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MOVEMENTS OF THE THORACIC CAGE AND DIAPHRAGM IN RESPIRATION*

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Comprehensive investigations of the movements of the diaphragm were made shortly after the introduction of radiology by Jamin (1906), Dally (1908) and Keith (1907, 1909). Jamin and Dally both reported difficulty in measuring the extent of diaphragmatic movement because in some subjects the whole chest lifts at the end of deep inspiration and with it the diaphragm which may lie at a higher level at the end of deep inspiration than at the end of quiet respiration. Dally attributed this to extension and flexion of the vertebral column which occurs in some subjects on deep inspiration.

The relationship between movements of the thoracic cage and the diaphragm has been investigated by Sewall & Pollard (1890) and Staehelin & Schutze (1912) who attempted to assess the diaphragmatic component of respiration by observing changes of circumference of the abdomen, and by Herxheimer (1949) who recorded ventilation with a spirometer and changes of chest circumference with a thoracometer designed by Verzar (1946). None of these workers observed diaphragmatic movements directly. Herxheimer has suggested that there is dissociation of the movements of the chest and diaphragm and that at different phases of deep respiration first one and then the other plays the predominant part in ventilating the lungs.

Wade & Gilson (1951) described a method of measuring diaphragmatic movement and showed that with changes of posture the extent of diaphragmatic movement in both quiet and deep respiration varied little, but the resting level of the diaphragm at the end of a quiet respiration changed greatly and the pattern of diaphragmatic movement in relationship to this resting level showed great changes. These authors realized, however, that some of their measurements of diaphragmatic movement were unreliable because vertical movements of the thoracic cage that occurred with respiration

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distorted the recording and measurement of the diaphragmatic movements. The studies here reported were made to determine the relationship between movements of the diaphragm and changes of chest circumference during respiration, and to determine whether there can be independent movements of the diaphragm and the chest wall and whether these are under voluntary control. In this investigation vertical movements of the thoracic cage have been recorded and measured so that error due to this cause in assessing the extent of movements of the diaphragm could be eliminated as far as possible.

TABLE 1. Corrections for geometric distortion made to measurements from records of diaphragmatic movement

Extent of movement of diaphragm away from its resting level as tracked from screen (cm)	Correction made (cm)
0–1·9	No correction
2–3·9	Subtract 0·5
4–5·9	Subtract 0·75
6–10	Subtract 1·0
10 or more	Subtract 1·3

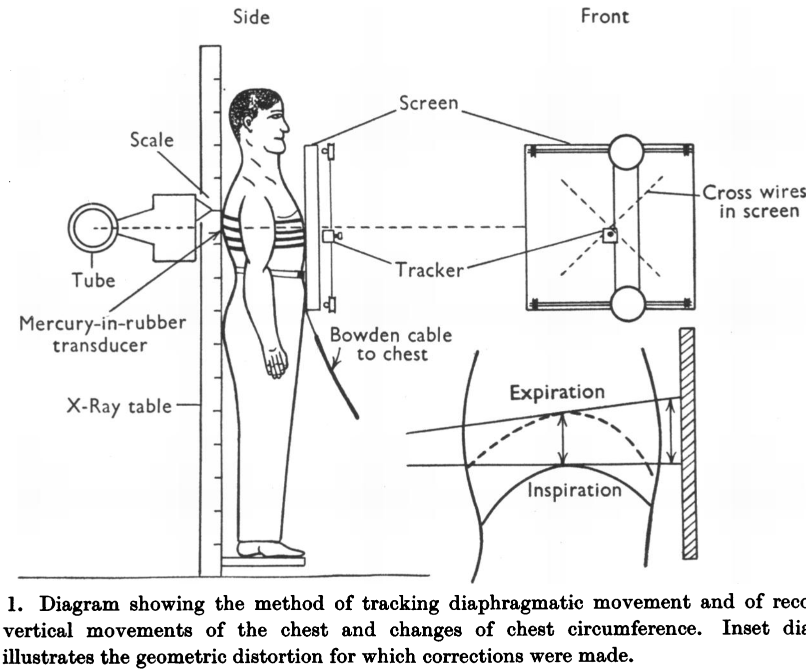

Fig. 1. Diagram showing the method of tracking diaphragmatic movement and of recording vertical movements of the chest and changes of chest circumference. Inset diagram illustrates the geometric distortion for which corrections were made.

METHODS

Respiration and diaphragm movements are recorded and measured by the method described by Wade & Gilson (1951). While a spirogram is being made, the subject is screened and the movements of the shadow of each dome of the diaphragm are tracked on a fluorescent screen (Fig. 1). Corrections (Table 1) are made for geometric distortion (Fig. 1).

In this investigation vertical movements of the front of the thoracic cage are also recorded. A small Perspex plate, part of the apparatus for recording changes in chest circumference, is strapped firmly to the chest wall over the sternoxiphisternal joint and vertical movements are recorded by a Bowden cable. The tension of the spring loading of this cable is 800 g. Fig. 2 shows a typical recording of respiration, diaphragmatic movement and vertical chest movement. The nomenclature employed in this study is also shown.

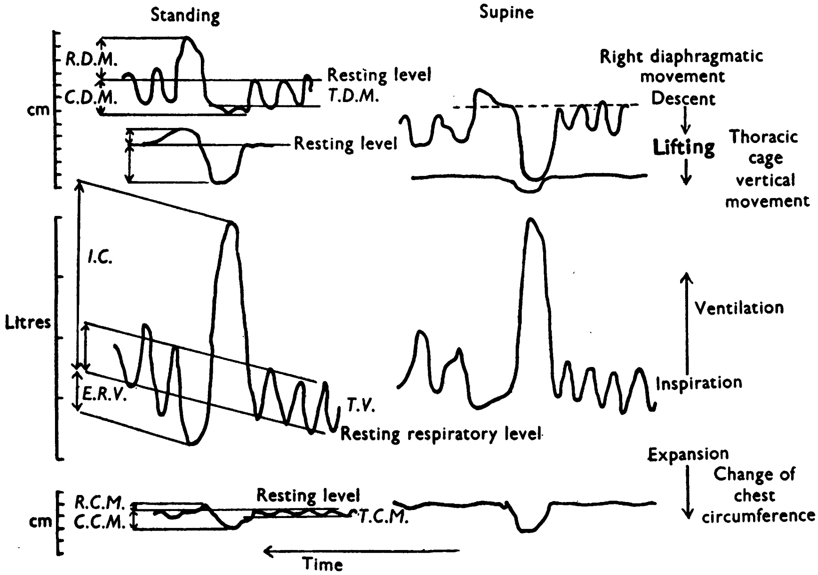

Fig. 2. Tracing of typical records of movements of the right leaf of the diaphragm, of vertical movements of the chest and of changes of chest circumference with simultaneous spirogram made in the supine and erect posture. *R.D.M.* = Reserve diaphragmatic movement. *C.D.M.* = Complemental diaphragmatic movement. *T.D.M.* = Tidal diaphragmatic movement. *I.C.* = Inspiratory capacity. *E.R.V.* = Expiratory reserve volume. *T.V.* = Tidal volume. *R.C.M.* = Reserve chest movement (change of circumference). *C.C.M.* = Complemental chest movement (change of circumference). *T.C.M.* = Tidal chest movement (change of circumference).

