BPP Trainer's Anatomy & Physiology Packet

Ron Dennis, Ed.D.

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Contents

1. Kapandji, The Physiology of the Joints, Vol. 3 The Trunk and the Vertebral Column, pp. 138-53.

Set your PDF application to view two pages at once so that you may see both the images and explanatory texts at the same time.

2. De Troyer, Actions of the respiratory muscles or how the chest wall moves in upright man.

3. De Troyer, Mechanical action of the abdominal muscles.

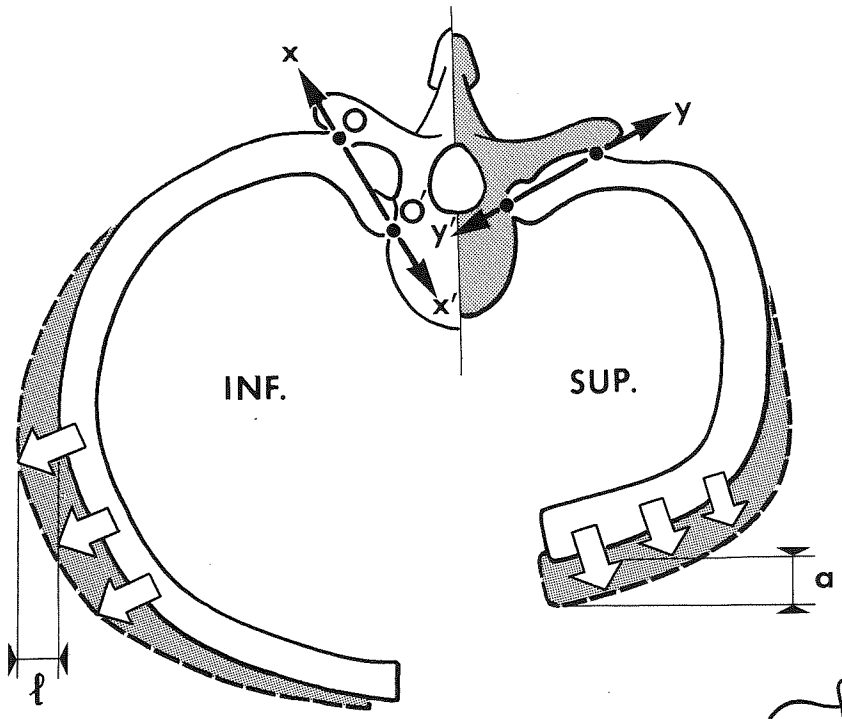
Both De Troyers best read in single page format, both scanned from 40-year-old copies, no others available.

MOVEMENTS OF THE RIBS AT THE COSTOVERTEBRAL JOINTS

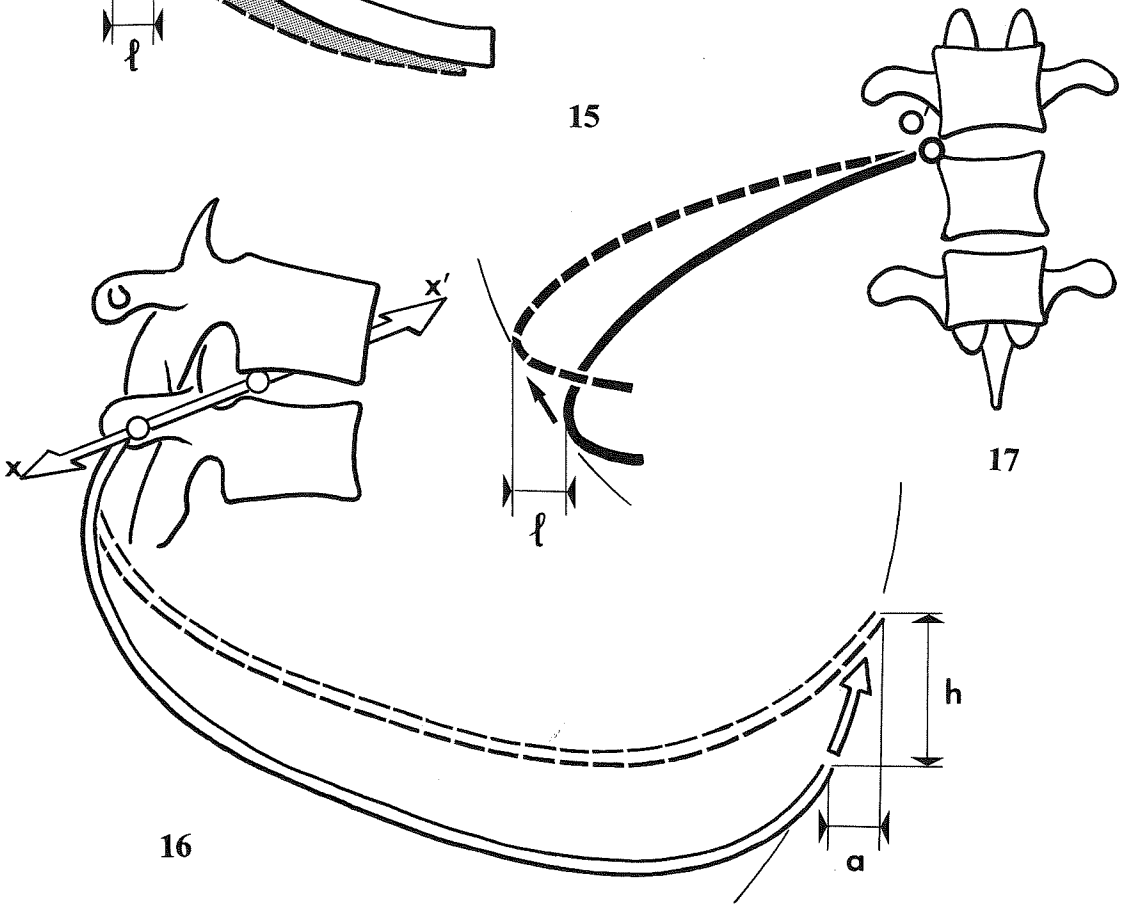
The costovertebral joint, on the one hand, and the costotransverse, on the other, form a *joint couple mechanically linked* (fig. 15), whose common movement can only be *rotation about an axis passing through the centre of each joint*. This axis XX′, running through the centre O of the costotransverse joint and the centre O′ of the costovertebral joint, acts as a swivel for the rib, which is thus 'suspended' from the vertebral column at two points O and O′. The direction of this axis with respect to the sagittal plane determines the direction of movement of the rib. For the **lower ribs** (left side of the figure) the axis xx′ lies nearly parallel to the sagittal plane and so elevation of the rib increases the transverse diameter of the thorax by a distance l. In fact (fig. 17), when the rib rotates about this axis, it describes an arc of a circle with centre O: it becomes less oblique and more transverse and as a result its most lateral border moves laterally over a distance l, which represents the increase in the transverse diameter of the thoracic outlet.

On the other hand, the axis yy′ for the **upper ribs** (fig. 15: right side) lies closer to the frontal plane. Therefore elevation of these ribs increases the anteroposterior diameter of the thorax by a distance a. In effect (fig. 16), when the anterior end of the rib is raised by a distance h, it describes an arc of a circle and is displaced anteriorly by a distance a.

It follows, therefore, that elevation of the ribs *increases the transverse diameter of the lower thorax and the anteroposterior diameter of the upper thorax*. In the midzone, the costovertebral joints have an axis lying obliquely at an angle of 45° to the sagittal plane so that both diameters are increased.



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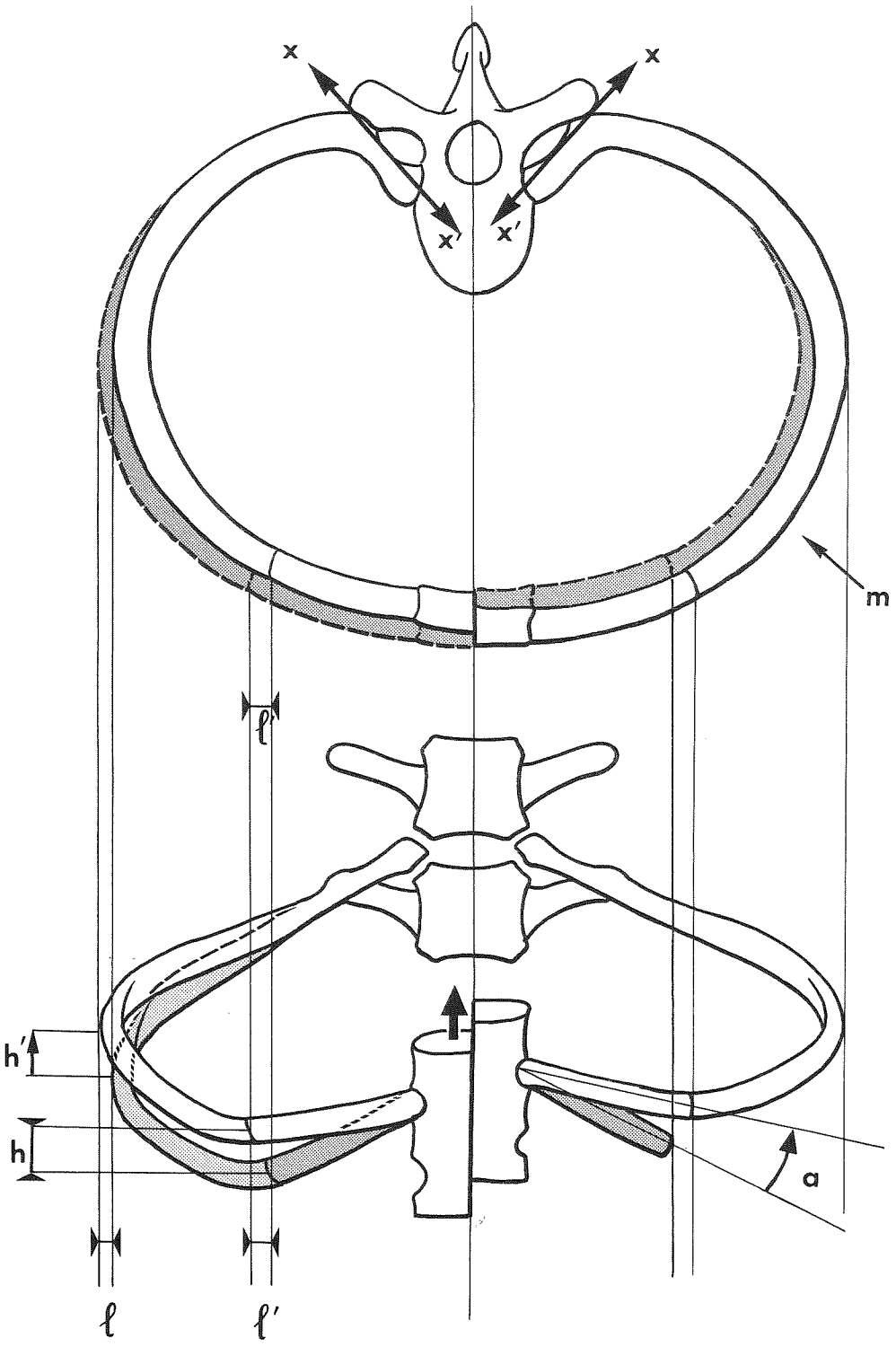
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16

