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Rib movement in health, kyphoscoliosis, and ankylosing spondylitis

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Costal movement was defined on living subjects by determining the spatial vectors along the ribs that are produced during inspiration. The determination of these vectors was achieved with an instrument specially designed for this purpose. Rib movement was studied on 61 ribs in 10 normal subjects and on 35 ribs in six patients suffering from kyphoscoliosis and ankylosing spondylitis. In normal subjects during smooth inspiration all the ribs studied, which ranged from the 2nd to the 9th, rotated round a single axis. The direction of the inspiratory movement of the ribs was oblique, upward, outward, and forward, and symmetrical in both hemithoraces. This direction is compatible with rotation around the rib-neck axis but not with other axes that have been postulated. In ankylosing spondylitis and in kyphoscoliosis the magnitude of rib movement was reduced but movement still took place solely around the rib-neck axis. In the patients with kyphoscoliosis the direction of this movement was altered due to a change in the position of the rib neck.

Hitherto research workers have not agreed about the manner in which ribs move. Some authors consider that there is mono-axial movement of the rib round the rib-neck axis (Agostoni, 1964; Ganong, 1965). Others postulate that, in addition to movement around the rib-neck axis, there is rotation on a second axis which may be antero-posterior (costosternal), the so-called 'bucket-handle' movement (Campbell, 1958; Last, 1959), or may be on a vertical axis with abduction of the ribs (Polgar, 1949; Grant and Basmajian, 1965). Among the authors who postulate multi-axial movement of the ribs there is no agreement about which axis is used in the upper ribs and which one in the lower ribs.

In this paper the results of an analysis of rib movement made with a new instrument are presented. These results suggest that both in healthy subjects and in patients with kyphoscoliosis and ankylosing spondylitis inspiratory movement takes place around a single axis, that of the rib neck.

THEORETICAL DETERMINATION OF RIB MOVEMENT

Each rib is considered as being made up of an infinite number of points along its long axis. Each of these points, called points Z, moves to a new position during inspiration. The straight line-segment between the expiratory (Ze) and the inspiratory (Zi) position of any costal point represents the spatial vector S (Fig. 1A). These spatial vectors show the amount as well as the direction of the inspiratory excursion of each point along the rib.

The direction of the vector S is related to the three planes of the chest (rectangular system). This system in the human thorax is formed by three co-ordinates which meet at right angles at each point Z (Fig. 1B). These co-ordinates are the sagittal (g), the transverse (t), and the vertical (v) diameter of the chest. The planes orientated by these diameters are the transverse (T), the sagittal (G), and the frontal (F).

The spatial vector of a costal point has a certain position in the rectangular system of the chest and it lies on a plane, called plane A (Fig. 1A). This plane (A) is perpendicular to the frontal plane (F) and meets the transverse (T) and the sagittal (G) planes along the sagittal (g) thoracic diameter. It is evident that there is only one position of the plane A within the rectangular system of the thorax at which the spatial vector S lies on this plane.

The direction of the vector S relative to the three planes of the chest is determined by measuring the angles ϕ and θ (Fig. 1A). Angle ϕ is formed on the plane A by the sagittal thoracic diameter (g) and the spatial vector S. Angle θ is formed on the frontal plane (F) by the transverse diameter (t) and the line of intersection of