The recording and measurement of chest expansion

A modification has been made of a method used by Whitney (1949) to measure changes in limb volume. A transducer of rubber tubes filled with mercury is wrapped round the chest. Stretching the tubes lengthens and narrows the columns of mercury and increases their electrical resistance. These mercury resistances form two arms of a balanced Wheatstone bridge and slight changes in the balance of the bridge which occur when the resistances vary, are amplified and recorded by a sensitive galvanometer (Fig. 3 and Appendix).

Design of the transducer

Four 60 cm lengths of rubber tubing of 0·5 mm bore and 1·5 mm external diameter are filled with mercury and plugged with pins formed from the heads of brass bolts. The bolts are fixed to two Perspex bars (Fig. 4) and are used as electrical contacts to incorporate the mercury resistances as part of the Wheatstone bridge circuit. The mercury filled tubing is looped over small pulleys countersunk into a Perspex plate. The instrument is wrapped horizontally round the chest, the plate is fixed firmly by strapping to the skin over the lower end of the sternum and the two bars are clipped together and strapped to the skin over the spine.

Each mercury-filled tube weighs 4 g and its resistance unstretched is 3·5 Ω. The weight of the whole instrument is 300 g. Fig. 5 is a graph showing the changes of tension that accompany changes of length of the whole instrument.

When the apparatus is fixed around the subject's chest, the Wheatstone bridge is balanced so that the galvanometer gives zero reading for the circumference of the chest corresponding to the resting respiratory level at the end of quiet expiration. The galvanometer gives a deflexion above zero when the chest contracts in expiration and below zero when it expands on inspiration. Although the apparatus records changes of chest circumference, it cannot be used to measure the initial circumference of the chest. This is done with a spring-loaded measuring tape (Morant & Gilson, 1945) to the nearest half inch when the subject is at the end of a quiet expiration.

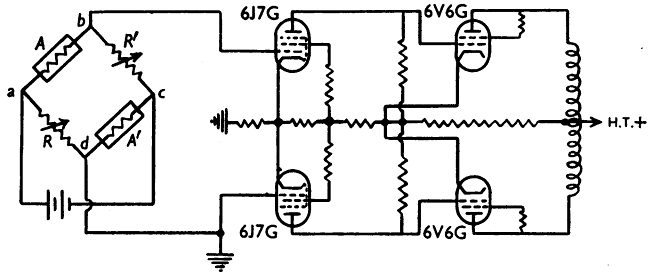

Fig. 3. Circuit for mercury-in-rubber transducer and Hughes pen recorder. *A* and *A'*, resistance of mercury-in-rubber transducer. *R* and *R'*, coupled variable resistance for balancing bridge circuit. Details of the circuit are given in an appendix.

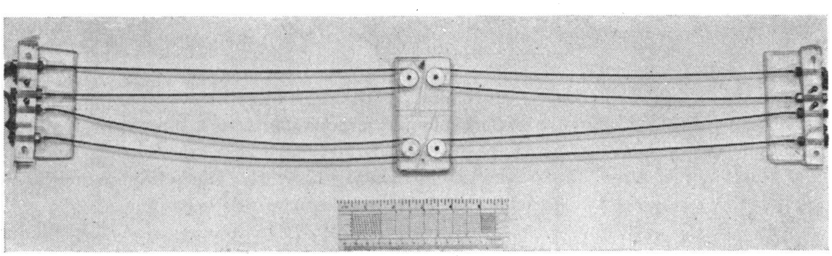

Fig. 4. The mercury-in-rubber transducer. The Bowden cable for recording vertical movements of the chest is attached to the central plate.

Calibration of the instrument

The response of the apparatus to changes in length is found to vary with the current across the bridge circuit, being more sensitive with high current (up to 400 mA), and when the initial state of stretch of the instrument is great. Fig. 6 is a graph showing the deflexion of the galvanometer needle that occurs with changes of length of the apparatus when the bridge circuit has been balanced (galvanometer reading zero) at an initial length of 30, 34, 36 and 39 in. and with currents of 230, 325 and 400 mA. Full scale deflexion of the galvanometer needle is 20 mm either side of zero and within most of this range its response to change of length is almost linear.

Speed of response of the instrument

The recording galvanometer is capable of responding accurately to signals of a frequency of 60 c/s. The limiting factor of frequency response is inertia of the mass of the mercury. Fig. 7 shows the response of the instrument when its length is changed manually by 10 cm as rapidly as possible (about 60 movements to a minute). It gives a full response whether being lengthened

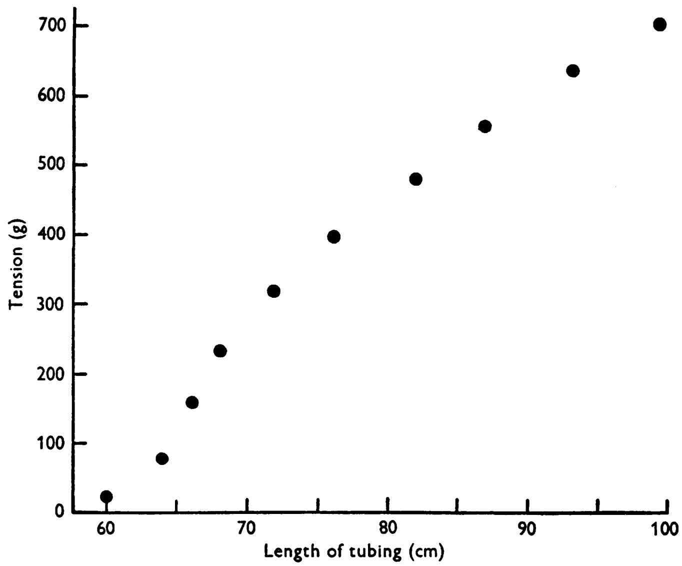

Fig. 5. Graph showing the tension required to stretch the rubber tubes of the mercury-in-rubber transducer over the range 60–100 cm.