MOVEMENTS OF THE COSTAL CARTILAGES AND OF THE STERNUM

So far only the movements of the ribs at the costovertebral and costotransverse joints have been considered but rib movements relative to the sternum and costal cartilages must also be taken into account. If these movements are viewed from above (fig. 18) and from the front (fig. 19) it is clear that, whereas the *most lateral part of the rib is raised* by a distance h′ and is pushed laterally by a distance l, the anterior end of the rib is raised by a distance h and is pushed anteriorly by a distance l′ (h = h′ and l′ = l). At the same time, the *sternum is raised* and the costal cartilage becomes more horizontal forming an angle a with its initial position. *This angular movement of the costal cartilage* relative to the sternum occurs at the *sternocostal joint*. Simultaneously another movement occurs at the costochondral junction, which will be discussed later.

When the rib is raised (fig. 18: right side), the point of maximum increase in thoracic diameter is the point most distant from the axis xx′. This geometrical fact explains how this point varies from rib to rib with changes in the obliquity of their axes.



18

19

THE SHAPE CHANGES OF THE THORAX IN THE SAGITTAL PLANE DURING INSPIRATION

Supposing that the vertebral column is fixed during inspiration (fig. 20), one need only consider the changes in shape of the flexible pentagon formed, on the one hand, by the vertebral column and, on the other, by the first rib, the sternum, the tenth rib and its costal cartilage. These changes are as follows:

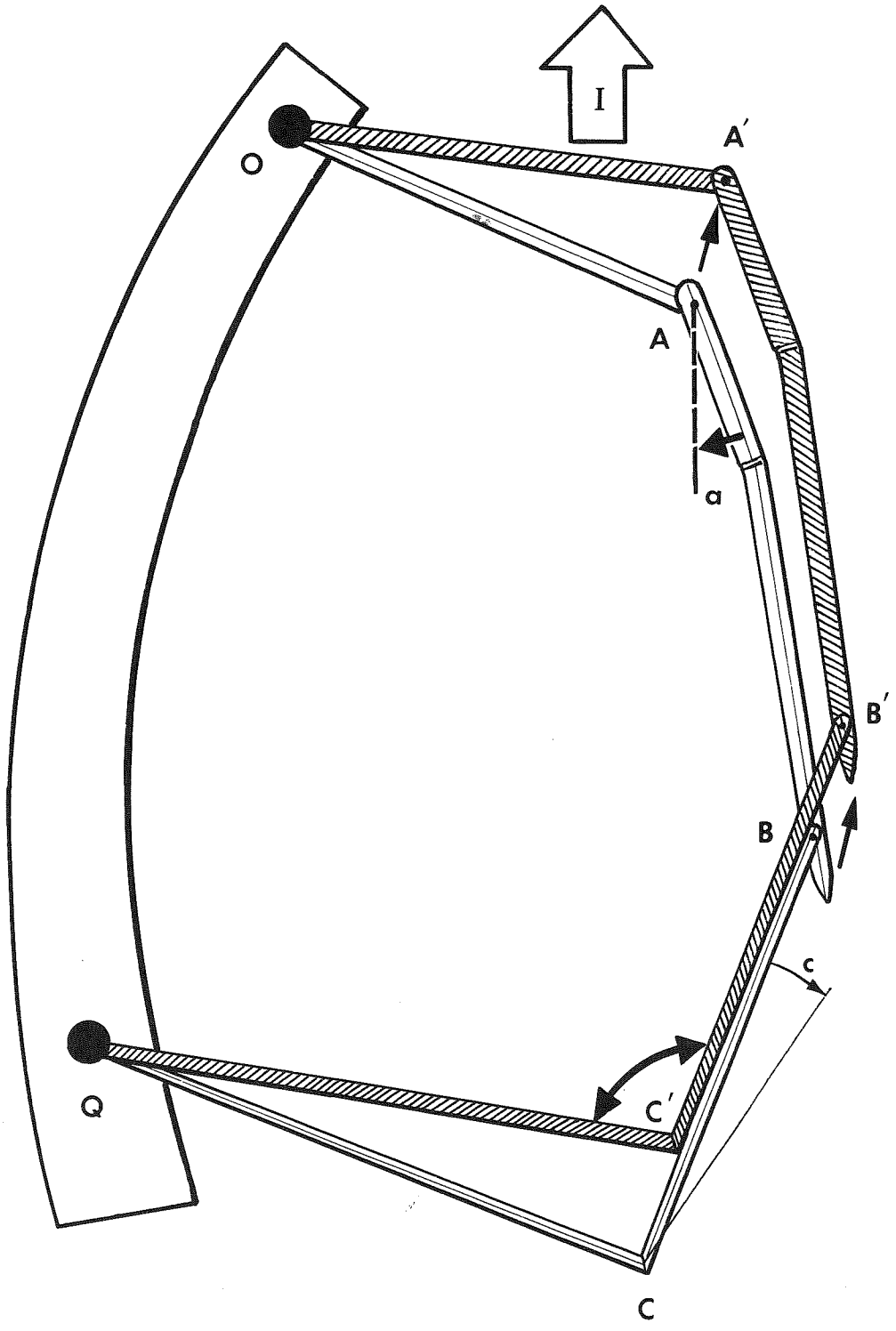
the first rib, being freely mobile about its costovertebral joint (O), is elevated so that its anterior end describes an *arc of a circle* AA′;

as the first rib is elevated *so is the sternum* which moves from AB to A′B′;

during this movement the *sternum does not stay parallel to its initial position* as the antero-posterior diameter of the upper thorax is increased more than that of the lower thorax. It follows that the angle between the sternum and the vertical (a) becomes slightly more acute and the angle OA′B′ is smaller than the initial angle OAB. The sternocostal angle is reduced as a result of axial rotation of the costal cartilage (see page 162);

the tenth rib is also raised, with Q as its centre of rotation, and its anterior end describes an arc of a circle CC′;

as both the tenth rib and the sternum are raised the tenth costal cartilage moves from CB to a roughly parallel position C′B′. It follows that the angle C′ is greater than the angle C by a value c which is equal to the angle C′QC—the angle of elevation of the tenth rib. The chondrocostal angle C′B′A′ is also greater than the original angle CBA. Once more, this widening of the angle is achieved by axial rotation of the cartilage. A similar axial rotation takes place in all the costal cartilages. We shall see later the role this has to play in maintaining the elasticity of the thorax.



20

MODE OF ACTION OF THE INTERCOSTAL MUSCLES AND THE STERNOCOSTALIS

A posterior view of the thorax and the vertebral column (fig. 21) shows three sets of muscles:

the **levator costae** (L), attached to the tip of the transverse process and the superior border of the rib below, acts by *elevating the rib*;

the **external intercostal muscle** (E), with its fibres running parallel to the levator costae as they course obliquely superiorly and medially. Therefore this muscle and the levator *elevate* ribs and act as *inspiratory* muscles;

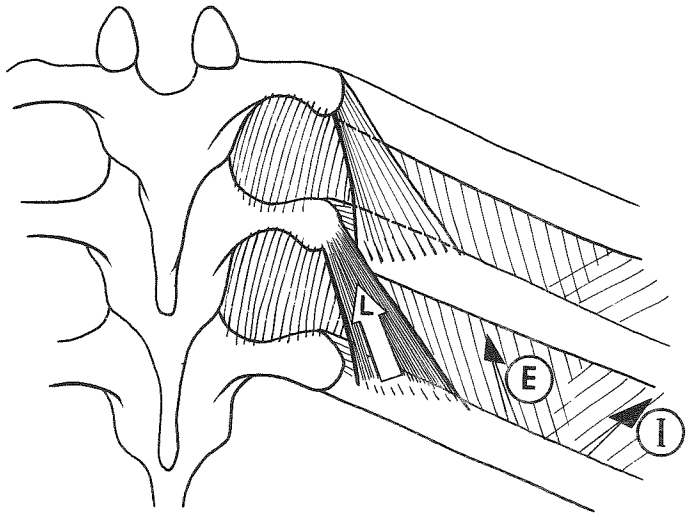
the **internal intercostal muscle** (I), with its oblique fibres running superiorly and laterally, *depresses the ribs* and so is an *expiratory* muscle.