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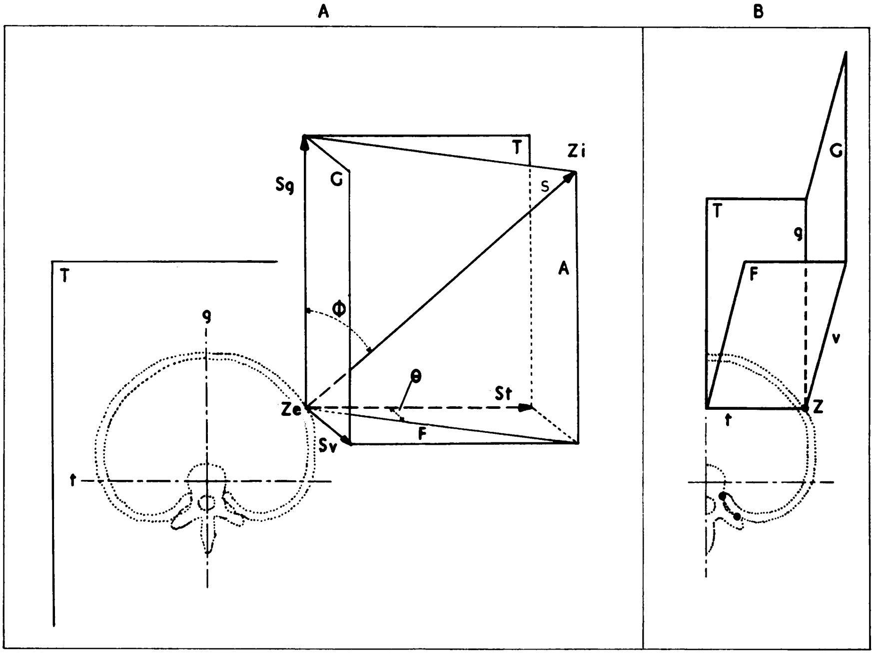


FIG. 1. (A) *A costal ring and* (B) *the right half of it, seen from above. The plane of the paper is the transverse plane (T) of the chest. Planes G and F are at right angles with one another and both the planes are at right angles with the plane T. Plane A is perpendicular to the frontal plane (F). Vector S lies on the plane A. Angle* ϕ *lies on the plane A, while angle* θ *lies on the plane F.*

the planes A and F. The common vertex of these angles is the point Z at the expiratory position of the rib (Ze).

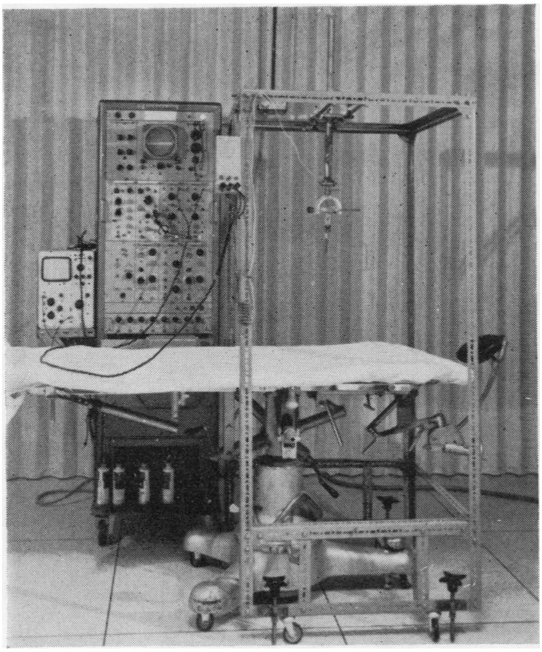
Vector S is oblique within the rectangular system of the thorax (g, t, v), as will be shown later. Consequently, this vector can be analysed at right angles to three components, Sg, St, and Sv, along the sagittal (g), the transverse (t), and the vertical (v) chest diameters respectively (Fig. 1A). These component vectors represent the change of the corresponding thoracic diameter at a certain costal point which covers the distance S during inspiration. The relation of these vectors, as a ratio over the initial vector S, to the size of the angles ϕ and θ is given by equations (1), (2), and (3):

$$Sg/S = \cos\phi \quad (1)$$
$$St/S = \sin\phi . \cos\theta \quad (2)$$
$$Sv/S = \sin\phi . \sin\theta \quad (3)$$