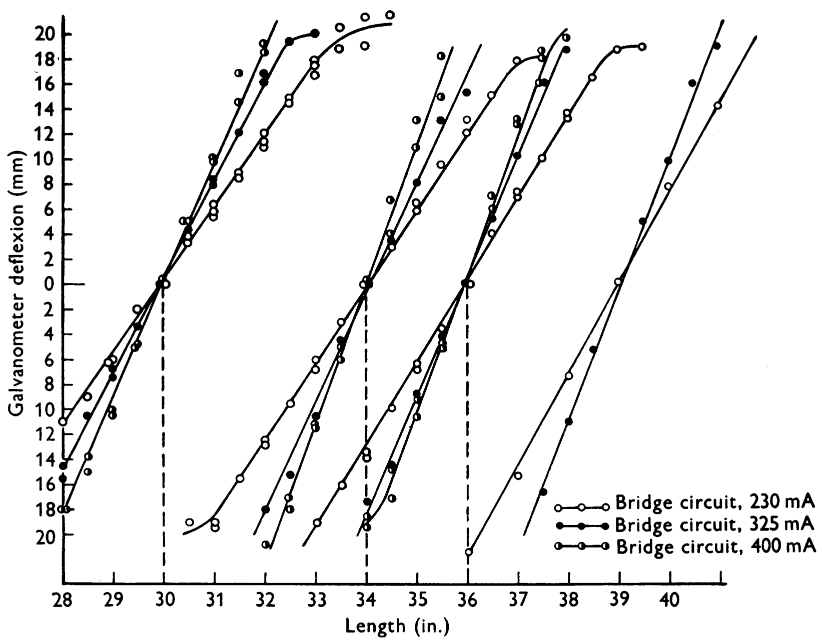

Fig. 6. Calibration of mercury-in-rubber transducer. Deflexion of galvanometer plotted against change in length of the strain gauge when balanced (galvanometer reading zero) at initial length of 30, 34, 36 and 39 in.

or shortened and shows no appreciable hysteresis under these conditions, and the response is, therefore, adequate to record change of chest circumference at the highest rate of respiration encountered.

The following are points of practical importance:

(1) The apparatus must be kept in the dark when not in use as the rubber tubes perish.

(2) The rubber tubes can be filled with mercury under slight positive pressure with a small hypodermic syringe and needle.

(3) Amalgam forms at the brass mercury junction and after periods of 3–4 months increases the resistances of the circuit and causes slight reduction in sensitivity of the instrument.

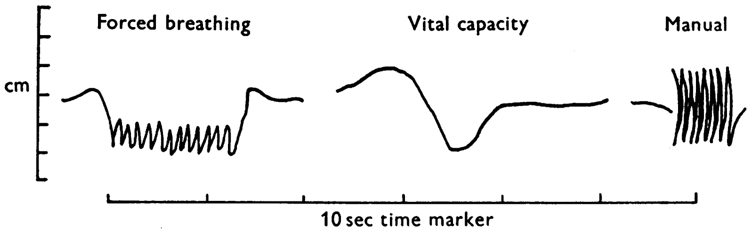

Fig. 7. Response of the mercury-in-rubber transducer.

Measurements from the records

The tidal volume, inspiratory capacity and expiratory reserve volume are measured from the resting respiratory level to the nearest 0·01 l. Volumes are corrected to 37° C fully saturated with water vapour. The vital capacity is taken as the sum of the two latter corrected volumes. Measurements of tidal, complemental and reserve diaphragmatic movement are made from the resting diphragmatic level to the nearest $\frac{1}{4}$ cm and are corrected for geometric distortion (Table 1). Measurements are made of vertical movement of the thoracic cage to the nearest $\frac{1}{4}$ cm. If these occur they distort the record of the complemental and the reserve diaphragmatic movement and to correct for this the amount of upward movement of the thoracic cage occurring during inspiration is added to the complemental diaphragmatic movement, and the amount of downward movement on expiration is added to the reserve diaphragmatic movement. The total diaphragmatic excursion is the sum of the resulting estimates of complemental and reserve diaphragmatic movement. To estimate the repeatability of measurement of diaphragmatic movement relative to the thoracic cage an analysis of variance of duplicate measurements of total diaphragmatic excursion in ten normal subjects (Table 2) was made. The standard error of a single observation is 0·45 cm.

For convenience, changes in the chest circumference are referred to as chest movement, although they are only one component of the change in shape of the thoracic cage on respiration. The tidal, complemental and reserve chest movement (Fig. 2), are measured from the resting level and are expressed in centimetres of change of chest circumference by reference to the calibration charts appropriate for the current and the initial resting circumference of the chest. The sum of the complemental and reserve chest movement is the total chest excursion, the 'chest expansion'. Duplicate records of the changes of chest circumference during deep respiration were made in ten subjects. The measurements were submitted to an analysis of variance (Table 2) and the standard error of a single observation of total chest movement is 0·57 cm.

Records of total chest excursion made with the apparatus are found to agree closely with measurements of 'chest expansion' made in the more usual way with the spring-loaded tape measure (Tables 3 and 5).

The present method of measuring movements of the diaphragm relative to the thoracic cage is only approximate. It has been implied that the movements of the shadows of the domes of the diaphragm are closely related to movements of the whole diaphragm. This cannot be fully justified but lateral chest radiographs taken at different levels of respiration show that the antero-posterior contour of the diaphragm does not change greatly even in deep respiration. It is also an approximation to assume that vertical movements of the diaphragmatic attachments to the thoracic cage can be accurately measured by recording vertical movement of the front of the chest. Most of the vertical movement is caused by extension and flexion of the vertebral column, and anterior parts of the chest move more than posterior parts. As the domes of the diaphragm lie anteriorly and as it is their movement which is being recorded it is reasonable to assume that the domes are lifted or lowered with vertical movement of the chest to about the same extent as the sternum.

TABLE 2. Analysis of variance of duplicate measurements of total diaphragmatic excursion and of total chest excursion made in ten normal subjects in the erect and supine postures

Total diaphragmatic excursion (left leaf of diaphragm)

	Sum of squares	Degree of freedom	Mean squares
Between postures	1·806	1	1·81
Between mean	113·400	9	12·60
Interaction	23·444	9	2·60
Error	4·125	20	0·21
Total variance	142·775		

Standard error of a single observation = 0·45 cm.

Total chest excursion

	Sum of squares	Degree of freedom	Mean squares
Between postures	2·05	1	2·05
Between mean	98·74	9	10·97
Interaction	9·72	9	1·08
Error	6·51	20	0·33
Total variance	117·02		

Standard error of a single observation = 0·57 cm.