The mode of action of these muscles is well explained by these diagrams (according to Hamberger):

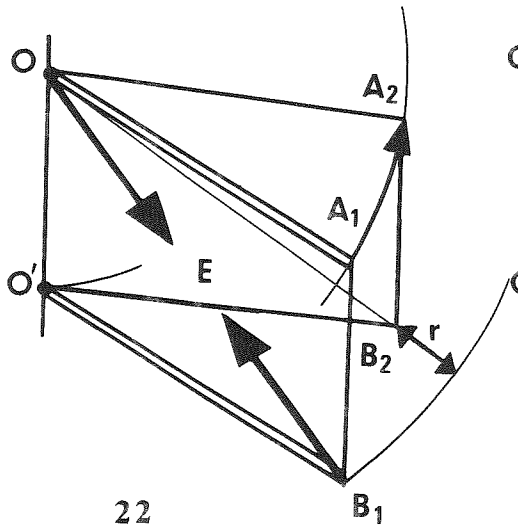
the action of the *external intercostal* (fig. 22) is easily grasped if one realises that the direction of its fibres is parallel to the long diagonal of the parallelogram OO′BA formed by the ribs connected to the vertebral column and the sternum. When the muscle contracts (E) the diagonal is shortened by a distance r and this distorts the parallelogram. Assuming that OO′ is fixed, this causes rotation of A_1 to A_2 and B_1 to B_2. Therefore contraction of the external intercostal *elevates the ribs* and the muscle is a *muscle of inspiration*;

the action of the *internal intercostal* (fig. 23) can be understood in a similar way except that the direction of the muscle fibres is parallel to the short diagonal of the parallelogram. When the muscle (I) contracts, the diagonal OA′ is shortened by a distance r′ which displaces A_1 to A_2 and B_1 to B_2, assuming that OO′ is fixed. The internal intercostal therefore *depresses the ribs* and *is active in expiration.* This demonstration of Hamberger was at one time contradicted by Duchenne de Boulogne's electrical stimulation experiments but more recent electromyographic studies have supported it.

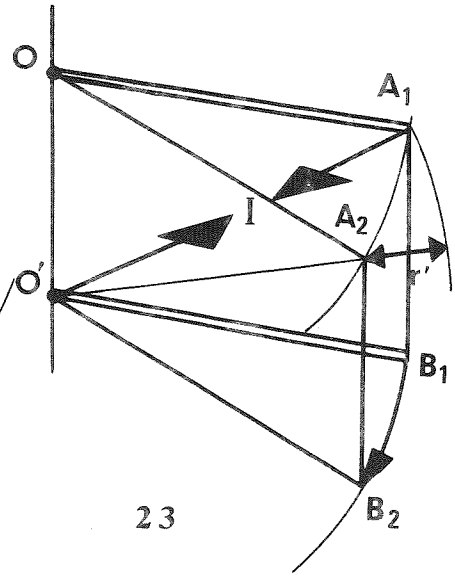
The **sternocostalis** is a small muscle which is usually ignored because of its retro-sternal location (fig. 24). It lies entirely on the deep surface of the sternum and its fibres, inserted into the second to sixth ribs, run obliquely inferiorly and medially. Contraction of its five muscle bands *depresses the corresponding costal cartilages relative to the sternum.* We have seen (fig. 19) that the costal cartilage is raised during inspiration and depressed during expiration; the sternocostalis, therefore, is a *muscle of expiration.*



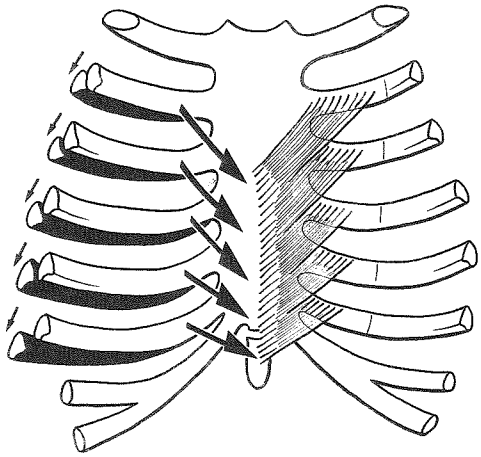
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THE DIAPHRAGM AND ITS MODE OF ACTION

The diaphragm is a *musculo-tendinous dome forming the floor of the thorax and separating the thorax and abdomen.* Seen from the side (fig. 25) this dome reaches farther down posteriorly than anteriorly and its apex is the central tendon (1). From this centre, bands of muscle fibres (2) radiate out to the periphery of the floor of the thorax and gain attachment to the deep surfaces of the costal cartilages, the tips of the eleventh and twelfth ribs, the costal arch, the vertebral bodies by means of crura (left crus 3 and right crus 4), the medial surfaces of the psoas (7) and the quadratus lumborum (8). This is more obvious when seen from in front (fig. 26), where it is easy to distinguish at the same time the apex of the diaphragm and its inner surface at the level of the crura. The openings in the diaphragm can also be seen as they allow the passage of the oesophagus (6) and the aorta (5). In this figure the opening for the inferior vena cava is not shown.

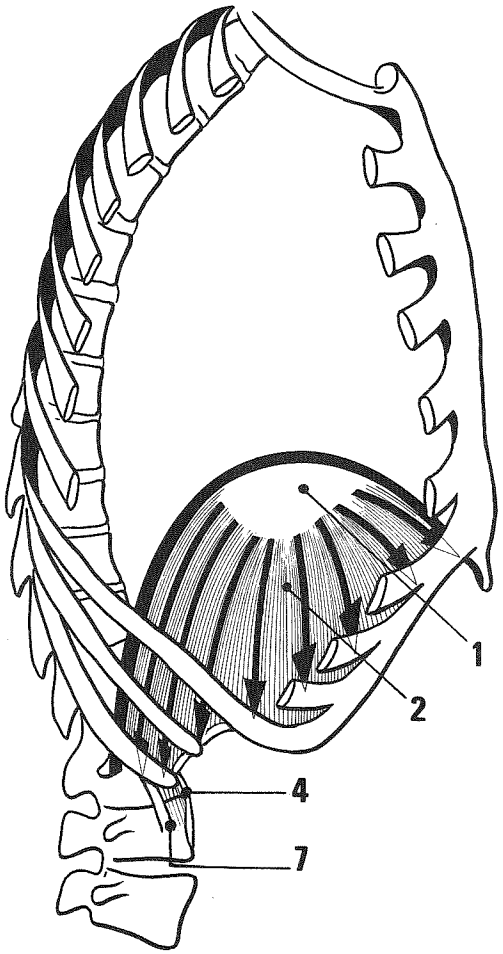
When the diaphragm contracts the *central tendon is pulled down* thus increasing the vertical diameter of the thorax. One can therefore compare the diaphragm to a piston sliding inside a pump. This depression of the central tendon is rapidly checked by the mediastinal constituents as they are stretched, and by the resistance offered by the abdominal organs. From this moment on (fig. 27) the central tendon becomes fixed (large white arrow) and the muscle fibres, now acting from the periphery of this central tendon (small white arrow), elevate the lower ribs. In effect, if one considers P as fixed and the rib as rotating about an axis O, the rib extremity describes an arc of a circle AB while the corresponding muscle fibres shorten by a distance of A'B. Therefore by elevating the lower ribs the *diaphragm increases the transverse diameter of the lower thorax* and simultaneously, with the help of the sternum, it also elevates the upper ribs, *thus increasing also the anteroposterior diameter of the thorax.* Therefore the diaphragm can be considered as the basic muscle of respiration as **it increases by itself all three diameters of the thoracic cavity**:

it increases the vertical diameter by pulling down the central tendon;

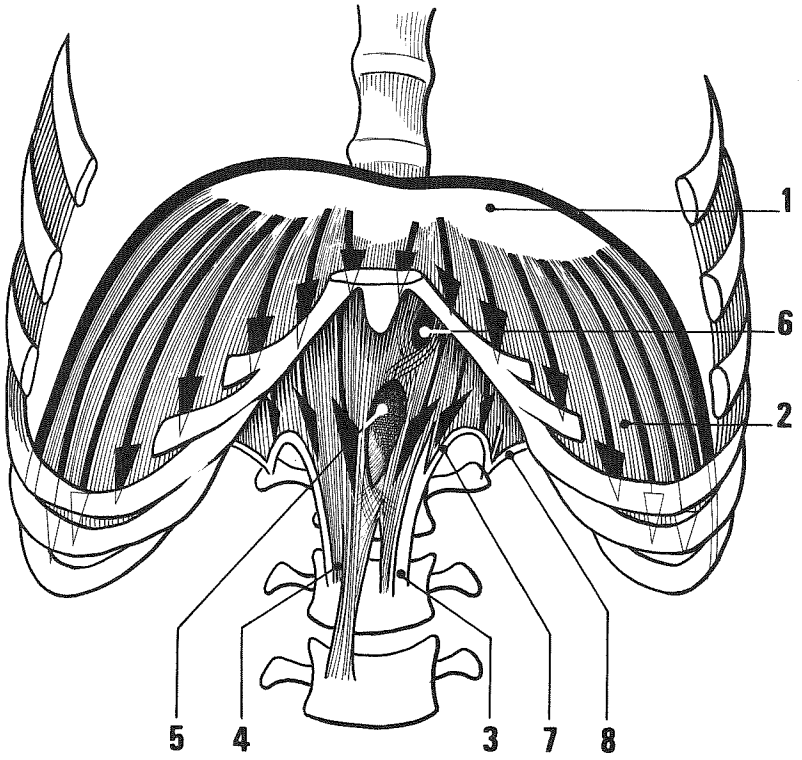
it increases the transverse diameter by elevating the lower ribs;

it increases the anteroposterior diameter by elevating the upper ribs with the help of the sternum;

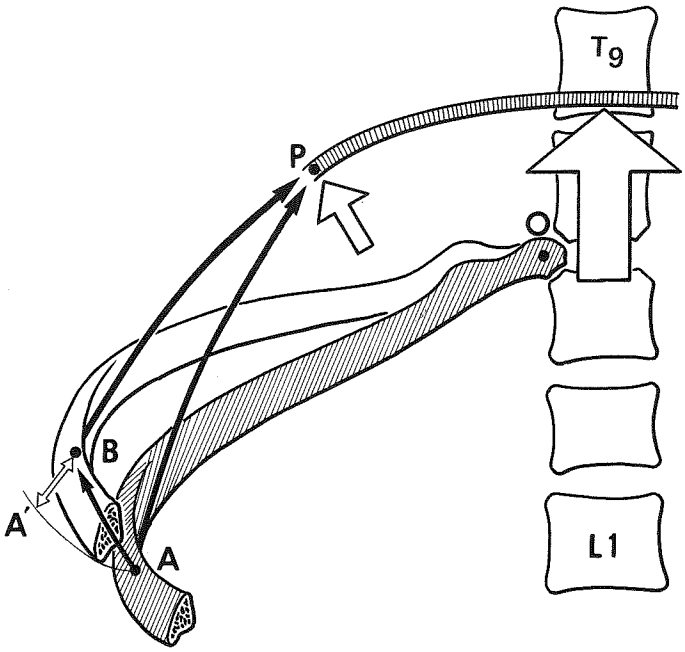
Its significance in the physiology of respiration is obvious.