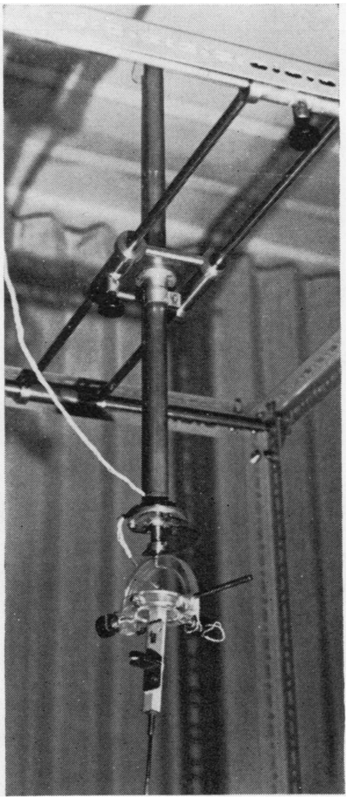
METHOD AND SUBJECTS STUDIED

The spatial vector S at any point along a rib of a living subject during tidal breathing was determined by an instrument specially designed for this purpose (Jordanoglou, 1967; Jordanoglou and Smith, 1969). The idea of this instrument is to set up a mechanical framework parallel to the rectangular system of the thorax when a patient is lying horizontal (Fig. 2a). Within the rectangular frame of the instrument a device is suspended (Fig. 2b) which will be called an Angular-Linear Displacement Indicator (A.L.D.I.), since it measures angular and linear displacements simultaneously. The A.L.D.I. is in reality a universal joint (Cardano system) with its two axes which will be called respectively the axes J and K, the whole of which can rotate about a vertical rod which will be called the L axis. The amount of rotation about L axis is measured on a protractor, and potentiometers (J and K) record the movement at each of the two axes of the universal joint. Finally, there is a transducer recording the up and down movement of a plunger suspended in the centre of the universal joint. It will be seen from Fig. 2b that the whole of the A.L.D.I. is on a carriage device which could be fixed at any point within the top of the rectangular frame by means of a system of rods parallel to this frame.

To use the instrument to determine the vector S, the subject, with the thorax naked, lay supine on the horizontal bronchoscopy table within the frame (Fig. 2a). In this position of the subject's chest, the sagittal diameter (g) was vertical, the vertical (v) was horizontal, and the frontal plane (F) was horizontal,



(a)



(b)

FIG. 2. (a) *The whole set-up for measuring the costal movement on living subjects* (*A.L.D.I., rectangular frame, recorder, bronchoscopy table*). (b) *The A.L.D.I. and the system of the rods and the carriage by which the A.L.D.I. moves parallel to any direction within the rectangular frame. See text.*

while the sagittal (G) and the transverse (T) chest planes, as well as the plane A, were vertical (Figs 1A and B). The subject was aligned so that an imaginary line along the sternum from the middle of the suprasternal notch to the apex of the subcostal angle was parallel to the frame. The relative position of the chest to the instrument was constant throughout the measurements and this alignment was checked four or five times during the measurement.

The A.L.D.I. was manipulated so that its plunger was in the 'position of alignment' during tidal breathing at four different points along a rib, which corresponded roughly to a parasternal (P.L.), mid-clavicular (M.C.L.), anterior axillary (A.A.L.), and mid-axillary line (M.A.L.) of the chest on either side.

The 'position of alignment' means that the vector S and the long axis of the transducer coincide so that the K axis of the universal joint, the shaft of the transducer, and the pointer of the protractor lie on the same plane as that of the vector S, which is the plane A in Figure 3A. At this position ('position of alignment') the shaft of the transducer is perpendicular to the axis of rotation of the rib (Jordanoglou, 1967). The 'position of alignment' (Figs 3A and B) is achieved when during tidal breathing the output of the K potentiometer remains constant at zero and the output of the J potentiometer also shows a constant deviation from the zero line. The angle θ is then read from the protractor and the angle ϕ is obtained from the output of the J potentiometer, while the magnitude of the vector S is obtained from the difference between the inspiratory and expiratory outputs of the linear transducer. Records obtained in a healthy man and in patients with kyphoscoliosis and ankylosing spondylitis are shown in Figure 4. Details of the method of calibrating the potentiometers are given elsewhere (Jordanoglou, 1967; Jordanoglou and Smith, 1969).