The movements of the thoracic cage during respiration are extremely complex (Keith, 1909) but in this work it has been assumed that the changes which occur in one circumference of the chest are indicative of the expansion and contraction of the whole of the thoracic cage; this assumption is only an approximation but its acceptance has allowed a practical approach to be made to the study of the part played by thoracic cage movements in pulmonary ventilation.

RESULTS

Chest and diaphragmatic movements in quiet and deep respiration

Ten normal male subjects were examined; their ages and anthropometric measurements are given in Table 3. Each subject was examined in the erect posture and then in the supine, and in each posture duplicate records of respiration, of movement of the right and left leaves of the diaphragm, of vertical movements of the thoracic cage and of changes of chest circumference were made first while breathing quietly, and then during a deep inspiration followed by a full expiration. Fig. 2 shows parts of a typical record made in both postures in one subject.

In this group of subjects the mean height of the iliac crest from the feet is 110·7 cm (standard deviation 6·1). The mean distance of the right leaf of the diaphragm above the iliac crest when erect, is 19·9 cm (S.D. 1·0) and when supine it is 23·7 cm (S.D. 1·4). The respective measurements for the left leaf of the diaphragm being 19·3 cm (S.D. 1·2) when erect and 22·2 cm (S.D. 1·4) when supine. Although there is a marked change in the resting level of the diaphragm with change of posture there is little change in the resting chest circumference. In the erect posture the mean is 90·5 cm (S.D. 8·0) and supine it is 91·6 cm (S.D. 8·0).

TABLE 3. Anthropometric measurements of ten normal subjects in which the relationship of chest and diaphragmatic movements to respiration was investigated

Name	Age (years)	Weight (kg)	Height (cm)	Chest circumference (cm) erect	Chest expansion measured to the nearest ¼ in. with spring-loaded tape measure and converted to cm (mean of 4 observations) erect
Hy.	36	68	171	102	6·3
Mo.	34	77	168	100	4·5
La.	32	65	174	82·5	12·0
McK.	31	74	185	89	7·6
Re.	30	74	178	87	5·1
Th.	35	68	170	83	5·7
Co.	35	74	184	91·5	8·3
Ri.	27	82	172	91·5	7·0
Jo.	35	90	183	100	6·4
Mor.	24	57	160	79	5·1
Range	24–36				
Mean		73	175	90·5	6·80
S.D.		9·2	8·0	8·0	2·2

Measurements made during quiet respiration

These are recorded in Table 4. The mean tidal volume erect is 799 ml. (S.D. 210) and supine it is 758 ml. (S.D. 161). The tidal movement of the right and left leaves of the diaphragm is almost identical in each subject and changes little with the change of posture. The mean right diaphragmatic tidal movement is 1·63 cm (S.D. 0·18) erect and 1·70 cm (S.D. 0·26) supine, and for the left leaf the respective figures are 1·65 cm (S.D. 0·27) erect and 1·78 cm (S.D. 0·25) supine. No vertical movement of the thoracic cage is recorded in any subject during quiet respiration. There is a decrease in the tidal movement of chest circumference with the change from the erect to the supine posture. The mean tidal chest movement erect is 1·2 cm (S.D. 0·4) and supine 0·7 cm (S.D. 0·2).

Measurements made during deep respiration.

These are recorded in Table 5. In deep respiration vertical movements of the thoracic cage occur. Their extent is very variable from individual to individual and is most marked at the end of deep inspiration and is always greater when subjects are erect than when supine. Despite the great differences in the vertical movement of the thoracic cage in the erect and supine postures the measurements of the total excursion of the diaphragm relative to the thoracic cage in these two postures are very similar. The mean total diaphragmatic excursion of the left leaf of the diaphragm is 10·28 cm (S.D. 2·23) erect, and 9·88 cm (S.D. 1·57) supine.

The change in the resting level of the diaphragm with change of posture leads, however, to considerable changes in the pattern of diaphragmatic movement. When erect the mean complemental movement of the left diaphragm is 6·35 cm (S.D. 0·97) and the mean reserve diaphragmatic movement is 3·93 cm (S.D. 1·62). When supine the mean complemental movement is 7·95 cm (S.D. 1·32) and the mean reserve diaphragmatic movement is 1·93 cm (S.D. 0·70). Measurements of movements of the right leaf of the diaphragm are similar throughout to movements of the left leaf—but are slightly smaller.

TABLE 4. Measurements of diaphragmatic movement, changes of chest circumference and ventilation in ten normal subjects during quiet respiration in the erect and supine postures

Subject	Tidal diaphragmatic movement (cm) (mean of 2 measurements)		Tidal volume (ml.) (mean of 4 measurements)	Tidal chest movement (cm) (mean of 4 measurements)
	Right leaf	Left leaf		
		ERECT		
Hy.	1·50	1·75	1250	1·6
Mo.	1·75	1·50	800	1·4
La.	1·50	1·50	575	0·8
McK.	2·00	1·75	700	1·1
Re.	1·50	1·50	980	1·5
Th.	1·50	1·50	650	1·1
Co.	1·75	1·75	950	1·0
Ri.	1·50	1·75	580	0·6
Jo.	1·50	1·25	700	0·7
Mor.	1·75	2·25	800	2·0
		SUPINE		
Hy.	2·00	1·50	1150	0·6
Mo.	1·75	2·25	780	0·5
La.	2·00	2·00	600	0·4
McK.	1·50	1·75	600	0·4
Re.	2·00	1·75	750	0·8
Th.	1·50	1·50	600	0·9
Co.	1·50	1·50	780	1·0
Ri.	1·25	1·75	750	1·0
Jo.	1·75	1·75	810	0·5
Mor.	1·75	2·00	760	0·8

A similar change in the pattern of respiration as judged by spirometry is observed in all subjects. The mean vital capacity is 4·86 l. (S.D. 0·84) erect and 4·80 l. (S.D. 0·77) supine, but in the erect posture the mean inspiratory capacity is 3·17 l. (S.D. 0·45) and the mean expiratory reserve volume is 1·68 l. (S.D. 0·52) and in the supine posture these are respectively 3·87 l. (S.D. 0·54) and 0·93 l. (S.D. 0·32).

No such change in the pattern of chest movement is found. The mean total chest excursion is 7·4 cm (S.D. 1·8) erect and 7·7 cm (S.D. 1·7) supine, the mean complemental chest movement is 5·9 cm (S.D. 1·5) erect and 6·0 cm (S.D. 1·6) supine and the mean reserve chest movement is 1·5 cm (S.D. 0·6) erect and 1·8 cm (S.D. 0·5) supine.