25



26



27

THE RESPIRATORY MUSCLES

From the foregoing, one can divide respiratory muscles into two groups: the **inspiratory muscles** which *elevate the ribs* and the **expiratory muscles** which *depress the ribs and the sternum.* These groups can be subdivided into two groups—the *primary* and the *accessory muscles*, the latter being recruited only when respiratory movements are unusually deep or strong.

These muscles can therefore be divided into four groups:

Group I: the **primary inspiratory** muscles—the external intercostals, the sternocostalis and above all the **diaphragm.**

Group II: the **accessory muscles of inspiration** (fig. 28, 29, 30):

the sternomastoid (1), the scalenus anterior (2), medius (3) and posterior (4) only help in inspiration when they can act on a cervical vertebral column fixed by other muscles (fig. 28);

the pectoralis major (4) and minor (5) when they act on the scapula and upper limb already in abduction;

the inferior fibres of the serratus anterior (5) and the latissimus dorsi (10), when the latter acts on the upper limb already in abduction;

the serratus posterior superior (11);

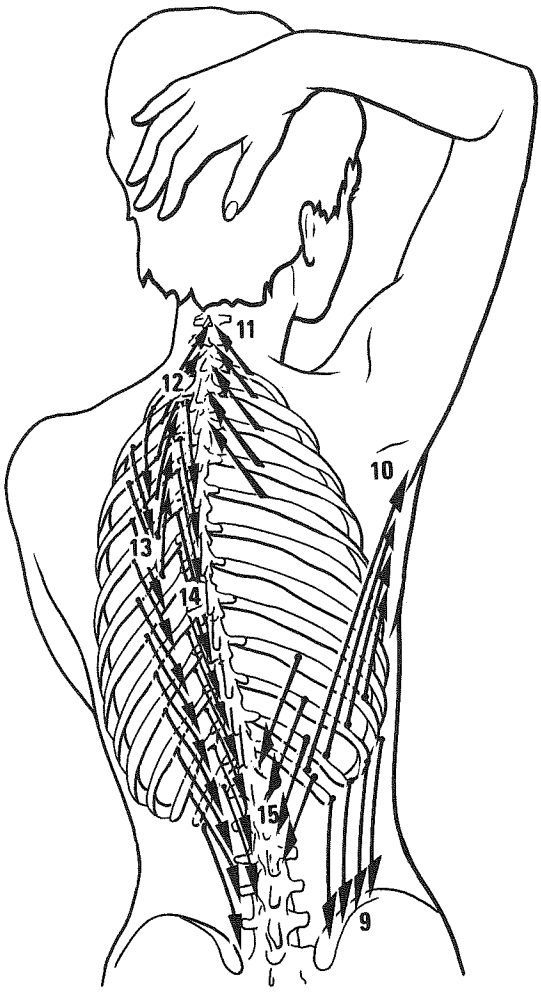
the superior fibres of the iliocostalis (12) which are attached superiorly to the last five cervical transverse processes and inferiorly to the first six costal arches. It resembles the levator costae in the direction of its fibres.

Group III: the primary expiratory muscles—the internal intercostals. In fact *normal expiration is a purely passive process due* to recoil of the thorax as a result of the *elasticity* of its osteochondral components and of the pulmonary parenchyma. The energy necessary for expiration derives from the energy developed by the inspiratory muscles and stored by the elastic components of the thorax and lungs. We shall see later the essential role played by the costal cartilages. Let us note also that during standing the ribs are pulled by their own weights and thus the *contribution of gravity* is not negligible.

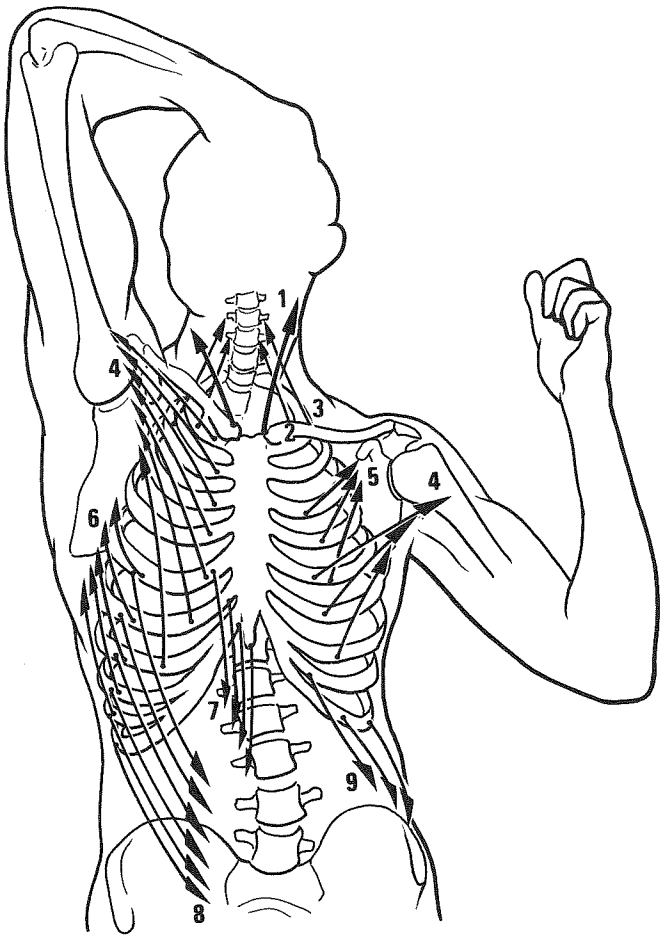
Group IV: the **accessory expiratory muscles.** Though accessory, they are no less important and they are extremely powerful. They allow **forced expiration** and the **performance of the Valsalva manoeuvre.**

The abdominal muscles (fig. 30), the rectus abdominis (7), the external oblique (8), the internal oblique (9) strongly depress the thoracic floor.

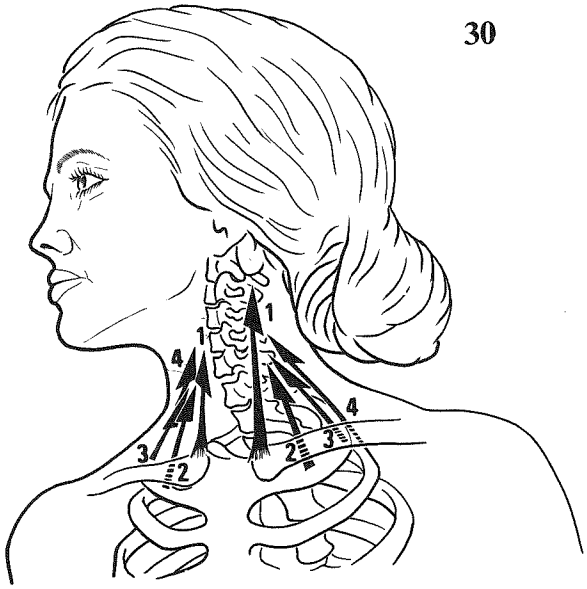
In the thoracolumbar region (fig. 29) other accessory muscles are present: the lowest fibres of the iliocostalis (13), the longissimus (14), the serratus posterior inferior (15) and the quadratus lumborum (not shown here).



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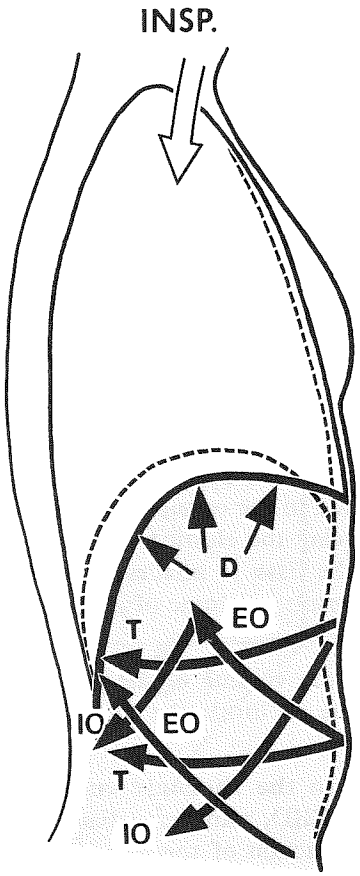
ANTAGONISM AND SYNERGISM OF THE DIAPHRAGM AND THE ABDOMINAL MUSCLES

As already shown, the diaphragm is the main inspiratory muscle and the abdominal muscles are accessory expiratory muscles of great strength, which can produce forced expiration. *Though apparently antagonistic these muscles are also synergistic.* In fact the diaphragm would be less effective in the absence of the abdominal muscles.