The sites of the points measured on the ribs, indicated by small steel balls stuck on to the skin, were checked by taking a chest radiograph just after the test while the subject was in the same position as during the measurement. Usually, the measurements were done on one or on both sides of the chest wall on two or three upper ribs (3rd to 6th, occasionally the 2nd) and two or three lower ribs (7th to 9th) and on the lower end of the sternum. In this way it was possible to compare the movement of the upper ribs with that of the lower ones. The number of the ribs and the points measured on them depended on the thickness of the thoracic wall (depending on excessive fat or greatly developed muscles).

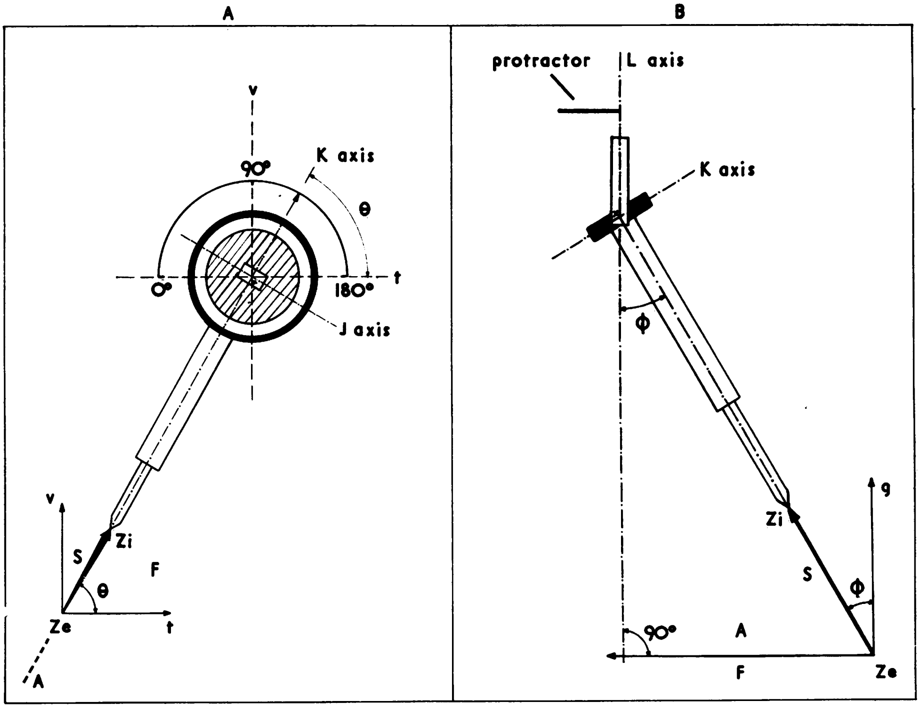


FIG. 3. (A) *The plane of the paper is the frontal plane (F) of the g, t, v rectangular system of the thorax. The direction of the v diameter is towards the upper opening of the chest. Points Ze and Zi correspond to a left rib seen from above while the chest is supine. The plane of the protractor is parallel to the plane F (horizontal), but it lies higher than it. The vector S has an oblique direction upward, toward the centre x of the A.L.D.I. A.L.D.I. is in 'position of alignment' with the vector S,* i.e., *the vector S, the long axis of the transducer, and the K axis lie on the same plane A. Plane A is perpendicular to the plane F. Angle θ on the plane F is equal to the angle θ on the protractor. See text.* (B) *The plane of the paper is the plane A. Points Ze and Zi belong to a left rib, as in Fig* 3A, *seen laterally from the right side. Line F is the line of the perpendicular intersection of the plane F with the plane A. A.L.D.I. is in 'position of alignment' with the vector S. Angle ϕ of the A.L.D.I. is equal to the angle θ of the vector S. See text.*

