0.2*	3.5 *0.96*	3.1 *0.44*
Supine	21.5 *2.1*	20.0 *2.1*	6.3 *1.2*	6.8 *1.0*	1.7 *0.7*	1.7 *0.6*	1.5 *0.3*	1.5 *0.2*	4.5 *0.7*	1.0 *0.2*	5.1 *0.71*	3.50 *0.50*
45° head down ..	23.9 *3.1*	22.8 *3.2*	7.2 *1.4*	7.5 *1.0*	0.5 *0.5*	0.5 *0.6*	1.8 *0.5*	1.8 *0.7*	4.1 *0.7*	0.6 *0.2*	6.8 *1.3*	3.6 *0.56*
Lying on right side	22.0 *2.0*	16.9 *2.2*	7.7 *1.0*	6.9 *1.0*	1.3 *0.8*	3.3 *1.0*	1.8 *0.4*	1.5 *0.2*	4.6 *0.7*	1.4 *0.4*		
Lying on left side	18.8 *1.8*	19.9 *1.4*	6.3 *1.2*	7.2 *1.4*	3.6 *1.1*	1.4 *0.8*	1.4 *0.2*	1.5 *0.2*	4.5 *0.8*	1.4 *0.5*		

* The figures in roman type are the means of the measurements in 12 subjects, and those in italics the standard deviations about the means.

TABLE VI

THE EFFECT OF POSTURE ON DIAPHRAGMATIC MOVEMENT†

Subject	Standing				45° Head Up				Supine				45° Head Down			
	C.D.M.	C.A.	R.D.M.	RvA.	C.D.M.	C.A.	R.D.M.	RvA.	C.D.M.	C.A.	R.D.M.	RvA.	C.D.M.	C.A.	R.D.M.	RvA.
O ..	2.50	3.59	4.63	2.29	3.13	3.65	3.75	1.93	5.13	4.10	1.25	1.42	7.25	4.30	0.50	0.85
L ..	4.25	3.46	3.38	1.81	3.25	3.43	2.50	1.58	6.50	3.93	2.00	1.08	4.88	3.17	0.75	0.74
C ..	3.13	3.41	3.50	2.09	3.75	3.68	2.79	1.72	5.38	4.18	1.50	1.22	5.25	4.16	1.75	0.82
Co ..	1.25	2.98	4.13	2.02	2.25	3.47	3.13	1.13	4.25	3.66	1.75	1.02	8.25	3.88	0	0.20
Ri ..	3.13	2.34	5.00	2.16	3.63	2.89	3.75	1.50	5.50	3.42	2.25	0.79	9.00	3.23	0.25	0.23
K ..	2.25	2.46	3.13	1.84	3.13	2.76	2.75	1.80	4.13	3.18	1.50	1.22	6.50	3.33	0	0.69
B ..	3.38	2.99	4.88	2.21	4.25	3.56	3.00	1.59	4.50	3.98	2.25	0.90	6.00	4.02	1.00	0.68
D ..	4.63	2.19	2.88	1.22	5.25	2.38	2.50	1.08	5.63	2.46	1.50	0.76	7.50	2.41	1.00	0.40
Re ..	2.88	3.29	3.75	1.64	4.00	3.22	3.38	1.58	4.88	3.16	1.75	0.91	6.50	3.58	0	0.62
M ..	1.50	2.68	3.75	2.42	2.00	3.04	3.00	1.96	5.00	3.54	0	0.96	7.00	3.58	0	0.62

† Left complementary diaphragmatic movement C.D.M. (in cm.), complementary air C.A. (in litres), left reserve diaphragmatic movement R.D.M. (in cm.), and reserve air RvA (in litres) in 10 subjects in four postures. The figures express the means of two measurements in each subject.

An analysis of variance (Table VII) shows that each regression coefficient is significant and that the differences between them are significant.

TABLE VII

RESERVE DIAPHRAGMATIC MOVEMENT AND RESERVE AIR* (ANALYSIS OF VARIANCE)

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Variance Ratio
Due to pooled regression	0.2142	1		
Difference between separate regressions and pooled regressions	0.1884	3	0.0628	3.27++
Separate regressions	0.4026	4	0.1007	5.24+++
Deviations from separate regressions ..	0.4416	23	0.0192	
Total	0.8442	27		

* Measurements in Table VI. ++ = significant at 5% level. +++ = significant at 1% level.

Complementary Air and Complementary Diaphragmatic Movement.—Although there is such a close relationship between the reserve air and the reserve diaphragmatic movement, there is no such close relationship between complementary air and complementary diaphragmatic movement.

Table VI gives the readings of complementary air and complementary diaphragmatic movement of 10 subjects in four postures. There is found to be no close relationship between these measurements in any of the postures. Analysis leads to the following equations.

Erect posture .. .. CA = 0.188 CDM + 2.396
Lying 45° head up .. .. CA = 0.119 CDM + 3.082
Supine .. .. CA = 0.181 CDM + 4.445
Lying 45° head down .. .. CA = 0.063 CDM + 6.588
where CA = complementary air; CDM = complementary diaphragmatic movement

An analysis of variance, however (Table VIII), shows that none of these is significant.

TABLE VIII

COMPLEMENTARY DIAPHRAGMATIC MOVEMENT AND COMPLEMENTARY AIR* (ANALYSIS OF VARIANCE)

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	Variance Ratio
Due to pooled regression	6.0389	1	6.0389	
Difference between separate regressions and pooled regressions	0.4968	3	0.1656	
Separate regressions	6.5357	4	1.6339	2.029
Deviations from separate regressions ..	18.5197	23	0.8052	
Total	25.0554	27		

* Measurements in Table VI.