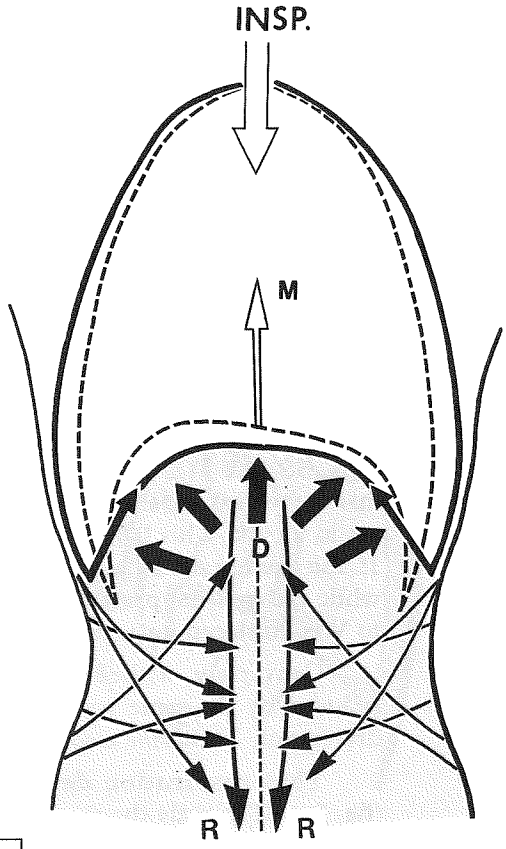
During inspiration (fig. 31: seen from the side; fig. 32: seen from the front) the contraction of the diaphragm brings down the central tendon increasing the vertical diameter of the thorax; but this is soon opposed by the elongation of the vertical mediastinal elements (M) and especially the *resistance of the abdominal viscera* (D). These are contained within the 'abdominal girdle' formed by the powerful abdominal muscles: the rectus muscles (R), the transversus muscles (T), the internal (IO) and external obliquus (EO). Without these muscles, the abdominal contents would be displaced inferiorly and anteriorly and the central tendon would not be stabilised to allow the diaphragm to elevate the lower ribs. *This antagonistic–synergistic action of the abdominal muscles therefore is essential for the efficiency of the diaphragm.* This is borne out in disease, e.g., in poliomyelitis, where the paralysis of the abdominal muscles reduces the ventilatory efficiency of the diaphragm. In fig. 31 (seen from the side) the directions of the fibres of the abdominal muscles represent a six-sided star.

During expiration (fig. 33: seen from the side; fig. 34: seen from in front) the diaphragm relaxes and contraction of the abdominal muscles lowers the thoracic floor thereby decreasing simultaneously the transverse and anteroposterior diameters of the thorax. Also by increasing the intra-abdominal pressure they push the viscera upwards and raise the central tendon. This decreases the vertical diameter of the thorax and 'closes' the costodiaphragmatic recesses. Therefore the abdominal muscles are the *perfect antagonists of the diaphragm* as they reduce simultaneously the three diameters of the thorax.

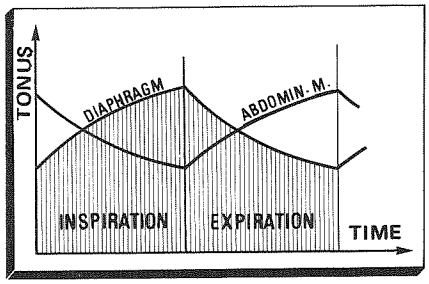
The respective roles of the diaphragm and abdominal muscles can be visualised as follows (fig. 35). Both sets of muscles are always in active contraction but their activity varies reciprocally. Thus, during inspiration the tonus of the diaphragm increases while that of the abdominal muscles decreases, and vice versa during expiration. Hence there exists between these two muscle groups a *floating equilibrium* constantly shifting in both directions; this is the basis of the antagonism–synergism of these muscles.


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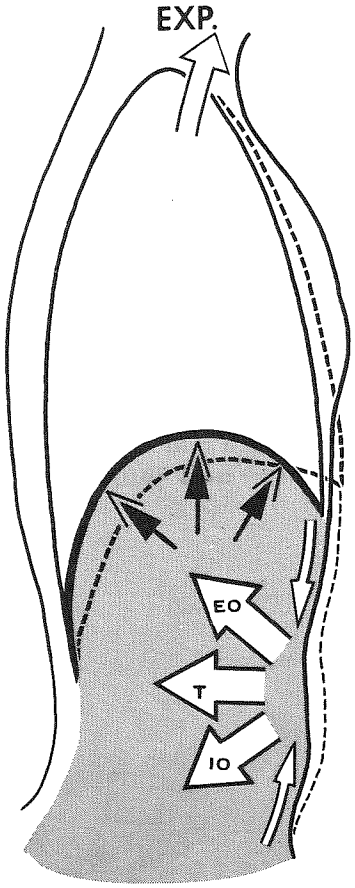
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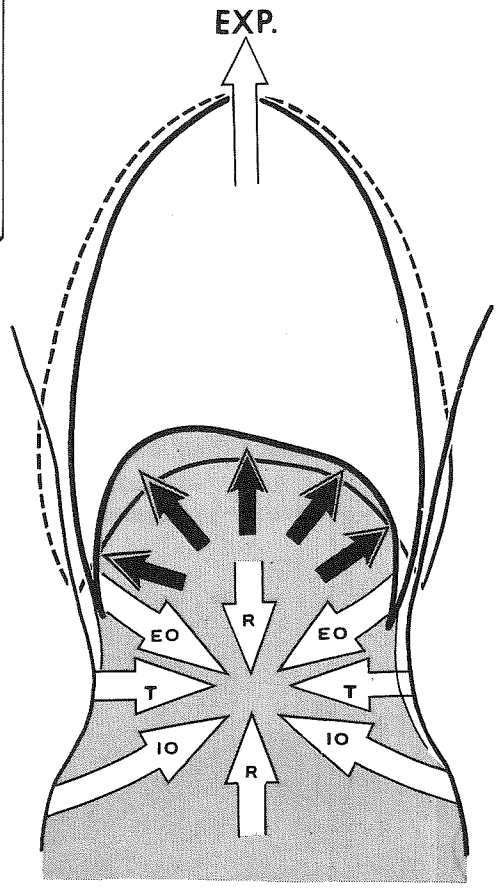
32


TONUS
DIAPHRAGM
ABDOMIN.-M.
INSPIRATION
EXPIRATION
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AIR MOVEMENT IN THE RESPIRATORY AIRWAYS

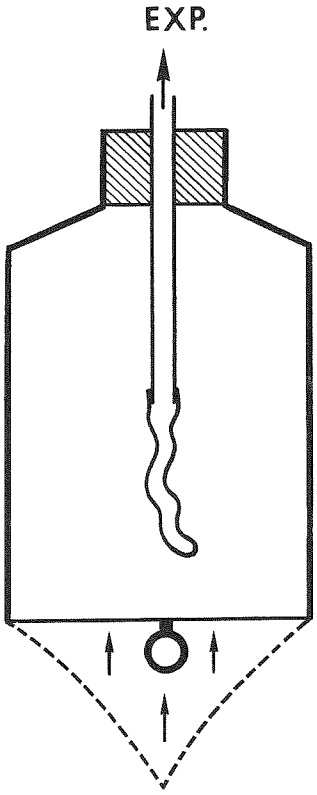
Air movement in the bronchial tree is demonstrated by the **classical experiment of Funck** (figs. 36 and 37). Replace the bottom of a flask by a watertight elastic membrane and insert inside the flask a balloon made of goldbeater's skin, which is connected to the outside by a tube set in a cork. This balloon can be inflated or deflated simply by moving the elastic membrane. If the membrane is pulled down (fig. 37) the internal volume of the flask is increased by V while the internal pressure falls below that of the atmosphere. As a result a volume of air equal to V is displaced inwards and inflates the balloon. *This is the mechanism of inspiration.*

Conversely, if the membrane is relaxed (fig. 36) it recoils and the volume of the flask is reduced by the same volume V while the internal pressure rises. The air inside the balloon is driven out. *This is the mechanism of expiration.*

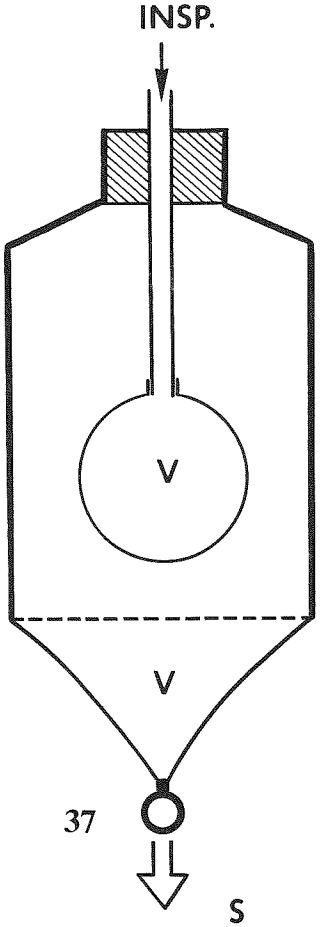
Thus **respiration depends upon the increase or decrease in the thoracic volume** (fig. 38). If initially the thorax is taken as a *truncated ovoid* with base ACBD, transverse diameter CD, anteroposterior diameter AB and vertical diameter SP, then the action of the inspiratory muscles, especially the diaphragm, increases all its diameters so that a greater ovoid A′C′B′D′ results with transverse diameter C′D′, anteroposterior diameter A′B′ and vertical diameter SP′. This situation differs from Funck's experiment in that *all the diameters of the container are increased* but the *similarities are quite striking* (fig. 39): the tube represents the trachea; the balloon represents the lungs; the elastic membrane represents the diaphragm. Two points need stressing:

on the one hand, the lungs fill the whole thoracic cavity and are connected to the thoracic wall by the *pleura* with its potential space. In fact its two layers are normally apposed and slide freely one on the other, thus ensuring *a tight mechanical link between the lungs and the thoracic wall*;