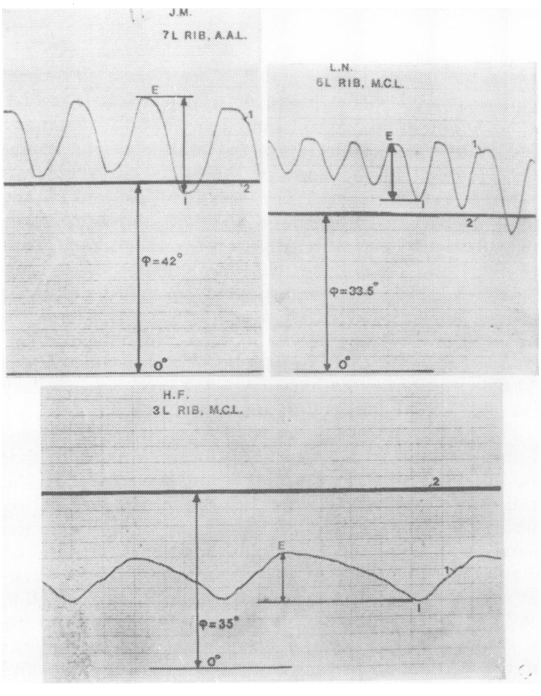


FIG. 4. *Recordings from a normal subject (J.M.) and two patients suffering from kyphoscoliosis (L.N.) and ankylosing spondylitis (H.F.). Line* 1 *shows the fluctuating output from the transducer of the A.L.D.I. The difference between the expiratory (E) and the inspiratory (I) level of this line is the magnitude of the costal excursion. The straight line* 2 *shows the constant output from the J potentiometer of the A.L.D.I. The distance between this line and the reference line* (0° *line) indicates the size of the angle ϕ.*

In this manner the movement of 61 ribs was studied in 10 normal subjects (eight males and two females) and on 35 ribs in six patients (five males and one female). Three of the patients suffered from kyphoscoliosis and three from ankylosing spondylitis. The age of the normal subjects was 20 to 33 years, while the age range of the patients was 16 to 56 years.

RESULTS

The results for the angles ϕ and θ and for the magnitude of the inspiratory excursion of the ribs (vectors S) in the normal subjects and in the patients are shown in Tables I and IIa and b. In these tables there are also shown the ratios Sg/S, St/S, and Sv/S for every rib calculated from the mean size of the angles ϕ and θ of the rib according to equations (1), (2), and (3).

From the results for the angles ϕ and θ in all the subjects studied it is indicated that the spatial vectors along any rib are parallel with one another. Furthermore, these results show that the vectors have an oblique direction relative to the three planes of the chest. In the normal subjects and in the patients with ankylosing spondylitis the direction of the vectors is antero-lateral and up during inspiration and symmetrical in both hemithoraces.

The costal movement in ankylosing spondylitis and in kyphoscoliosis is restricted as compared with that in normal subjects. The results on the ratios show that in the normal subjects there is a tendency for the St/S to increase from the 2nd to the 9th rib (Fig. 5). The Sv/S and the Sg/S ratios do not show any consistent changes.

The movement of the sternum takes place on the sagittal thoracic plane, as is shown either from the angle θ at the lower end of the sternum ($\theta=90°$) or from the St/S ratio at the two costal points on the transverse diameter of a costal ring (St/S right=St/S left).