Discussion.—These observations show (1) that the total diaphragmatic excursion was not significantly changed by posture but tended to be greatest when subjects were sitting or lying tilted at 45° head down; (2) that the tidal diaphragmatic movement was barely affected by posture; (3) that the resting level of the diaphragm rose when subjects were supine and rose still further when they were lying tilted 45° head down; (4) that as the subjects were tilted backwards, the reserve diaphragmatic movement became considerably smaller; (5) that at the same time the reserve air became considerably decreased although the vital capacity was only slightly decreased.

The change of the resting level of the diaphragm and the pattern of diaphragmatic movement must, in part at least, have been determined by mechanical factors such as the pressure differences between the abdominal and thoracic cavities, which would change with changes of posture, and it seems possible that the change in reserve air might also in part have been so determined.

The relationship between the resting diaphragmatic level and the reserve diaphragmatic movement is shown in Fig. 6. As the resting level of the diaphragm moved higher in the thorax, the movement of the diaphragm above the resting level, the reserve diaphragmatic movement, became smaller.

There was a highly significant correlation between the size of the reserve diaphragmatic movement and the size of the reserve air, but little relation between the size of the complementary diaphragmatic movement and the complementary air. This lack of correlation appeared to be due to lifting of the thoracic cage. For, although the diaphragm descended during inspiration relative to its attachment to the thoracic cage, it was lifted up relative to the fixed fluorescent screen on which its movement was being followed by the observer, because the whole thoracic cage was lifted. If, as occurred in some subjects, the thoracic cage lifting was greater than the diaphragmatic descent, the record showed an overall rise of the diaphragm. To a varying degree, therefore, the thoracic cage lifting interfered with the relationship between complementary air and complementary diaphragmatic movement.

Lifting of the Thoracic Cage During Deep Inspiration

We have found only one previous description of the lifting of the diaphragm due to movement of the thoracic cage in deep inspiration (Jamin, 1906).

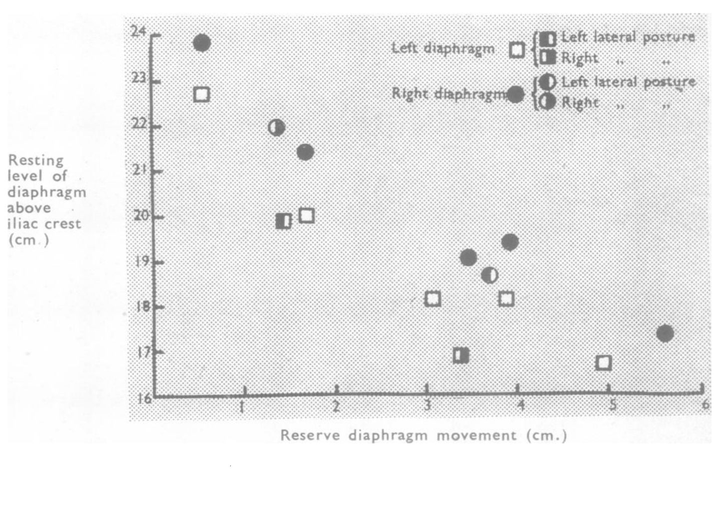


FIG. 6.—Graph showing relationship between resting level of the diaphragm and the extent of reserve diaphragmatic movement.

Mean of measurements in 12 subjects (Table V).

Fig. 7 shows tracings of records of diaphragmatic movement from three normal subjects in the erect posture. In subject E 68 there is relatively little lifting of the thoracic cage: in E 5 the thoracic cage and the diaphragm were lifted at the end of deep inspiration, but the lifting was not accompanied by any increase in the volume of the lungs. In E 108 the lifting of the thorax was so great that the diaphragm rose during the whole phase of inspiration, and it lay at a higher level after deep inspiration than after quiet inspiration.

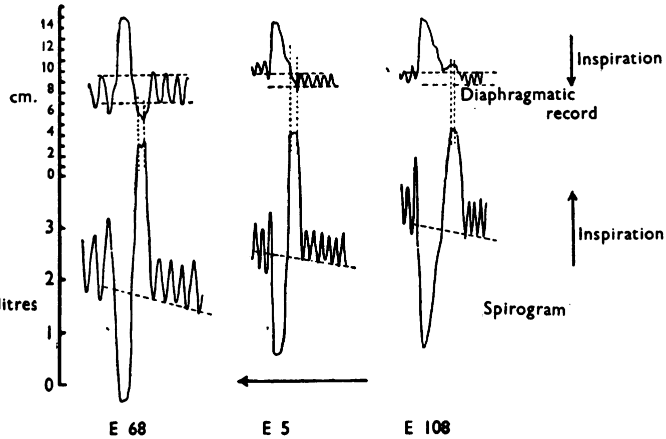


FIG. 7.—Tracings of records of right diaphragmatic movement and of spirograms in three norma subjects in the erect posture, showing lifting of the diaphragm on inspiration in two subjects.

The lifting of the diaphragm during deep inspiration in the erect posture was investigated in 48 normal subjects aged 23–58 (mean 42). The diaphragm rose during inspiration in 29 subjects, and in 20 of these 29 it was lifted to such an extent that it lay at a higher level after deep inspiration than after a quiet tidal inspiration. This occurrence was in no way related to the age of the subjects.