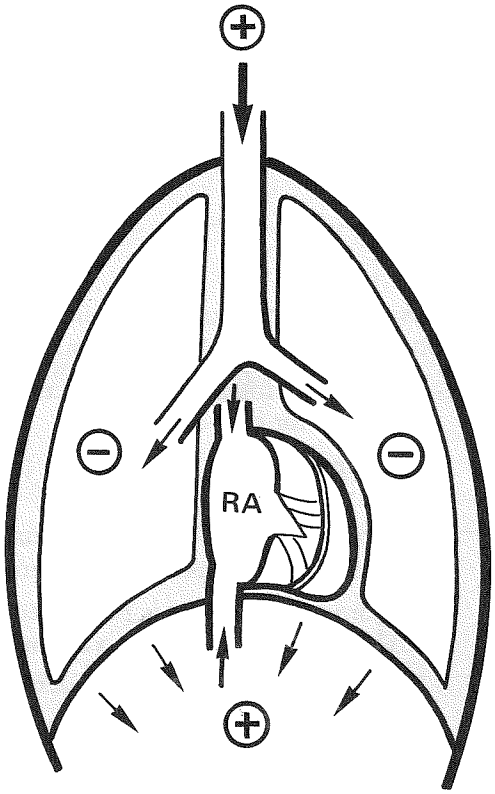
during inspiration the intrathoracic pressure falls and becomes negative not only relative to the outside but also *relative to the abdominal cavity*. As a result air enters the trachea and the lungs and *the venous return to the right atrium (RA) is speeded up*. Thus inspiration improves cardiac filling and, with the help of the lesser circulation, *brings venous blood into contact with the newly inspired air*. Thus inspiration **at once ensures air entry and pulmonary vascular perfusion.**



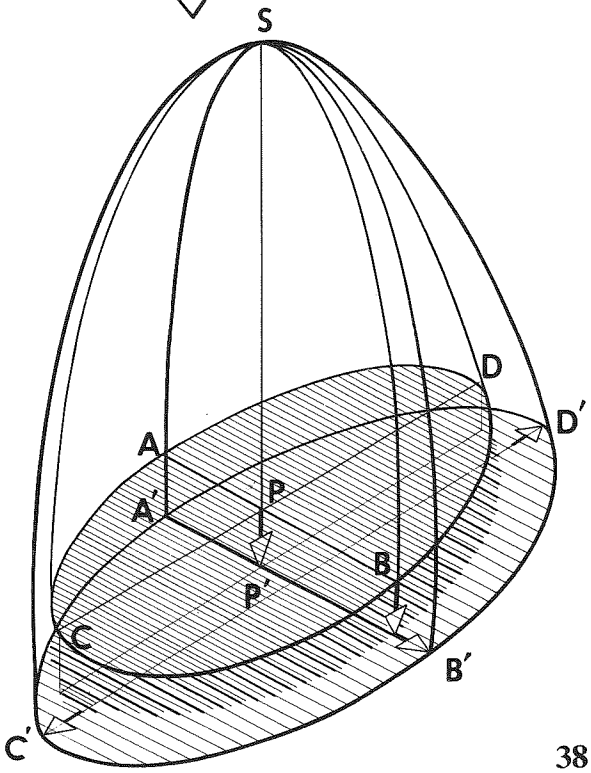
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39



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Bull. Eur. Physiopathol. Respir.
1984, *20*, 409-413

ACTIONS OF THE RESPIRATORY MUSCLES OR HOW THE CHEST WALL MOVES IN UPRIGHT MAN

A. De Troyer *

Since the studies of KONNO and MEAD [21] on the partition of breathing between the rib cage and abdomen, it has been recognized that quiet breathing in upright humans generally occurs on the relaxed thoracoabdominal configuration (fig. 1). Under these circumstances, not only does the chest wall (*i.e.*, the rib cage-abdomen system) move on its relaxation characteristic (panel A), but also the rib cage does behave with a single degree of freedom of motion (panels B and C). The mechanism of this extraordinarily effective « coupling » between the rib cage and abdomen has been a matter of considerable interest among respiratory physiologists for the past 15 years, in particular since GOLDMAN and MEAD [19] published their famous hypothesis that in upright humans breathing quietly the diaphragm was the only important contracting muscle, driving the entire chest wall, including the rib cage, on its relaxed configuration.

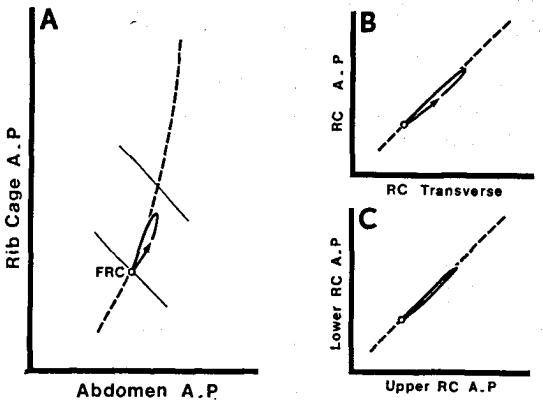


Fig. 1. — Pattern of thoracoabdominal motion in a « relaxed » normal subject breathing quietly in the upright posture. In each panel, the broken curve represents the relaxation characteristic and the open circle corresponds to end-expiration. The solid loops represent the tidal volume loops ; their direction is indicated by arrows. Note that the chest wall moves on its relaxed configuration (panel A) and that the rib cage (RC) behaves with a single degree of freedom of motion (panels B and C). A-P : anteroposterior diameter.

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THE DIAPHRAGM

That the diaphragm has an inspiratory action on the rib cage has been recognized from ancient times [12, 16]. The mechanisms of this action, however, have only recently been assessed, due to the recognition of some fundamental but long overlooked anatomic features. Understanding the action of the diaphragm thus requires clear understanding of its functional anatomy.

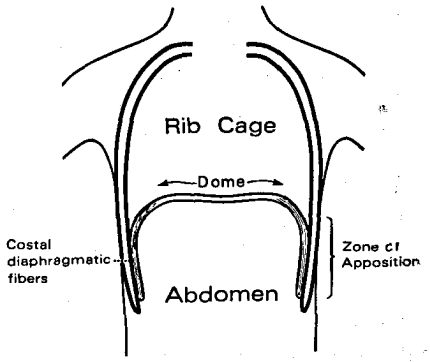


Fig. 2. — Frontal section of the respiratory system at end-expiration, illustrating the functional anatomy of the diaphragm. Note the orientation of the costal diaphragmatic fibres, which run parallel to the rib cage axis and are directly apposed to the inner aspect of the lower rib cage (zone of apposition).

In relation to its function, the human diaphragm can be considered as an elliptical cylindroid capped by a dome (fig. 2). The cylindrical portion of the diaphragm corresponds to the portion directly apposed to the inner aspect of the lower rib cage (zone of apposition) [23]. The dome of the diaphragm corresponds mainly to the central tendon. Its shape and size are relatively constant during breathing [2] and because it has no direct attachment to any solid structure, its motion mainly depends upon the relative resistance to motion of the abdominal contents and the lower ribs. When the costal diaphragmatic muscle fibres shorten during inspiration, the axial length of the apposed portion diminishes and the dome of the diaphragm descends relative to its costal insertions. The most important change in diaphragmatic shape, the one responsible for most of the volume displace-

ment, is thus a piston-like axial displacement of the dome related to the shortening of the axial length of the apposed muscle fibres. This phenomenon has three major consequences : 1) it decreases the intrathoracic pressure and, depending on whether the airways are open or closed, it increases lung volume or decreases the alveolar pressure ; 2) it pushes the abdominal contents caudally, resulting in a rise in intraabdominal pressure and outward motion of the ventral abdominal wall ; and 3) the rib cage is displaced.

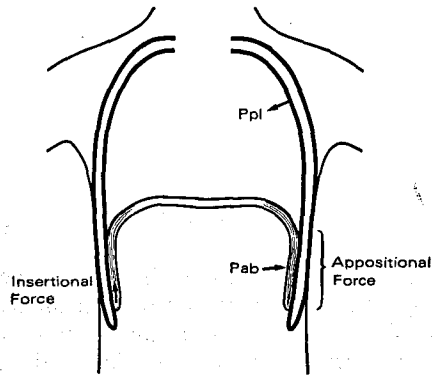


Fig. 3. — Frontal section of the respiratory system at end-expiration, illustrating the three forces through which the diaphragm operates to displace the rib cage. See text for description.

There are three forces by which the diaphragm operates to displace the rib cage (fig. 3). The first is related to the decrease in pleural pressure which, by itself, tends to reduce rib cage size. The second is related to the rise in abdominal pressure which, by acting over the zone of apposition of the diaphragm to the rib cage, tends to inflate the lower rib cage. This component of diaphragmatic action has been named « appositional force » [15, 22], and it depends on the magnitude of rise in abdominal pressure during inspiration and the size of the zone of apposition. Clearly, the appositional force is greater when the abdominal compliance is reduced (causing a larger rise in abdominal pressure) and when the size of the zone of apposition is increased, such as at low lung volumes. The third force by which the diaphragm acts to displace the rib cage relates to its insertions on the lower ribs (« insertional force ») [14, 15]. Indeed, because the costal diaphragmatic fibres insert into the lower ribs and are directed cranially, parallel to the rib cage axis, their contraction must exert a force that tends to elevate the lower ribs, moving them outward.

It is clear that this insertional force can only operate if there are solid structures that resist the descent of the diaphragmatic dome. Early work in this controversial area has focused on the nature of the solid structures which enable the diaphragm to expand the rib cage by way of its insertions. BEAU and MAISSIAT [1] believed that restraining of the diaphragmatic dome by the pericardium was sufficient to produce this effect, whereas DUCHENNE [16] concluded that the abdominal viscera provided the solid « fulcrum » against which the contracting diaphragm pushed to elevate the ribs. This latter mechanism has since been convincingly confirmed. Indeed, DE TROYER *et al.* [15] have shown in dogs that removing the abdominal viscera from the abdominal cavity caused the costal diaphragmatic fibres to contract, rather than expand, the lower rib cage, whereas sectioning the pericardial attachments of the diaphragmatic dome did not affect the rib cage expanding action of the diaphragm. D'ANGELO and SANT'AMBROGIO [4] have also reported that the rib cage deflation produced by the diaphragm in eviscerated rabbits was reversed into a rib cage expansion when the diaphragmatic dome was presented from descending by mechanical means. The abdominal contents thus provide the solid fulcrum through which the diaphragmatic insertions on the ribs operate to lift the lower ribs and expand the rib cage. And the more effective the abdominal fulcrum is, the greater the insertional force developed by the contracting diaphragm to lift the lower ribs. If the abdominal muscles contract so as to reduce abdominal compliance and fix the diaphragmatic dome, the apposed diaphragmatic muscle fibres thus have a greater tendency to lift the lower ribs when they shorten. The abdominal compliance thus affects the insertional and appositional components of diaphragmatic action in the same direction.