The duplicate measurements of diaphragmatic movement, of respiratory ventilation and of changes of chest circumference made in the two postures

TABLE 5. Measurements of diaphragmatic movement, changes of chest circumference, movements of the thoracic cage and ventilation in ten normal subjects during deep respiration

	Diaphragmatic movements (cm)* (mean of 2 measurements)						Ventilation (litres) (mean of 4 measurements)			Change of chest circumference (cm) (mean of 4 measurements)			Vertical chest movement (cm) (mean of 4 measurements)	
	Right leaf			Left leaf										
Subject	*C.D.M.*	*R.D.M.*	*T.D.E.*	*C.D.M.*	*R.D.M.*	*T.D.E.*	*I.C.*	*E.R.V.*	*V.C.*	*C.C.M.*	*R.C.M.*	*T.C.E.*	Inspiration lifting	Expiration lowering
							ERECT							
Hy.	4·00	2·75	6·75	5·00	1·75	6·75	3·28	1·41	4·69	4·6	1·2	5·8	0·3	0
Mo.	4·75	2·75	7·50	5·75	3·00	8·75	3·30	0·92	4·22	4·0	0·6	4·6	1·8	0
La.	5·25	6·00	11·25	6·50	6·00	12·50	3·08	2·28	5·36	8·0	2·0	10·0	2·8	0·1
McK.	6·25	5·50	11·75	7·50	6·00	13·50	3·34	2·14	5·48	6·6	1·8	8·4	2·9	0·4
Re.	4·00	4·75	8·75	5·00	4·25	9·25	3·18	2·28	5·46	6·2	0·9	7·1	2·0	0
Th.	4·50	4·75	9·25	6·75	3·75	10·50	2·82	1·46	4·28	7·4	1·8	9·2	2·0	0·4
Co.	6·00	7·25	13·25	7·50	6·00	13·50	3·77	1·96	5·73	7·2	1·9	9·1	5·3	2·3
Ri.	4·25	2·75	7·00	5·50	3·75	9·25	2·68	1·35	4·03	4·4	2·4	6·8	2·1	0·3
Jo.	4·75	4·50	9·25	7·25	2·50	9·75	3·85	2·04	5·89	6·3	1·9	8·2	3·1	0·3
Mor.	5·00	2·25	7·25	6·75	2·25	9·00	2·44	0·99	3·43	4·2	0·9	5·1	3·3	0
							SUPINE							
Hy.	6·25	1·50	7·75	6·00	1·50	7·50	3·50	0·92	4·42	3·5	2·0	5·5	0·1	0
Mo.	6·00	1·50	7·50	6·50	1·25	7·75	3·23	0·35	3·58	5·9	0·7	6·6	1·7	0·1
La.	9·25	2·25	11·50	10·00	1·75	11·75	3·95	1·22	5·17	8·2	2·1	10·3	1·7	0·3
McK.	9·25	2·50	11·75	9·00	1·75	10·75	3·91	1·11	5·02	4·9	2·0	6·9	1·4	0·2
Re.	5·75	1·75	7·50	6·50	1·75	8·25	3·89	1·14	5·03	6·8	0·9	7·7	1·8	0
Th.	8·00	1·50	9·50	9·00	1·50	10·50	3·89	0·52	4·41	8·7	2·1	10·8	1·9	0
Co.	9·00	2·00	11·00	9·00	2·00	11·00	4·77	1·37	6·14	6·3	2·3	8·6	3·8	0·3
Ri.	6·75	1·25	8·00	8·00	3·75	11·75	3·72	0·74	4·46	4·9	1·9	6·8	1·9	0·3
Jo.	8·00	1·50	9·50	8·00	1·75	9·75	4·69	1·02	5·71	5·7	1·8	7·5	1·9	0
Mor.	6·75	2·50	9·25	7·50	2·25	9·75	3·15	0·90	4·05	4·6	1·9	6·5	2·1	0·7

* Corrected for vertical chest movement and geometric distortion.

C.D.M. = Complemental diaphragmatic movement.
R.D.M. = Reserve diaphragmatic movement.
T.D.E. = Total diaphragmatic excursion.
I.C. = Inspiratory capacity.
E.R.V. = Expiratory reserve volume.
V.C. = Vital capacity.
C.C.M. = Complemental chest movement.
R.C.M. = Reserve chest movement.
T.C.E. = Total chest excursion.

were submitted to analysis of variance. Variance due to change of posture constitutes 80 and 87 %, respectively, of the total variance observed of complemental and reserve diaphragmatic movement but only constitutes 13 % of the variance of measurements of total diaphragmatic excursion. Similarly the variance due to posture constitutes 81 and 87 %, respectively, of the total variance observed of inspiratory capacity and expiratory reserve volume measurements but only a small proportion of the variance of vital capacity measurements. In contrast, in measurements of change of chest circumference the variance due to posture is only 7 and 12 %, respectively, of the total variance found in measurements of complemental and reserve chest movements.

The relationship between diaphragmatic and chest movements and the volume of air ventilated

The relationships between the movement of the diaphragm and the changes of chest circumference and the volume of air ventilated are extremely variable from subject to subject and the regression coefficients obtained are not statistically significant. This is to be expected in view of the arbitrary nature of the measurements used as representative of the diaphragmatic movement and chest movement. A movement of the shadow of the diaphragm of a centimetre or a change of chest circumference of a centimetre would not be expected to be associated with the same amount of ventilation in two individuals of different build.

It is possible however to consider the mean values of movement of both leaves of the diaphragm, chest movement and respiratory ventilation in the group, and the following equations can be postulated for each posture and can be solved simultaneously.

Equation 1 (erect)

5·6 cm complemental diaphragmatic movement + 5·9 cm complemental chest movement ≡ 3·17 l. ventilated.

Equation 2 (supine)

7·7 cm complemental diaphragmatic movement + 6·0 cm complemental chest movement ≡ 3·87 l. ventilated.

This gives the result:

1 cm of complemental diaphragmatic movement ≡ 0·33 l. ventilated.
1 cm of complemental chest movement ≡ 0·22 l. ventilated.

Similar equations can be postulated for the expiratory reserve volume and when solved give the result:

1 cm of reserve diaphragmatic movement ≡ 0·37 l.
1 cm of reserve chest movement ≡ 0·17 l.

These figures suggest that in a full vital capacity about one-quarter of the ventilation is due to chest expansion and three-quarters to diaphragmatic movement.