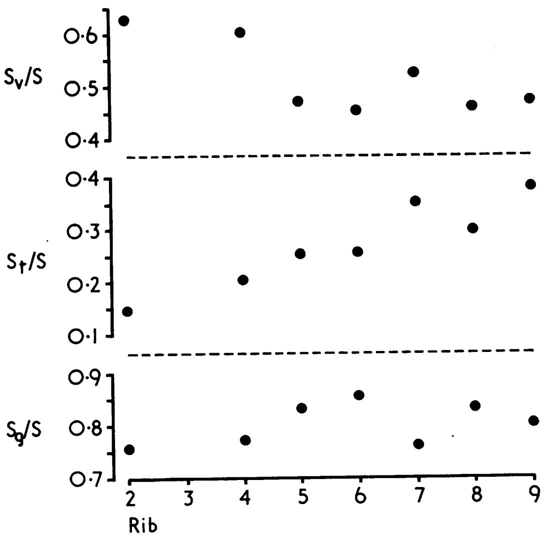


FIG. 5. *Mean values of the Sg/S, St/S, and Sv/S ratios for all the ribs (2nd to 9th), except the 3rd, in normal sub ects.*

TABLE I

RESULTS IN NORMAL SUBJECTS

Rib	φ°	θ°	S (cm.)	Sg/S	St/S	Sv/S
2	40·0±0·0	78·0±1·0	1·40±0·30	0·76	0·14	0·63
3	—	74·0±0·0	1·55±0·05	—	—	—
4	40·0±0·5	66·0±5·0	0·95±0·15	0·77	0·20	0·60
5	33·5±7·5	61·5±9·0	1·00±0·25	0·83±0·07	0·26±0·12	0·47±0·11
6	31·5±5·0	59·0±6·0	1·10±0·10	0·85±0·04	0·26±0·04	0·45±0·05
7	40·5±10·0	56·0±6·0	1·20±0·60	0·76±0·14	0·35±0·04	0·52±0·15
8	33·5±3·0	56·7±6·0	1·00±0·30	0·83±0·03	0·29±0·05	0·46±0·02
9	37·6±5·0	51·0±10·0	1·13±0·30	0·79±0·06	0·38±0·06	0·47±0·08
Lower end of sternum ..	29·5±11·0	90·0±1·0	0·76±0·25	0·86±0·10	0·00±0·01	0·48±0·10

TABLE IIa

RESULTS IN PATIENTS WITH ANKYLOSING SPONDYLITIS

Rib	φ°	θ°	S (cm.)	Sg/S	St/S	Sv/S
3	31·5±4·0	66·0±4·0	0·45±0·10	0·83±0·04	0·23±0·07	0·49±0·04
4	26·0±3·0	71·0±3·0	0·56±0·20	0·89±0·02	0·15±0·05	0·42±0·03
5	21·0	54·0	0·45	0·93	0·21	0·30
6	34·0	60·0	0·40	0·82	0·29	0·49
7	30·0±6·0	57·5±3·0	0·60±0·20	0·85±0·05	0·26±0·02	0·42±0·09
8	34·0±2·0	57·5±6·5	0·53±0·07	0·83±0·02	0·30±0·07	0·47±0·01
9	21·0	59·0	0·40	0·93	0·19	0·31
Lower end of sternum ..	22·0±0·0	90·0±1·0	0·57±0·13	0·92±0·00	0·00±0·01	0·37±0·00