For anatomical reasons, it is obvious that the appositional and insertional forces primarily apply to the lower portion of the rib cage. They do not affect, or only to a limited extent, the upper portion of the rib cage. Hence, the net action of the diaphragm on the lower rib cage depends on the balance between the fall in pleural pressure, which tends to deflate the rib cage, and the appositional and insertional forces, which both tend to expand the rib cage. On the other hand, the action of the diaphragm on the upper rib cage should be predominantly determined by the effect of the fall in pleural pressure. And indeed, quiet breathing does not occur on the relaxed thoracoabdominal configuration in seated tetraplegic subjects, when the diaphragm is really the only important contracting muscle [5, 18, 24]. As illustrated in figure 4, the tidal volume loop in such subjects departs substantially from the chest wall and rib cage relaxation characteristic : the abdominal expansion predominates

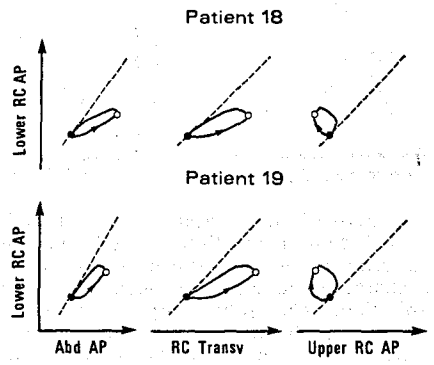


Fig. 4. — Pattern of thoracoabdominal and rib cage (RC) motion in two seated tetraplegic subjects breathing quietly. Abd : abdomen ; AP : anteroposterior diameter. In each panel, the broken line represents the relaxation characteristic, and the solid loop represents tidal volume cycle. The direction of the loops is indicated by arrows. Closed circle : end-expiration ; open circle : end-inspiration. See text for description.

over rib cage expansion, the lower rib cage expands proportionately more along its transverse than anteroposterior diameter, and the upper rib cage moves inward during inspiration. It is clear, therefore, that GOLDMAN and MEAD's hypothesis [19] is incorrect and that the diaphragm acting alone is not able to drive the chest wall on its relaxed configuration *. It thus needs a good deal of help from other inspiratory muscles to do so, and recent work in this area suggests that most of this help is provided by the parasternal intercostals and the scalene muscles.

THE INSPIRATORY RIB CAGE MUSCLES

The parasternal intercostals

Since TAYLOR's electrical recordings from the intercostal muscles in humans [27], it is well established that the interchondral portion of the internal intercostals (the « parasternals ») is electrically active during quiet inspiration [7, 9, 13]. In line with GOLDMAN and MEAD's hypothesis, however, this parasternal inspiratory EMG activity was perceived as being the consequence, rather than the cause of the rib cage displacement [8] ; it would occur through activation of the spindle mechanism to prevent the rib cage distortions that the diaphragm would otherwise produce by way of the fall in pleural pressure. Recent studies, however, have shown that the parasternals, unlike the external and internal interosseous intercostals, are poorly supplied with muscles spindles [17]. In addition, EMG studies in humans have shown that the parasternal EMG activity is reduced or abolished in the presence of rib cage distortion during diaphragmatic isovolume manoeuvres [13] or during breathing against inspiratory mechanical loads [26]. Other studies in dogs have further demonstrated that the inspiratory contraction of the parasternals is a real miometric (as opposed to isometric or pliometric) contraction ; these muscles actively shorten during quiet, spontaneous inspiration and lengthen during expiration [6]. Although the length changes undergone by the parasternals during breathing in humans have not yet been measured, it thus appears that the parasternals are real agonists (as opposed to fixators) and actively contribute to inspiration.

Anesthetized dogs provide a good experimental setting for assessing the mechanical action of the parasternals on the chest wall. Indeed, after bilateral section of the phrenic nerve roots in the neck, the parasternals contribute most of the tidal volume [10]. Figure 5 compares the changes in thoracoabdominal

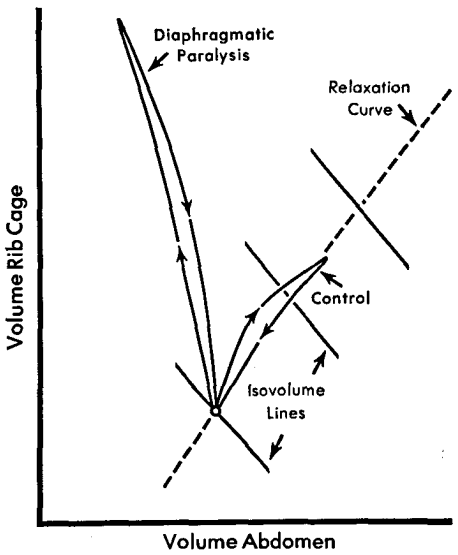


Fig. 5. — Pattern of thoracoabdominal motion during quiet breathing in a supine dog before (control) and after bilateral section of the phrenic nerves. Broken line represents the chest wall relaxed configuration. The solid loops represent tidal volume cycles ; their direction is indicated by arrows. Open circle : end-expiration. (Reproduced, with permission, from DE TROYER and KELLY [10]).

configuration that occur during quiet breathing before and after bilateral phrenicotomy in a supine anesthetized animal. As can be seen, quiet breathing in the intact animal is virtually superimposed upon the chest wall relaxed configuration. After phrenicotomy, however, the tidal volume loop considerably departs from it. The rib cage still expands during inspiration, clearly indicating that the parasternals actually have an inflationary action on the rib cage, but at the same time, because the fall in pleural pressure is transmitted across the flaccid diaphragm to the abdomen, there is paradoxical inward motion of the abdomen. In addition, the increased inspiratory rib cage expansion after phrenicotomy takes place in a considerably distorted fashion [10]. This is illustrated in figure 6, where the changes in rib cage anteroposterior and transverse diameters and the axial (cephalo-caudal) displacements of the sternum and the ribs that occur during breathing after phrenicotomy are compared with those observed during mechanical ventilation. The contraction of the parasternals during inspiration causes the rib cage to expand more along its transverse than anteroposterior diameter relative to its relaxed configuration (obtained during mechanical inflation), but, in addition, the axial displacement of the rib cage is profoundly disturbed. Whereas both the ribs and the sternum move in a cranial direction during mechanical inflation (*i.e.*, when the parasternals are inactive), the sternum moves in a caudal direction during inspiration after phrenicotomy. This is due to the insertions of the parasternals on the lateral border of the sternum and the upper border of the costal cartilages, which thus produce a rotation of the chondrosternal junctions when they contract (« bucket-handle » action) [10].

Similar deformations of the rib cage are seen when normal humans inhibit the diaphragm and attempt to breathe with the parasternals alone (A. De Troyer, M. Estenne and V. Ninane, unpu-

* Measurements obtained in tetraplegic subjects may somewhat underestimate the rib cage expanding action of the diaphragm. Indeed, the abdominal muscles are paralysed in these subjects, making the abdominal fulcrum less effective than in normals. Recent phrenic nerve stimulation experiments in healthy volunteers (A. DE TROYER *et al.*, unpublished observations), however, have confirmed that the rib cage expanding action of the diaphragm is far less than that postulated by GOLDMAN and MEAD, whose observations are largely attributable to specific experimental conditions facilitating the respiratory action of the diaphragm on the rib cage (that is, marked stiffening of the abdomen and enlargement of the zone of opposition by external abdominal compression).

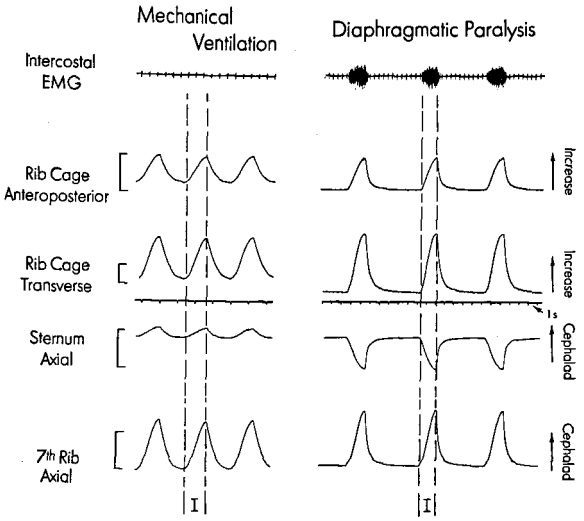


Fig. 6. — Pattern of rib cage motion during mechanical ventilation (left) and during quiet breathing after bilateral phrenicotomy (right) in a supine, anesthetized dog. Intercostal EMG was recorded in the parasternal area (3rd intercostal space). I indicates the duration of inspiration. Note that, after phrenicotomy, the rib cage expands proportionately more in its transverse diameter and the sternum moves in a caudal direction during inspiration. The vertical brackets on left edge of tracings represent a 5 mm displacement. (Reproduced, with permission, from DE TROYER and KELLY [10]; slightly modified).

blished observations). During such efforts, the rib cage expands considerably more along its transverse than anteroposterior diameter relative to its relaxed configuration and, as is the case in phrenicotomized dogs, the sternum moves caudally in the early part of inspiration, especially when the activation of the scalenes is delayed. Indeed, the scalenes, which in man insert into the transverse processes of the lower five cervical vertebrae and the upper border of the first two ribs, also contribute to quiet inspiration in humans.

The scalene muscles

Earlier studies by CAMPBELL [13] in normal humans have reported that the scalenes are usually inactive during quiet breathing, being recruited only when ventilation increases. As a result, these muscles, together with the sternocleidomastoids and several other muscles which run between the rib cage and the spine or the shoulder girdle and participate in respiratory acts only in some particular circumstances, have traditionally been described under the heading « accessory muscles ». However, these observations where obtained with skin surface electrodes, a technique which is generally unable to recognize low levels of EMG activity.