*The Effect on Diaphragmatic Movement of the Usual Posture for Chest Radiography.**—The total diaphragmatic excursion of a subject can be measured from records of diaphragmatic movement and can also be assessed from chest radiographs: the radiographs are taken in full inspiration and full expiration and are superimposed so that the change of level of the diaphragm that has occurred can be measured. In a group of 25 normal subjects on whom these two measurements were made, we found that the measurements made from the chest radiographs were systematically larger than the measurements made from our records (Fig. 13). To explain this it was suggested that the chest radiographs were taken with the subjects standing with chest and shoulders pressed firmly against an x-ray cassette and that in this position it was not easy to lift the thoracic cage, while during our screening for the tracking of diaphragmatic movement subjects stood normally erect, and

* In the posture we have used for chest radiography, the subject stands with the chin forward, the chest and shoulders pressed firmly forward against the x-ray casette, the dorsum of the hands on the loins, and the elbows pressed firmly forwards.

many of them lifted their chests during deep inspiration and modified the downward movement of the diaphragm.

To test this hypothesis a group of 11 normal men aged 25–52 (mean 35) was studied. Before investigating the effect of a change of posture, it was necessary to show that measurements made from the records of diaphragmatic movement and from the inspiratory and expiratory chest radiographs were comparable if both observations were made when subjects were standing normally erect. As the radiographs were taken at the moment of fullest inspiration and expiration, it was necessary to measure off from our records the change of level of the diaphragm which occurred between deepest inspiration and deepest expiration, so that the two measurements would be comparable. The method by which this was done is shown in Fig. 8. The two measurements of diaphragmatic excursion in the 11 subjects are given in Table IX (cols. 1 and 2) and are plotted against each other in Fig. 9.

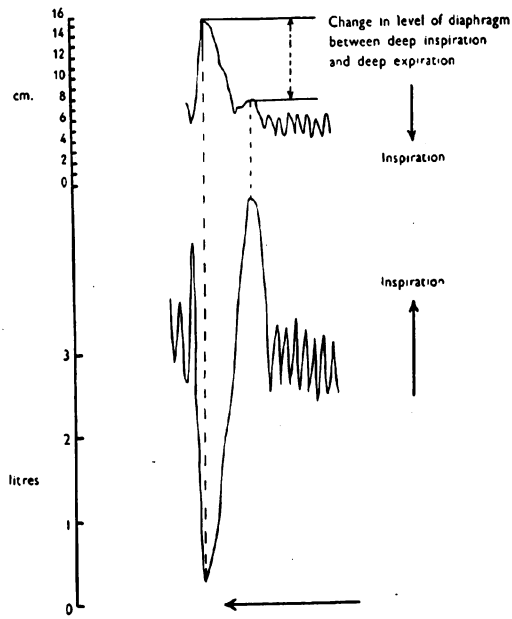


FIG. 8.—Tracing of the record of diaphragmatic movement and spirogram from a subject in the erect posture. There is lifting of the diaphragm during inspiration. The method of measuring the change in level of the diaphragm between the moment of deepest inspiration and deepest expiration is shown.

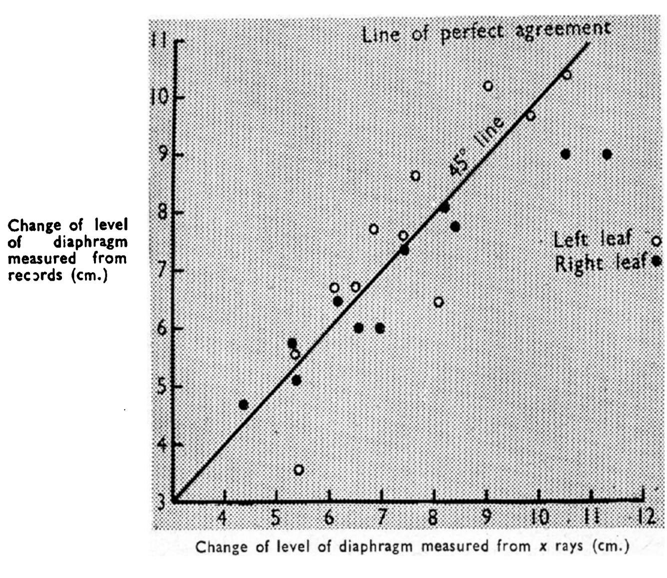


FIG. 9.—Graph showing relationship between measurements of the change of level of the diaphragm during deep respiration made from records of diaphragmatic movement (screening) and from spirometrically controlled radiographs; subjects standing in the normal erect posture. (See Table IX, cols. 1 and 2.)

There was no need to correct for geometrical distortion, as both observations were made under similar conditions. The relationship between these measurements was close.

TABLE IX

MEASUREMENTS OF CHANGE OF LEVEL OF THE DIAPHRAGM BETWEEN DEEP INSPIRATION AND DEEP EXPIRATION IN 11 SUBJECTS UNCORRECTED FOR GEOMETRICAL DISTORTION

Subject	From Records of Diaphragmatic Movement (cm.)		From 3′ Radiographs (cm.)		From 6′ Radiographs (cm.)		From 6′ Radiographs (cm.)		Comments on Screening
	Normal Erect Posture		Normal Erect Posture		Normal Erect Posture		Position for Chest Radiography		
	Right	Left	Right	Left	Right	Left	Right	Left	
M ..	9.0	10.4	11.3	10.5	9.8	10.0	6.5	7.7	No lifting of thoracic cage
W ..	7.7	8.6	8.4	7.7	6.9	7.5	5.7	5.8	,, ,, ,, ,, ,,
L ..	9.0	9.7	10.5	9.8	9.2	8.2	8.0	8.9	,, ,, ,, ,, ,,
G ..	5.1	6.65	5.4	6.5	5.0	7.6	8.0	9.1	Lifting of thoracic cage
Co ..	6.5	6.7	6.2	6.1	4.7	5.3	8.0	7.5	,, ,, ,, ,,
O ..	6.0	7.7	6.6	6.8	3.5	5.2	8.2	8.4	,, ,, ,, ,,
Wr ..	4.7	3.5	4.4	5.4	2.3	3.0	5.0	3.9	,, ,, ,, ,,
R ..	8.1	10.2	8.2	9.0	6.8	6.5	8.0	8.2	Flattening of diaphragmatic tracing
P ..	6.0	6.4	7.0	8.1	6.6	6.6	7.5	7.3	Lifting of thoracic cage
H ..	7.4	7.6	7.4	7.4	6.7	7.6	8.4	7.7	,, ,, ,, ,,
Wi ..	5.7	5.6	5.5	5.3	4.4	5.0	7.7	6.7	,, ,, ,, ,,