TABLE IIb

RESULTS IN PATIENTS WITH KYPHOSCOLIOSIS

Rib	φ°	θ°	S (cm.)	Sg/S	St/S	Sv/S
Patient J. F. (M.). Convexity towards R. Kyphotic element predominant						
4R	44·0±4·0	87·0L±1·0	0·40±0·20	0·72	−0·04	0·69
4L	45·0±3·0	89·0R±1·0	0·45±0·10	0·71	−0·01	0·71
6L	38·0±1·0	88·5R±0·5	0·40±0·05	0·79	−0·01	0·61
7R	43·0±2·0	89·0L±1·0	0·40±0·05	0·73	−0·01	0·68
7L	39·5±2·0	90·0±0·0	0·30±0·10	0·77	0·00	0·64
Lower end of sternum ..	39·5	90·0	0·55	0·77	0·00	0·64
Patient L. N. (F.). Convexity towards L						
3R	20·0±1·0	52·5±0·5	1·10±0·10	0·94	0·21	0·27
3L	39·0±1·0	60·0±1·0	1·00±0·10	0·78	0·31	0·55
5R	22·0±1·0	51·5±0·5	0·60±0·10	0·93	0·23	0·29
5L	39·5±0·5	74·0±1·0	1·00±0·10	0·77	0·17	0·61
6L	32·5±1·0	69·0±1·0	0·50±0·10	0·84	0·18	0·50
7R	44·5±1·5	53·5±1·5	0·65±0·10	0·71	0·42	0·57
7L	32·5±0·5	70·0±2·0	0·45±0·05	0·84	0·18	0·50
9L	29·0±0·0	74·5±2·5	0·37±0·07	0·87	0·13	0·47
Lower end of sternum ..	47·0	90·0	0·55	0·68	0·00	0·73
Patient L. P. (M.). Convexity towards R						
4R	19·5±0·5	37·0L±1·0	0·50±0·10	0·94	−0·27	0·20
4L	44·0±1·0	50·5±0·5	0·50±0·10	0·72	0·44	0·54
5R	21·5±0·5	33·5L±0·5	0·55±0·05	0·93	−0·31	0·20
5L	46·0±1·0	52·0±1·0	0·70±0·10	0·69	0·44	0·57
6L	43·7±3·7	53·0±2·0	0·70±0·40	0·72	0·42	0·55
7R	29·5±0·5	29·0L±1·0	0·40±0·10	0·87	−0·42	0·23
7L	49·0±1·0	48·5±1·5	0·45±0·05	0·66	0·50	0·56

R=right; L=left.

DISCUSSION

LIMITATIONS OF METHOD

Alignment of patient with rectangular system of measuring device It is important for the patient to be initially aligned so that the rectangular co-ordinates of the chest are parallel to those of the measuring equipment. The alignment can be assessed by confirming that the sternum was moving on the sagittal thoracic plane (angle $\theta = 90°$). It can be seen from the results that this criterion of alignment was achieved in all except one patient with kyphoscoliosis (L.P., Table IIb) in whom the sternum and the whole rib cage moved to the left during inspiration.

Errors due to movement of soft tissues This error was reduced by applying gentle pressure to the plastic pad over the rib so that it followed the rib during its excursion and by continuous recording of at least four respiratory cycles. This error should not be large in thin subjects.

Repeatability of technique The repeatability of the technique for measuring the angle ϕ was checked in 69 points on several ribs and for measuring the angle θ in 77 points in normal subjects and patients. The measurements on each of these points were repeated two to six times in random order. The standard deviation from the mean for the angle ϕ was $0° - \pm 4{\cdot}25°$ and for the angle θ $0° - \pm 3{\cdot}5°$. At some costal points the angles ϕ and θ were measured once. However the difference in the size of each angle between two points along a rib measured once was not bigger than the difference between the values of each angle measured repeatedly on one point. The range of the standard error of the mean, mainly of the angle ϕ, was higher than the standard error ($0° - \pm 2{\cdot}7°$) in the experiments on the excised rib by which the function of the instrument was checked (Jordanoglou, 1967). This wider range of error could be explained by the following reasons:

(1) The change of the expiratory position of the ribs: however, in successive respiratory cycles in which the resting respiratory level of the rib was continuously recorded it was shown that the angles ϕ and θ did not vary with a change of the end-expiratory position of the rib of about 0·25 cm.

(2) The change of the inclination angle of the rib (angle a) from point to point along the long axis of the rib (Jordanoglou, 1967):

(3) Some of the measurements were taken on the upper border of the rib while others were taken on about the middle between the upper and the lower costal margin. It is evident that a distance of 0·5 cm. between two points on a rib

lying on the same vertical diameter with a radius of about 15 cm. may produce an error in the angle ϕ of about 2°. This change in position of the point of measurement on the rib was due to technical reasons (shape of the pad and position of minimal gliding movement of the skin over the rib).