These estimates must be treated with extreme reserve for a number of assumptions have been made. It has been assumed that respiratory ventilation can be expressed solely in terms of diaphragmatic movement and chest movement, as measured by the methods described, and that its relationship to these movements is linear, and, further, other factors which must affect the respiratory volumes such as changes in the volume of blood in the thorax have been neglected.

The co-ordination of chest and diaphragm movements

There is no evidence in any of the records reported above that in any part of deep inspiration or expiration, the movements of the diaphragm and the changes of chest circumference are dissociated. But it is found that lifting of the thoracic cage tends to occur mainly at the end of full inspiration. This movement, variable from individual to individual, appears to be produced mainly by movements of extension of the vertebral column, but its presence or absence makes little difference to the extent of diaphragmatic movement, or to the ventilation.

Three subjects were examined by the method ingeniously devised by Herxheimer (1949). While records of respiration and of chest and diaphragmatic movements were being made, each subject was asked to start a deep inspiration, to pause for 3 sec when the inspiration was half completed and then to finish the inspiration; they were then asked to breathe out pausing at the same level of respiration again. The interruptions of respiration were recorded on the spirogram and were accompanied by interruptions of the records of chest and diaphragmatic movement (Fig. 8), so that it was possible to find from the records whether a volume of air inspired was accompanied by the same amount of movement of the chest and diaphragm when it was expired. None of the records give support to the suggestion that the beginning of expiration after a deep inspiration is accompanied by much movement of the diaphragm and by little change of chest circumference. Vertical lifting of the thoracic cage occurs mainly near the end of deep inspiration, but the chest is lowered steadily throughout the expiration of the complemental air till it is again at its resting level and in some subjects it is further lowered during the expiration of the expiratory reserve volume.

Voluntary control of the chest and diaphragmatic movements

It is claimed by physiotherapists (MacMahon, 1934; Asthma Research Council, 1937) that it is possible to control the chest and the diaphragm separately by voluntary effort during respiration.

Four subjects, one a trained physiotherapist, one a teacher of singing and two patients who had training in breathing exercises, all claiming to be able to take breaths that were predominantly 'thoracic' or 'diaphragmatic', were examined in the erect posture. Each subject was asked to breathe quietly and then to inspire and expire as fully as possible, attempting on the first occasion to use the chest predominantly and on the second the diaphragm

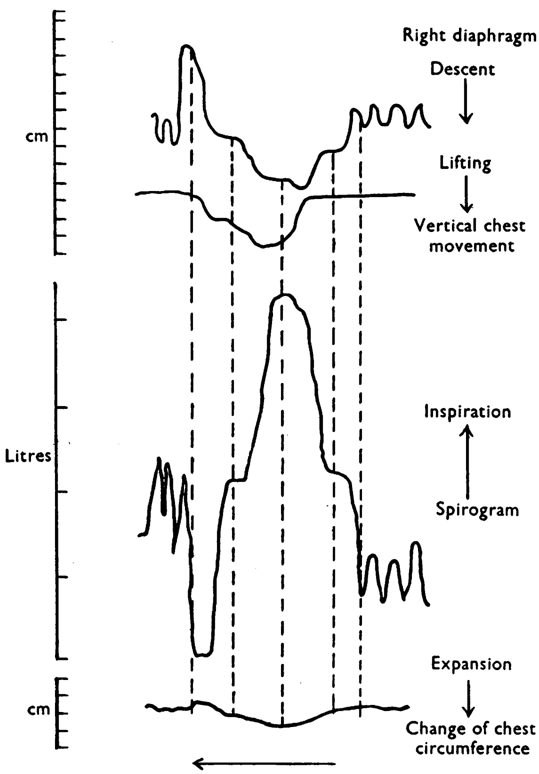

Fig. 8. Tracing of records of respiration, diaphragmatic movement, vertical chest movement and changes of chest circumference showing the effect of pausing during the inspiration and expiration of the inspiratory capacity. The record of vertical chest movement is displaced 8 mm to the left.

predominantly, while records of respiration, movements of the diaphragm, vertical movements of the thoracic cage and changes of chest expansion were recorded. Tracings of part of the record from one of the subjects and the measurements made from the original record are given in Fig. 9. These experiments show that the main difference between these two breaths, each with approximately the same ventilation, is the difference in the vertical movement of the thoracic cage; the diaphragmatic movement, measured relative to the thoracic cage, is substantially the same in the 'costal' and the 'diaphragmatic' breaths. But in the 'diaphragmatic breathing' the thoracic cage is not lifted during inspiration and the anterior abdominal wall is protruded, and in the 'costal breathing' the thoracic cage is lifted very greatly during inspiration and the abdominal wall is retracted and becomes scaphoid at the end of deep inspiration. The subjects all believed that movements of the diaphragm were indicated by the movements of the anterior abdominal wall; when the anterior

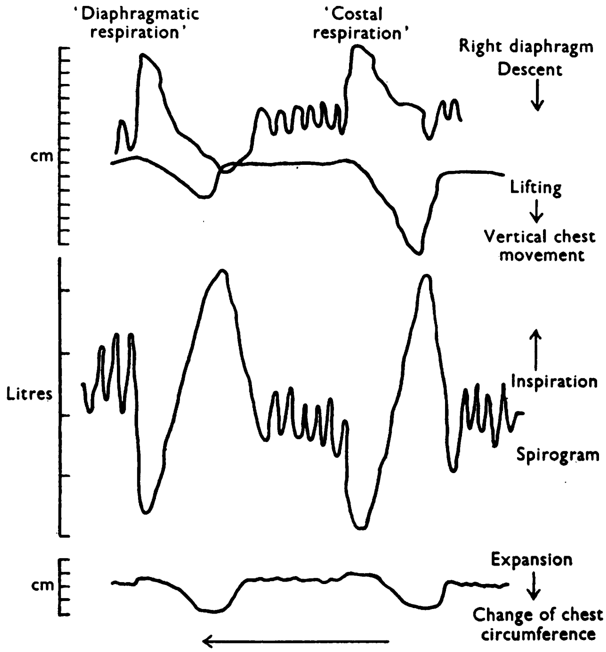

Fig. 9. Tracing of records made when a subject took a deep breath attempting to use the chest predominantly and then attempting to use the diaphragm predominantly. Standing.

	'Diaphragmatic respiration'	'Costal respiration'
Ventilation (l.)	4·3	4·2
Total diaphragmatic excursion (cm)	10·5	12·5
Total chest movement (cm) (change of circumference)	6·2	7·1

abdominal wall was protruded at the end of inspiration they assumed the diaphragm had descended greatly, and when it was retracted at the end of a full inspiration they assumed it had not descended at all.