Inspiratory and expiratory radiographs were then taken of the subjects in the normal erect posture and as positioned for chest radiography. The measurements of the change of level of the diaphragm from these two sets of radiographs are given in Table IX, and they are plotted in Fig. 10. It can be seen that there was a poor relationship between these measurements, because the measurements made from the

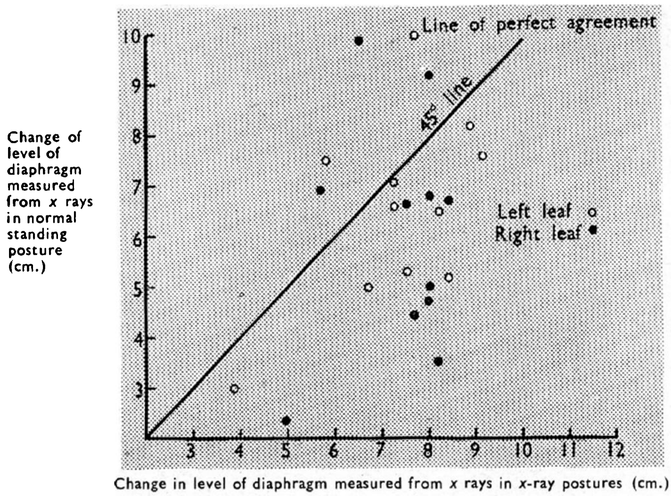


FIG. 10.—Graph showing relationship of the change in level of the diaphragm during deep respiration made from spirometrically controlled radiographs in a group of subjects standing normally erect and standing in the posture adopted for chest radiography. (See Table IX, cols. 3 and 4.)

radiographs taken in the normal chest radiography position were larger than the measurements made or from radiographs taken in the normal erect posture in those subjects who lifted the thoracic cage during inspiration when standing erect.

Discussion.—Although lifting of the diaphragm is often difficult to observe unless movement is being recorded relative to a fixed point, it is not at all uncommon in normal subjects in the normal erect posture, and it probably accounts for the poor relationship we found between complementary diaphragmatic movement and complementary air (Table VI).

The posture adopted during chest radiography tends to diminish this lifting of the thoracic cage and in many subjects causes an increase of the apparent descent of the diaphragm. It has been suggested (Grossmann and Herxheimer, 1948) that the level of the diaphragm relative to the iliac crest as seen in an inspiratory radiograph can be used in the assessment of emphysema, and it is important to realize that this level may vary with the posture adopted for radiography. In future investigations of diaphragmatic movement it might be helpful to reduce or limit the lifting of the thoracic cage.

Diaphragmatic Movement in the Lateral Postures

Early Observations.—Since the introduction of chest radiography many observations have been made of the movement of the diaphragm in the lateral postures, but few observers have made any attempt to measure what they have observed, and this failure is probably responsible for the contradictory statements reported. Link (1902) claimed that lying in the lateral postures had a beneficial effect on a diseased lower lung, partly because in this posture the ventilation of the lower lung was diminished and partly because of an increased hyperaemia of this dependent lung ; he stated that the lateral postures had little effect on the movement of the diaphragm.

Four years later, Jamin (1906) gave a very careful description of the changes in the resting level of the diaphragm which occur on adopting the lateral postures. He described the lower leaf as lying high in the thorax, and the upper leaf as lying low in the thorax in these postures, and he attributed this to changes in the distribution of weight of the abdominal viscera. He studied the movement of the diaphragm in quiet tidal respiration, and in one young subject he reported the tidal movement of the diaphragm as just over 1.5 cm. except when the patient lay in the right lateral posture, when the right diaphragmatic tidal movement was slightly reduced. He also described a slight shift of the mediastinum towards the lower side, and he believed that ventilation of the lower lung in either lateral posture was reduced.

Webb, Forster, and Gilbert (1921) stated that when subjects adopted the lateral postures the tidal movement of the lower diaphragm was much greater than that of the upper diaphragm. They noted that after an interval of about an hour a slight shift of the mediastinum occurred towards the lower side and that the diaphragmatic movement on this side became reduced so that it was no longer greater than on the upper side. They believed the function of the lower lung to be reduced and advised that subjects with unilateral pulmonary tuberculosis should lie on the diseased side. In 1928 Butler and Dana described the movement of the lower diaphragm in the lateral postures as being much larger than that of the upper diaphragm.

Adams and Pillsbury (1922) repeated Jamin's observations on the changes of resting level of the diaphragm that occur on adopting the lateral posture. They reported that the movement of the lower diaphragm was no greater than that of the upper diaphragm, but they believed that its excursion had a " greater respiratory efficiency " than the excursion of the upper diaphragm, a belief that seems to have been based on the lighting up of the basal part of the lower lung which they observed during inspiration.

Pierson and Newell (1936) described the lower diaphragm as moving more freely than the upper one in quiet respiration, and they noted that there was less expansion of the ribs on the lower side. They believed, partly as a result of their investigations on dogs, that the diaphragm played a very important part in ventilating the lungs and that in the lateral postures the tidal ventilation of the lower lung was increased because the diaphragmatic movement was increased.

Howkins (1948) also reported that the lower diaphragm had a larger excursion in either lateral posture.