SIGNIFICANCE OF RESULTS IN NORMAL SUBJECTS Since the spatial vectors at different points along a given rib proved to be parallel to each other the rib must be moving round one axis only. This movement can only be a rotation taking into account that the rib cannot be displaced in parallel during respiration. The obliquity of the vectors excludes mono-axial movement of the ribs round any antero-posterior, tranverse or vertical axis, since in these instances the vectors should lie on a frontal, sagittal or transverse thoracic plane respectively. The oblique direction of the vectors suggests that the axis of movement is located on the costal neck passing through the two synovial articulations at the costo-central and costo-transverse joints.

The vectors proved to be parallel to each other as low as the 9th rib, so it appears that movement is mono-axial even in the lower ribs. Nevertheless there was a tendency for the increase in the transverse vector St to be greater for a given size of vector S in the lower ribs (Fig. 5), so that there would be more lateral expansion of the thoracic cage with movement of the lower ribs; this change occurs because the necks of the lower ribs are directed more backwards (Agostoni, 1964).

RESULTS IN PATIENTS In the patients with kyphoscoliosis and ankylosing spondylitis the vectors at different points along a given rib remained parallel, suggesting once again that there was mono-axial movement around the rib-neck axis. The obliquity of this movement in kyphoscoliosis was different from that in the normal subjects; also it was different between the two ribs of a given pair. In the patients with kyphoscoliosis the vertebrae were tilted so that the axis of movement relative to the sagittal, transverse, and frontal thoracic plane was shifted. In one subject with kyphoscoliosis (L.P.), for example, the spatial vectors on the 5th right rib were upward, forward, and toward the left side, forming a 22° angle (ϕ) with the sagittal diameter and an angle with the transverse diameter (θ) of 33° open to the left side. According to that the vectors along the rib are at right angles with the axis of rotation (Jordanoglou, 1967); this means that the neck axis of this rib was shifted forward instead of being backward as in normal spinal columns.

CHANGES WITH VIGOROUS INSPIRATORY EFFORTS The reported measurements were made during quiet tidal breathing. It was noted that in some of the subjects the direction of the vectors at various points along the ribs ceased to be parallel to each other when a large tidal volume was produced by vigorous inspiratory effort. This deviation could be caused in two ways: first, in deep inspirations movement of the spinal column may occur (Dally, 1908; Wade, 1954), so that the position of the rib-neck axis in relation to the rectangular system of the chest is itself changing over a breath; secondly, in vigorous inspiratory efforts there may be elastic deformation of the rib-vertebra system. It has been shown that deformation of the chest wall occurs during deep breathing (Agostoni and Mognoni, 1966). This second dynamic mechanism appeared to be important, since it was found that the inspiratory level at which the vectors deviated from the parallel depended on the velocity of the inspiratory excursion. In slow inspiratory efforts deviation first occurred at larger lung volumes than with fast efforts.

CONCLUSIONS

As the vectors at various points along a given rib are almost parallel to each other one can predict that the most important movement of the rib is around a single axis. This appears to be true of all the ribs tested, that is from the 2nd to the 9th rib. The results are not compatible with significant movement around more than one axis or with mono-axial movement around an antero-posterior (costo-sternal, 'bucket-handle' movement) or a vertical axis. The results are compatible with mono-axial movement around an oblique axis, that of the rib-neck.

The present results show that elastic deformation of the rib cage (which would result in rotation of the rib on an elliptical circumference) during tidal breathing must be small compared with the amount of rotation around the neck axis. With vigorous inspiratory efforts at large lung volumes, however, elastic deformation becomes significant and the vectors along a rib cease to be parallel to each other.

The ratios Sg/S, St/S, and Sv/S, if measured more extensively, may give valuable information about the change in shape of the costal rings during quiet and deep inspiratory movements. Furthermore, these ratios in association with a theoretical analysis of the rib movement

(Jordanoglou, 1967, 1969) may help to draw conclusions about the dynamic behaviour of the rib-vertebra system during respiration.

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