There is no evidence that the diaphragm is under any direct voluntary control; the extent of its movement seems to be determined entirely by the depth of breath that is taken and it is under voluntary control only in the sense that respiration is under partial voluntary control.

The vertical movements of the thoracic cage are caused by flexion and extension of the vertebral column; these movements can be completely controlled by voluntary effort.

Although subjects have no direct control over the diaphragm during respiration, they have some direct control over movements of expansion and contraction of the chest for they are sometimes able to inhibit these movements when they attempt to use the diaphragm alone. The physiotherapist believed that she had more separate control over the diaphragm and the chest

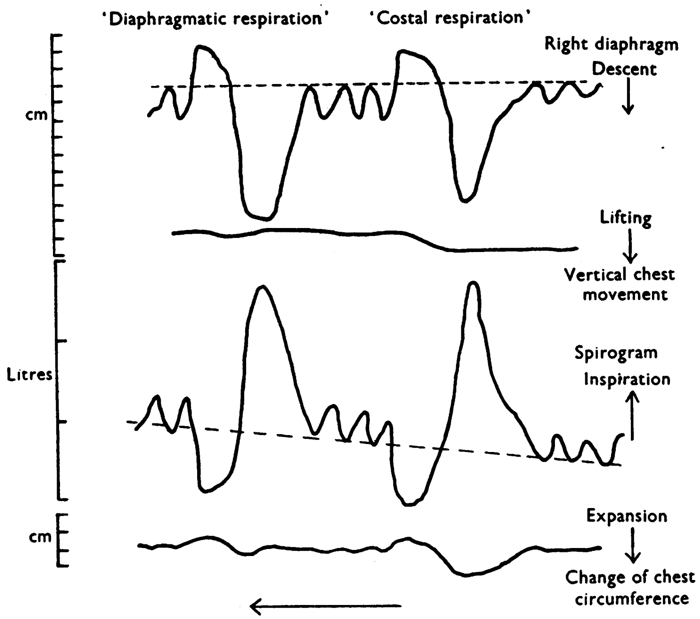

Fig. 10. Tracing of records made during deep 'costal' and 'diaphragmatic' breaths in the supine posture.

	'Diaphragmatic respiration'	'Costal respiration'
Ventilation (l.)	2·80	3·08
Total diaphragmatic excursion (cm)	8·50	8·25
Total chest movement (cm) (change of circumference)	2·8	5·6

when she was supine than when she was standing. Fig. 10 is a tracing of part of the records made from this subject when supine, and it shows that although the extent of diaphragmatic movement was almost identical in the costal and the diaphragmatic breaths, the complemental chest movement was considerably reduced when she attempted to use the diaphragm alone.

After examining the records this subject suggested that she might find it possible to be able to move the chest or the diaphragm alone if she only took small breaths. Fig. 11 is a tracing of part of the records of one of her most successful attempts. Over a very limited range of ventilation she had considerable control over movements of expansion and contraction of the chest, but diaphragmatic movement was only slightly smaller when she used her 'chest alone' than when she used the 'diaphragm alone', even though she was making very great efforts not to use the diaphragm.

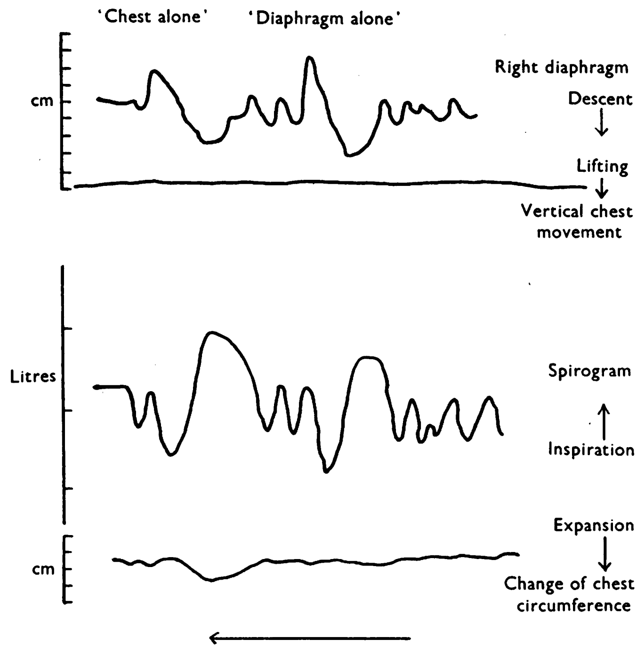

Fig. 11. Tracings of records made when a subject tried to breathe using the 'diaphragm alone' and then the 'chest alone'.

	'Chest alone'	'Diaphragm alone'
Ventilation (l.)	1·70	1·58
Diaphragmatic movement (cm)	4·0	5·0
Change of chest circumference (cm)	3·9	1·1

Forced respiration

Fig. 12 is a tracing of part of some records of diaphragmatic movement, vertical movement of the thoracic cage and chest expansion made while untrained normal subjects were hyperventilating. Unfortunately it was not possible to make simultaneous records of respiration as the resistance of the closed circuit and the characteristics of the spirometer, although otherwise satisfactory, were unsuited for recording rapid respiration. The records show that in these subjects the diaphragmatic movement and the chest expansion movements that occur in forced respiration occur in the range of movements associated with the complemental diaphragmatic movement and the complemental chest movement. They also show that during forced respiration there is very marked and rapid vertical movement of the thoracic cage which is in the opposite direction to the movements of the diaphragm and which seems to aid the rapid movements of the diaphragm which are needed in this artificial form of forced respiration. The most interesting finding is that in all subjects the chest circumference is increased at the beginning of this forced

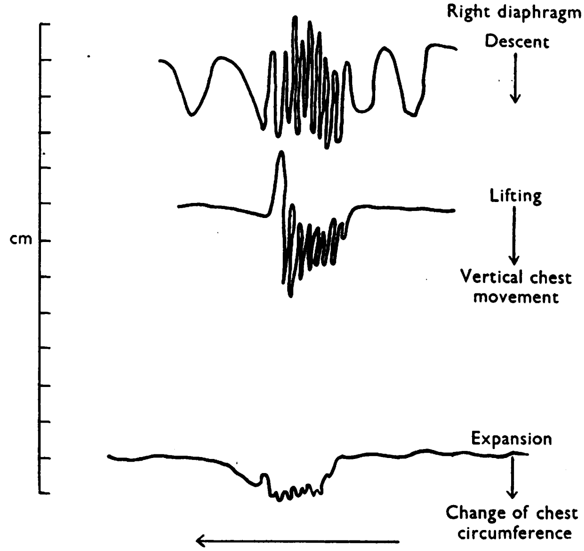

Fig. 12. Tracing of records made during forced hyperventilation.

respiration but in many subjects the movements of the chest about this increased circumference are small. This increased circumference of the chest is only maintained as long as subjects make an effort to continue the forced breathing, and it is possible that the increase in circumference increases the ventilatory efficiency by increasing the effective area of the diaphragm. Verzar (1946) has previously shown that the chest circumference is increased during exercise.