Experimental Results.—In the lateral postures we have found a considerable difference in the resting levels of the two leaves of the diaphragm (Table V). The difference is especially marked when subjects lie in the right lateral posture, when the right diaphragm lies very high in the thorax and the left diaphragm very low. This finding was confirmed by taking chest radiographs at the end of quiet expiration in a normal subject in the left and right lateral postures.

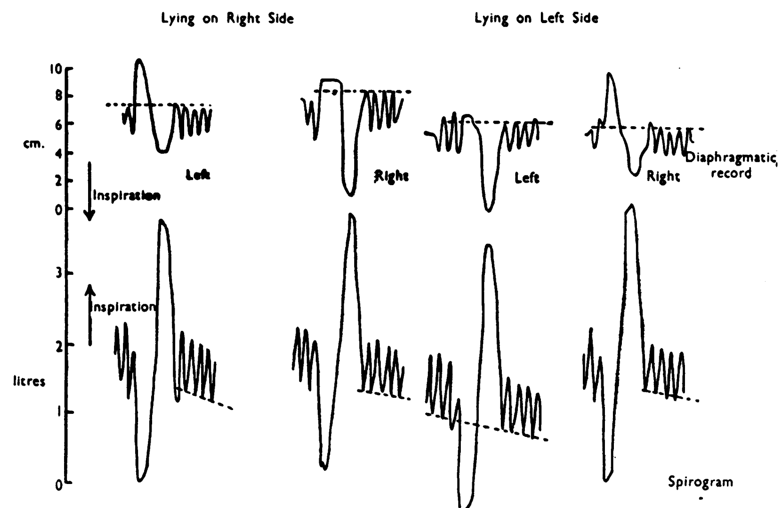


FIG. 11.—Tracings of the spirogram and the record of diaphragmatic movements in one subject in the right and left lateral postures.

Fig. 11 is a tracing of the record of diaphragmatic movement and respiration from one subject lying in the right and left lateral postures. A study of this tracing and of the figures given in Table V for the whole group of subjects shows that the tidal diaphragmatic movement in quiet respiration and the total diaphragmatic excursion in deep respiration were very slightly increased on the lower side in either posture. But the pattern of movement on the two sides was very different. On the upper side the resting diaphragmatic level was low in the thorax, the complementary diaphragmatic movement was small, and the reserve diaphragmatic movement above the resting level was large. The position and movements of the upper leaf were thus similar to those of both leaves in the erect posture. On the lower side in either lateral posture, the resting diaphragmatic level was high in the thorax, the complementary diaphragmatic movement was large, and the reserve diaphragmatic movement was small. Thus the lower leaf behaved like both leaves when the subject was lying supine or tilted 45° head down. The relationship between the resting level of the diaphragm and the extent of its reserve movement is the same in the lateral postures as in the other postures (see Fig. 6).

Discussion.—In either lateral posture the factors that determine the resting level and pattern of movement of the lower leaf of the diaphragm seem to be similar to those that affect both leaves when the subject is supine or lying tilted 45° head down. In these latter two positions the resting level of the diaphragm and its tidal movement are high in the thorax and both lungs seem compressed, while in the lateral postures it is the lower diaphragm alone which lies high in the thorax and the lower lung which seems compressed, especially when subjects lie on the right side. When subjects are lying tilted 45° head down, the vital capacity is reduced. In the lateral posture it seems unlikely that the ventilation of the lower lung is increased, as has been claimed by some workers. There is a tendency for the mediastinal structures to fall towards the lower side, the expansion of the lower parts of the thoracic cage is reduced, and movement of the lower diaphragm is only very slightly greater than that of the upper diaphragm. Bronchospirometric investigations of lung ventilation in the lateral postures were made by Björkman (1934), who, on rather inconclusive evidence, suggested that ventilation of the lower lung was increased. More recently West (1950) has made further investigations which, although not yet complete, suggest that ventilation of the lower lung is less than that of the upper lung.

As the pattern of movement of the diaphragm is different on the two sides in the lateral postures, it would be expected that the components of vital capacity in each lung would also differ and that the lower lung would have a small reserve air and the upper lung a large reserve air.

The Value of Spirometry in Chest Radiography

The Achievement of Full Excursion of the Diaphragm.—It has been previously mentioned that we were interested in comparing measurements of the total diaphragmatic excursion made by our method and made from chest radiographs taken in inspiration and expiration.

Sixty-two normal working men aged 23–58 (mean 43) were investigated. Some of these men were colliers, the others were men attending at local labour exchanges to change their jobs. All were clinically examined. None had symptoms or signs of cardiac disease. None of them had any respiratory complaint, but on close questioning nine of them admitted to tightness of the chest occasionally, at times other than when they had colds. All their chest radiographs were normal. Their ages were, as far as was possible, within the limits of ± 2 of 25, 35, 45, and 55 years.

They were divided into two groups: (1) an "uncontrolled group" of 37 men whose inspiratory and expiratory chest radiographs were taken by a radiographer who simply instructed them to breathe in or out fully, watched them from a few feet away, and made an exposure when inspiration or expiration seemed complete; (2) a controlled group of 25 men whose radiographs were taken while they were breathing into a closed circuit so that a spirogram could be watched by the radiographer, enabling him to make the exposure at the moment of deepest expiration or inspiration. The spirograms were later compared with other measurements of vital capacity made from the same subjects, so that it was possible to check that full inspiration and expiration had been made during radiography.

These inspiratory and expiratory chest radiographs were superimposed and measurements of the diaphragmatic excursion were made from the films and compared with measurements of diaphragmatic excursion made by the method of tracking diaphragmatic movement. There was a closer relationship between these two measurements in the group with spirometric control of x rays than in the other group (Figs. 12 and 13). It is likely that the difference between the two groups was in

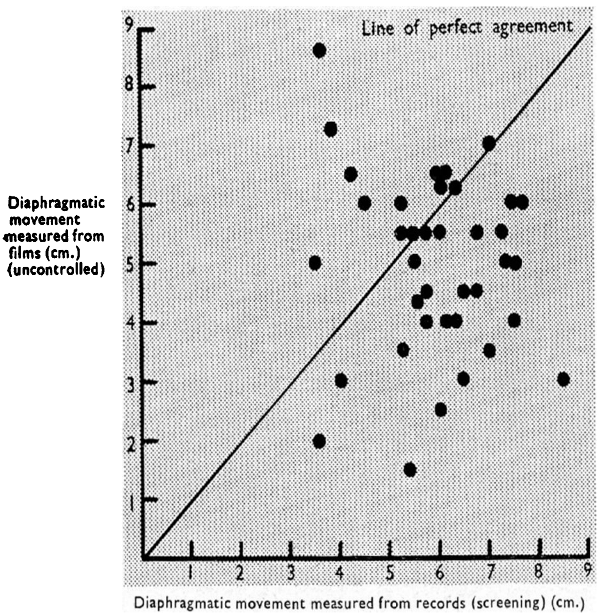


FIG. 12.—Scatter diagram showing the poor relationship between measurements of diaphragmatic excursion made from records of diaphragmatic movement and from "uncontrolled" radiographs of 37 normal subjects. (Radiographs taken in usual posture for chest radiography.)

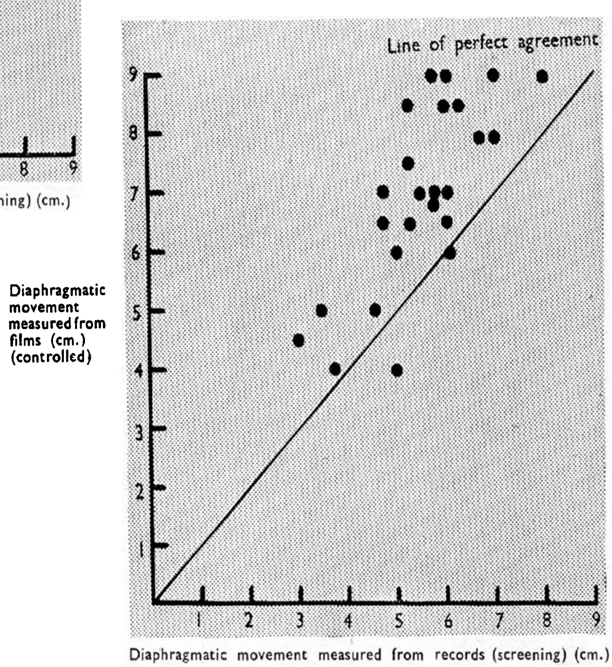


FIG. 13.—Scatter diagram showing improved relationship if spirometric control of respiration during radiography is used (25 normal subjects).

part due to a failure of the men in the uncontrolled group to achieve full inspiration and expiration.

Use in Measuring Radiological Chest Volumes.—The area of the inspiratory and expiratory radiographs of each man in the controlled and uncontrolled groups was

TABLE X

MEASUREMENTS OF TOTAL LUNG VOLUME, RESIDUAL AIR, VITAL CAPACITY, AND RADIOLOGICAL CHEST VOLUMES FROM INSPIRATORY AND EXPIRATORY RADIOGRAPHS OF 37 NORMALS OF THE UNCONTROLLED GROUP

Subject No.	Age	T.L.V. (litres)	Rd. Air (litres)	Rd. Air (as % of T.L.V.)	V.C. (litres)	R.C.V. Insp. (litres)	R.C.V. Exp. (litres)	Diff. R.C.V. Insp. and R.C.V. Exp.
29	24	6.23	1.92	30.8	4.38	11.58	7.65	3.93
68	24	7.79	2.19	28.1	5.77	12.57	11.22	1.35
80	24	6.25	1.64	26.2	4.63	14.40	7.85	6.55
115	24	5.63	1.39	24.7	4.61	12.68	7.60	5.08
120*	24	8.06	2.09	25.9	5.86	14.47	9.12	5.35
32	27	6.27	1.71	27.2	4.45	13.49	10.01	3.48
94	33	6.40	1.75	27.3	4.37	15.65	8.70	6.95
110	33	5.64	2.09	37.1	3.54	11.00	7.49	3.51
50	34	6.11	1.41	23.0	4.48	12.65	7.66	4.99
57	34	7.57	2.24	29.6	4.45	16.35	8.32	8.03
100	35	8.38	2.75	32.8	5.28	13.56	11.01	2.55
130	36	8.41	3.60	42.8	4.02	16.66	13.34	3.32
55	36	7.13	2.32	32.5	4.91	15.02	10.41	4.61
31	36	6.61	1.88	28.4	4.54	14.94	9.68	5.26
92	37	7.26	2.01	27.7	4.90	15.96	9.90	6.06
123	41	7.08	2.12	29.9	5.29	17.82	11.85	5.97
44	42	6.66	1.40	21.0	4.84	15.86	8.66	7.20
137*	42	7.35	2.02	27.5	5.50	17.47	10.79	6.68
124	43	6.71	2.41	35.9	4.58	17.71	11.50	6.21
119	43	7.65	2.44	31.9	5.21	16.51	11.13	5.38
97	44	4.05	1.69	41.7	2.64	11.55	7.59	3.96
36	45	5.82	1.59	27.3	4.27	16.19	10.73	5.46
96	46	6.02	1.88	31.2	4.28	11.71	8.08	3.63
118*	46	5.68	2.32	40.8	3.32	16.01	14.68	1.33
112	47	6.87	2.79	40.7	3.74	15.66	9.21	6.45
140*	50	6.64	3.07	46.2	3.28	16.62	10.77	5.85
132*	53	5.84	1.55	26.5	4.04	13.30	9.90	3.40
116	54	5.42	1.29	23.8	3.82	18.43	17.55	0.88
108	54	7.93	3.30	41.6	4.74	15.89	9.97	5.92
56	54	6.70	2.46	36.6	3.93	16.03	10.20	5.83
42	54	5.37	2.61	48.6	2.30	12.96	9.94	3.02
33	54	8.76	3.83	43.7	4.48	19.23	13.47	5.76
39	55	7.86	2.10	26.7	5.40	18.20	12.98	5.22
107*	55	5.54	2.09	37.7	3.35	11.49	8.15	3.34
69	55	6.66	2.44	36.6	3.40	18.38	12.25	6.13
103*	55	6.55	2.50	38.1	3.10	13.70	10.56	3.14
125	57	5.96	2.85	47.8	2.69	16.24	13.10	3.14