DISCUSSION

Many workers, Dally (1908), Keith (1909) and Wade & Gilson (1951), have reported that the diaphragmatic movement in quiet respiration is about 1–2 cm and this is here confirmed. Herxheimer's (1949) assumption that the diaphragm moves more in the erect posture than in the supine during quiet respiration has not been confirmed.

Most previous investigators have found the full excursion of the diaphragm in deep breathing to be about 5–7 cm. Keith (1907) and Dally (1908) found smaller movements. The larger movements recorded in this investigation are due to the regard given to vertical movements of the thoracic cage. These movements are variable from subject to subject and are more marked in the erect posture than in the supine. It is to variations in these movements that the main difference between so-called 'costal' and 'diaphragmatic' respiration is due, and movements of the anterior abdominal wall have been shown to be no indication of the extent of diaphragmatic movement in respiration. In a full vital capacity it has been shown that movement of the diaphragm plays a larger part in ventilating the lungs than does change of circumference of the chest. The diaphragm is directly affected by postural redistribution of visceral weight and the consequent changes in the pattern of its movement clearly reflect the well-known changes in lung volume similarly induced.

No evidence has been found that subjects have any direct control over the diaphragm except in as much as they have some control over respiration. This conflicts with opinions that are widely held by many physicians and physiotherapists. It supports the concept (Jones, 1926) that there can only be cortical voluntary control over movements of which man has conscious knowledge, and that no such control can be exerted over individual muscles or over structures such as the diaphragm which are inaccessible to direct observation and of which there is no postural sensibility that reaches consciousness.

The thoracic cage is a large and massive structure and the redistribution of visceral weight that occurs with change of posture makes little difference either to its circumference or to the pattern of its movement. The smallness of the movements of chest expansion during rapid forced respiration may be related to the mass and inertia of the thoracic cage. Movements of chest expansion differ from diaphragmatic movements in that they can to some extent be inhibited voluntarily, at any rate in trained subjects.

SUMMARY

1. A method of recording and measuring movements of the diaphragm relative to the thoracic cage, is reported and a mercury-in-rubber strain gauge for recording and measuring changes in chest circumference is described. The accuracy and repeatability of the measurements have been investigated.

2. The relationship between diaphragmatic movements, chest movements and ventilation has been investigated in ten normal subjects.

3. In quiet respiration the tidal diaphragmatic movement is about 1·5 cm. The tidal change in chest circumference is about 1·2 cm when the subjects are erect, and 0·7 cm when supine. In deep respiration the total diaphragmatic excursion is between 7 and 13 cm and the change in chest circumference is between 5 and 11 cm. The measurements suggest that in a full vital capacity about one-quarter of the ventilation is due to chest expansion and three-quarters to diaphragmatic movement.

4. The change from the erect to the supine posture causes a marked change in the pattern of movement of the diaphragm about its resting level. This

change parallels the change in the pattern of the inspiratory capacity and the expiratory reserve volume that accompanies the change in posture. No such change in the pattern of movements of chest expansion is found.

5. There is close co-ordination between movements of the diaphragm and movements of chest expansion. An exception to this is found during voluntary hyperventilation.

6. Vertical movements of the thoracic cage occur in some subjects mainly at the end of deep inspiration and are usually most marked when they are standing. The movements are caused by flexion and extension of the vertebral column. They seem to play little part in ventilating the lungs. They are especially marked during voluntary hyperventilation and here they may aid the rapid and large movements of the diaphragm that occur.

7. No evidence has been found that subjects have any direct voluntary control over the diaphragm. Movements of the anterior abdominal wall do not indicate the extent of diaphragmatic movements. There is evidence that some subjects are able to inhibit changes of chest circumference during respiration.

I wish to acknowledge the advice and helpful criticism I received at every stage of this work from my colleagues at the Pneumoconiosis Research Unit, and in particular from the Director, Dr C. M. Fletcher. I am deeply indebted to Mr A. D. Thomas who designed the amplifying circuit and to Messrs Dunlop Special Products Ltd., who supplied the fine-bore rubber tubing.

APPENDIX

The bridge circuit and amplifying circuit of the mercury-in-rubber transducer

1. *The bridge circuit*

(*a*) The circuit consists of a basic Wheatstone bridge (Fig. 3) where A and A' are two mercury-in-rubber transducers and R and R' are two equal variable resistances mechanically coupled. When the bridge is balanced, any slight change in the value of A, A' or of both, upsets this balance and gives rise to an out of balance voltage across the junctions b and d of the bridge.

(*b*) By making the mercury-in-rubber transducer in two halves, A and A', and connecting them as the opposite arms ab and cd of the bridge, the sensitivity of the instrument is twice that which it would be if both transducers were incorporated as one arm of the bridge only.

(*c*) By mechanically linking the two equal variable resistances R and R' it is possible to bring the bridge to a balance at the initial length of the mercury-in-rubber transducers. In practice this means that the bridge can be balanced whatever the resting level of chest circumference of an individual.

(*d*) For any given value of A, A', R and R' the sensitivity of the instrument is varied by altering the flow of current across the bridge; this is done by means of a small variable resistance in series with the battery, the current being indicated by a milliameter in the battery circuit.

2. *The amplifying circuit*

(*a*) Since the output signal from the bridge is small a considerable degree of direct coupled (d.c.) amplification is necessary to drive the recording pen, which like most commercial fast-recording instruments needs about 5 W. Conventional d.c. amplifiers are rather unstable and to eliminate this error as much as possible, a two-stage amplifier with valves in push–pull is used. Any change of the high tension voltage is thus compensated for as it affects both valves simultaneously and there is no need for elaborate regulations of the power supply.

(*b*) The recording instrument, a Hughes pen recorder, has a centre tapped coil. This is connected to the anode circuits of both the output valves and it is then possible to make use of the full-scale deflexion of the instrument either side of its zero.

(*c*) The recording instrument can be switched out of the circuit, compensating resistors being automatically switched in so that the amplifying characteristics of the circuit remain unchanged. This arrangement prevents the delicate galvanometer being damaged when the instrument is being adjusted on subjects.

(*d*) The sensitivity of the recording instrument at any frequency between zero and 60 c/s is nowhere more than 6% different from its sensitivity at zero frequency.

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