T.L.V. = total lung volume by helium dilution method. Rd. Air = residual air by helium dilution method. V.C. = vital capacity measured at the time of the chest radiography. R.C.V. Insp. = radiological chest volume in inspiration. R.C.V. Exp. = radiological chest volume in expiration. Diff. of R.C.V. Insp. and R.C.V. Exp. = difference between radiological volume inspiration and expiration in litres. Rd. A. % = residual air as percentage of total lung volume.

* Subject suffered occasional tightness of chest.

obtained by planimetry, and the radiological chest volume* (Hurtado and Fray, 1933) calculated and compared with the chest volumes of the subject determined by a helium dilution method (Gilson and Hugh-Jones, 1949).

TABLE XI

MEASUREMENTS OF TOTAL LUNG VOLUME, RESIDUAL AIR, VITAL CAPACITY, AND RADIOLOGICAL CHEST VOLUMES FROM INSPIRATORY AND EXPIRATORY RADIOGRAPHS OF 25 NORMALS OF THE CONTROLLED GROUP

Subject No.	Age	T.L.V. (litres)	Rd. Air (litres)	Rd. Air (as % of T.L.V.)	V.C. (litres)	R.C.V. Insp. (litres)	R.C.V. Exp. (litres)	Diff. R.C.V. Insp. and R.C.V. Exp.
157	34	5.90	1.48	25.2	3.74	13.80	8.27	5.53
170	34	6.49	2.01	31.0	4.62	14.03	7.58	6.45
178	35	7.10	1.74	24.5	5.18	17.88	8.82	9.06
152	36	4.34	0.95	21.9	3.37	12.02	5.57	6.45
180	37	6.22	1.54	24.7	4.79	15.71	7.88	7.83
151	38	5.03	1.44	28.6	3.45	12.51	6.88	5.63
165	41	6.35	2.19	34.5	4.72	15.85	8.44	7.41
192	42	9.84	4.78	48.6	5.35	19.72	11.92	7.80
169†	42	7.78	4.08	52.5	3.50	18.45	12.29	6.16
159	43	8.55	3.34	39.1	5.22	18.30	7.86	10.44
176	43	5.63	1.47	26.2	4.04	13.39	6.68	6.71
190	45	6.08	1.69	27.8	4.13	17.24	10.79	6.45
148	45	7.04	2.61	37.0	4.53	16.86	9.48	7.38
161	45	6.64	3.70	55.8	2.47	17.47	12.03	5.44
149	45	6.98	2.18	32.2	4.66	15.23	9.40	5.83
181	46	5.76	1.35	23.4	4.44	14.96	7.49	7.20
147†	47	7.44	2.68	36.0	4.30	17.86	10.20	7.66
162	47	6.24	2.70	43.3	3.46	14.76	9.05	5.71
182	49	6.97	2.19	30.0	4.52	16.27	9.32	6.95
174	53	6.41	3.01	46.9	3.62	15.03	10.54	4.49
150	55	6.02	1.79	29.7	4.37	18.00	9.98	8.02
153	55	5.72	1.84	32.2	3.57	14.66	9.04	5.62
164	55	5.08	2.11	41.6	2.86	13.16	7.50	5.66
185	55	6.08	2.49	41.0	3.89	16.13	8.94	7.19
172	56	6.25	2.02	32.3	4.69	17.16	9.19	7.97

T.L.V. = total lung volume by helium dilution method. Rd. Air = residual air by helium dilution method. V.C. = vital capacity measured at the time of the chest radiography. R.C.V. Insp. = radiological chest volume in inspiration. R.C.V. Exp. = radiological chest volume in expiration. Diff. of R.C.V. Insp. and R.C.V. Exp. = difference between radiological volume inspiration and expiration. Rd. A. % = residual air as percentage of total lung volume.

† Subject suffered occasional tightness of chest.

Table X gives the measurements of the uncontrolled group and Table XI the measurements of the controlled group. In Table XII the correlation between these measurements is compared with similar correlations reported by other workers. It will be seen that spirometric control improved our results very greatly. . The correlation which we found between radiological chest volumes and the vital capacity

* The formulae used to determine the radiological chest volume were as follows:

Inspiratory radiological chest volume = the radiological chest area of the inspiratory chest radiograph (in cm.^{2}) × anterior-posterior diameter of the subject's chest in full inspiration (in cm.).

Expiratory radiological chest volume = the radiological chest volume of the expiratory chest radiograph (in cm.^{2}) × the anterior-posterior diameter of the subjects chest in full expiration (in cm.).

A.P. chest diameters were measured with calipers.

TABLE XII

COEFFICIENTS OF LINEAR CORRELATION BETWEEN LUNG VOLUMES AND RADIOLOGICAL CHEST VOLUMES

Observers	Subjects	Coefficient of Correlation	95% Confidence Limits of Coefficients of Correlation*
Hurtado and Fray, 1933	50 normal males (age 18–30, mean 23)	T.L.V. and R.C.V. insp. r = 0.6366 Rd. Air and R.C.V. exp. r = 0.3826 V.C. and R.C.V. insp. r = 0.7174	(0.42–0.73) (0.13–0.58) (0.55–0.83)
Kaltreider, Fray, and Hyde, 1938 ..	50 normal males (age 18–30, mean 23)	T.L.V. and R.C.V. insp. r = 0.6089 V.C. and R.C.V. insp. r = 0.7174	(0.41–0.76) (0.55–0.83)
	50 normal males (age 38–63, mean 48)	T.L.V. and R.C.V. insp. r = 0.8497 V.C. and R.C.V. insp. r = 0.7283	(0.76–0.92) (0.58–0.84)
Aslett, D'Arcy Hart, and McMichael, 1939	66 normal males (age 19–63, mean 38)	T.L.V. and R.C.V. insp. r = 0.80 V.C. and R.C.V. insp. r = 0.63	(0.70–0.88) (0.44–0.74)
This paper	38 normal males (age 24–57, mean 42) No spirometric control (Table X)	T.L.V. and R.C.V. insp. r = 0.47 Rd. Air and R.C.V. exp. r = 0.34 V.C. and diff. R.C.V. insp. and R.C.V. exp. r = 0.36	0.16–0.68 0.01–0.60 0.03–0.62
	25 normal males (age 34–56, mean 45) spirometric control (Table XI)	T.L.V. and R.C.V. insp. r = 0.82 Rd. Air and R.C.V. exp. r = 0.76 V.C. and diff. R.C.V. insp. and R.C.V. exp. r = 0.77	0.62–0.92 0.51–0.88 0.52–0.89

* Calculated from tables of the correlation coefficient (David, 1938).

and total lung volume in our controlled group was not very different from that found by some of the other workers, and the relationship between the expiratory radiological chest volumes and residual air was much better than that previously reported.

Discussion.—Although it is not mentioned as a serious difficulty by other workers, we found that full inspiration and expiration were not easy to attain during routine chest radiography without spirometric control.

A good relationship between radiological chest volumes and the lung volumes measured by other methods was only obtained if care was taken that radiographs were made when subjects had inspired or expired completely, and to achieve this spirometric control was most valuable.

Spirometric control may prove valuable in routine radiography on other occasions. It is sometimes necessary to obtain repeated radiographs of the same individual over a number of years, and at the same time desirable that the technique of each film should be identical (Fletcher, Mann, Davies, Cochrane, Gilson, and Hugh-Jones, 1949). It is also possible that emphysema can be assessed by comparing the inspiratory and expiratory radiographs of an individual. For both these purposes spirometric control would be valuable.

In this paper we have only dealt with diaphragmatic movement in normal subjects. Since the method gives objective measurements of the position and movements of the diaphragm, it can be applied to various conditions in which diaphragmatic movement is affected. We have made observations on the movement of the diaphragm in patients with pneumoconiosis which will be published elsewhere. The method has been used to make records of diaphragmatic movement in subjects who were given curare-like drugs (Mushin, Wien, Mason, and Langston, 1949) and is applicable in studies of the effect of lesions of the central nervous system on movement of the diaphragm (Robinson, 1950).

SUMMARY

By a mechanical device for tracking the movement of the shadow of the diaphragm on the fluorescent screen and a spirometer, a simultaneous record of diaphragmatic movement and respiration was made. The standard error of a single measurement of the total diaphragmatic excursion was 0.6 cm.

Twelve normal subjects were examined in a sequence of postures from standing to lying tilted 45° head down. In all postures the movement of the right and left diaphragm during quiet breathing was about 1.5 cm. and during deep respiration was about 6 or 7 cm. With the change of posture there was a progressive rise of the resting level of the diaphragm relative to the iliac crest (total rise 6.3 cm.) and a change in the pattern of diaphragmatic movement. A close relationship was found between the volume of the reserve air and the extent of movement of the diaphragm above its resting level. Regression equations relating these are given. No such relationship was found between the complementary air and the movement of the diaphragm below its resting level. This was in part due to lifting of the thoracic cage which occurred during deep inspiration and modified the downward movement of the diaphragm. In 20 of 48 other normal subjects the diaphragm was lifted so much during inspiration that it lay higher at the end of a deep inspiration than at the end of a quiet inspiration. Slight changes of posture, such as the adoption of the usual position for chest radiography, alter the extent of this lifting considerably.

When lying on the side, the pattern of movement of the lower diaphragm is similar to that of both domes when the subject is lying supine or tilted 45° head down. The lower lung appears to be relatively compressed.

In routine chest radiography films in full inspiration and expiration could be obtained with certainty only by using a spirogram. In 25 normal subjects coefficients of correlation between the radiological chest volumes and the lung volumes measured by a helium dilution method were between RCV (insp.) and TLV $r=0.82$ and between RCV (exp.) and RdA. $r=0.76$.

A short review of previous studies of diaphragmatic movement is given and a bibliography is appended.

We are grateful to members of the M.R.C. Pneumoconiosis Research Unit for help with the experiments, to Mr. P. D. Oldham for his advice and assistance with the statistical analysis, and to Dr. F. Lavenne for the planimetry of radiographs.

We are indebted to Mr. Clarke and the staff of our radiological department for much valuable assistance, and to Mr. A. V. Lambert, who has prepared the figures. We wish to thank Dr. C. M. Fletcher, the director, for continual encouragement and advice.

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