And indeed, using needle electrodes directly inserted into the muscle, RAPER *et al.* [25] and others [7, 20] have subsequently documented a scalene phasic inspiratory EMG activity in most normal humans breathing at rest. As illustrated in figure 7, the scalene EMG activity has a time course which closely resembles that of the diaphragm and parasternals [9]. This EMG activity usually starts together with the beginning of inspiration, increases progressively in intensity as inspiration proceeds, and reaches its peak at the end of inspiration. Further, it persists into the first part of expiration, suggesting that, together with the diaphragm and the parasternals, these muscles oppose the passive elastic recoil of the respiratory system in producing expiratory airflow. Finally, normal seated humans cannot suppress inspiratory EMG activity in the scalenes during quiet breathing until tidal volume becomes trivial (less than 100 ml). There

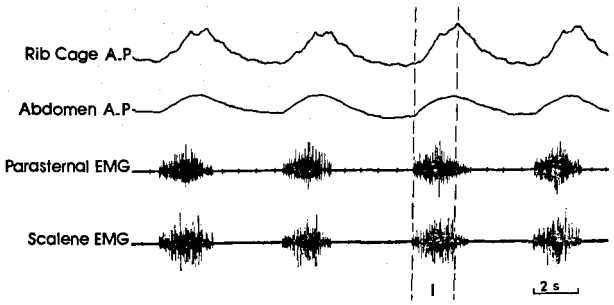


Fig. 7. — Electromyographic (EMG) activity detected in the scalenes and parasternal intercostals in a seated normal subject breathing quietly. The inspiratory phase of the breathing cycle (I) is indicated by an increase in rib cage and abdomen anteroposterior (A-P) diameter.

is thus no reason for using the qualifying adjective « accessory » in describing the scalenes. These muscles in humans are primary, not accessory, muscles of inspiration [9].

The mechanical action of the scalenes in humans is poorly defined, presumably because there is no clinical setting that spares the scalenes and causes paralysis of all the other inspiratory muscles. In the dog, however, selective stimulation of the scalenes is primarily associated with an axial displacement of the ribs and the sternum in a cranial direction [11]. This cranial displacement of the ribs, in turn, causes the rib cage to expand along both its anteroposterior and transverse diameters but, because of the muscle's anatomic insertions, the rib cage expansion is proportionately greater along its anteroposterior than transverse diameter (« pump-handle » action). In addition, recent evidence has been obtained in normal humans, which suggests that the EMG activity present in the scalenes during quiet inspiration is not simply an electrical event [9]. As illustrated in figure 8, normal subjects in seated posture were coached to breathe first naturally (left panel), and then to maximize

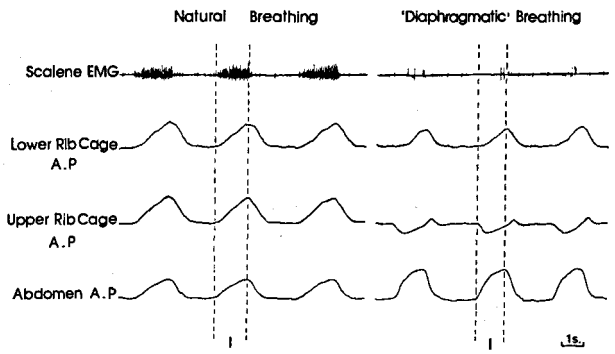


Fig. 8. — Scalene electromyographic (EMG) activity and changes in anteroposterior (A-P) diameter of upper and lower rib cage and abdomen (increase upwards) in a seated normal subject during natural, quiet breathing (left) and during attempts to perform tidal volume inspiration with the diaphragm alone (right). I indicates the duration of inspiration. Note that diaphragmatic tidal breathing is associated with a marked decrease in scalene inspiratory EMG activity and considerable cephalo-caudal distortion of the rib cage.

diaphragmatic use during tidal volume breathing (right panel). During natural breathing, while the scalenes are electrically active during inspiration, the lower and upper portions of the rib cage expand in phase with the abdomen. By contrast, as the subject attempts to breathe with the diaphragm alone and augments abdominal expansion with inspiration, a marked decrease or even an abolition of scalene EMG activity occurs, accompanied by a reduced inspiratory expansion of the lower rib cage in its anteroposterior diameter and an inward, paradoxical displacement of the upper rib cage. This cranio-caudal deformation of the rib cage is most likely to result from the observed inhibition of the scalenes, since it is associated with a recruitment rather than an inhibition of the parasternal intercostals [9]. Although additional studies are required, it thus appears that the scalene muscles normally contribute to quiet inspiration in normal humans, acting to counteract the parasternals in their action on the sternum and to expand the (upper) rib cage primarily along its anteroposterior dimension.

CONCLUSION

On the basis of these observations, it thus appears that the rib cage in humans is more distortable than conventionally thought. Its inherent structural stability is not sufficient to ensure a unitary behaviour and, if it moves with a single degree of freedom during quiet breathing, it is because of co-ordinated activity between the diaphragm, the parasternal intercostals and the scalenes.

Isolated paralysis of the sternocleidomastoids should not affect the pattern of thoracoabdominal motion during quiet breathing, since these muscles are not active in normal humans breathing at rest. Nor should this pattern be substantially affected by paralysis of the external and internal interosseous intercostals whose mechanical contribution to tidal breathing appears to be negligible. In contrast, if for whatever reason the diaphragm, the parasternals or the scalenes are inhibited or paralysed, or if the precisely co-ordinated pattern of activation of these three muscle groups is altered, the rib cage is distorted and quiet breathing does no longer occur on the chest wall relaxed configuration.

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COURNAND LECTURE *

MECHANICAL ACTION OF THE ABDOMINAL MUSCLES

ACTION MÉCANIQUE DES MUSCLES ABDOMINAUX

A. De Troyer **

The mechanical action of any skeletal muscle in the body is primarily defined by the anatomy of the muscle and the loads this has to displace. This rule applies equally to the abdominal muscles. Understanding the action of the abdominal muscles, therefore, requires clear understanding of their anatomy and of the structures they displace when they contract. The present account will accordingly begin with a brief review of the most relevant features of the anatomy of the abdominal muscles and of the structure of the abdominal cavity. It will next discuss some current ideas concerning the mechanical actions of these muscles and their interaction with other respiratory muscles. In this discussion, without neglecting older, more conventional viewpoints, I have tended to emphasize some concepts that have developed recently and are based on the recognition of some fundamental but long overlooked anatomic features. In that, they add force to a remark offered 25 years ago by W.O. FENN [16] : « The mechanics of breathing is a problem requiring on the one hand the detailed knowledge of a classical anatomist and on the other hand the analytic understanding of an engineer. »

Functional anatomy

The abdominal muscles that have significant respiratory activity in man and are therefore of interest in the present context are those which constitute the anterolateral wall of the abdomen. These muscles are the rectus abdominis, the obliquus externus, the obliquus internus, and the transversus abdominis. They are all supplied by branches of the lower six thoracic nerves (T7-T12) and the first lumbar nerve.

The *rectus abdominis* originates from the ventral ends of the fifth, sixth, and seventh costal cartilages and the sternum and runs axially along the whole length of the ventral wall of the abdomen to insert into the pubis. This muscle is thus medial and is enclosed in a sheath formed by the aponeuroses of the three muscles situated laterally. The *obliquus externus* is the most superficial of these three flat muscles. It originates by fleshy digitations from the external surface of the lower eight ribs in the mid-axillary line ; it is, therefore, superficial to the intercostal muscles in the lower half of the rib cage. Its fibres run caudally and ventrally and insert into the iliac crest and the linea alba. The *obliquus internus* lies deep to the obliquus externus. Its fibres arise from the iliac crest and the inguinal ligament, and diverge to insert into the anterolateral surface of the lower three costal cartilages and, by means of an aponeurosis, into the linea alba. The deepest of the muscles of the lateral abdominal wall is the *transversus abdominis*, so called from the direction of its fibres. It arises from the inner surface of the lower six costal cartilages, the lumbar fascia, the iliac crest and the inguinal ligament, runs circumferentially and terminates in an aponeurosis which forms the posterior lamina of the rectus sheath.

These four muscles have important functions as flexors and rotators of the trunk but as respiratory muscles, their main action relates to the inward displacement of the ventral abdominal wall and the rise in intraabdominal pressure that take place when they contract (fig. 1). In this review, I will consider the

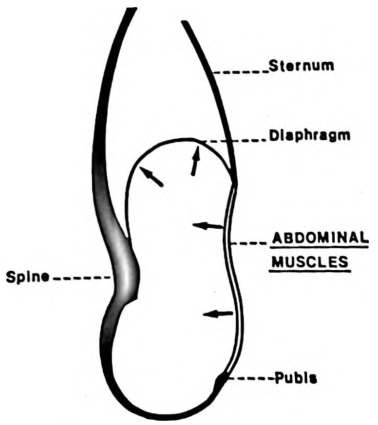


Fig. 1. — Sagittal section illustrating the functional anatomy of the abdominal container.

* Given on June 23, 1983, in Bratislava, Czechoslovakia, at the annual meeting of the SEPCR.

** Chest Service, Erasme University Hospital, 808, route de Lennick, 1070 Brussels, Belgium.

functional implications of this phenomenon 1) on the lung ; 2) on the rib cage ; 3) on the inspiratory muscles.

Action of the abdominal muscles on the lung

From a mechanical standpoint, the abdomen is conventionally thought of as a fluid-filled container. That is, its contents are virtually incompressible, and hence any inward displacement somewhere in the surrounding container must result in an equal outward displacement elsewhere [1]. In fact, many parts of the abdominal container in man are virtually immobile : these are the spine posteriorly, the pelvis caudally, and the iliac crests which nearly meet the rib cage laterally. Hence, the major part of the abdominal container that is mobile and can be displaced during abdominal muscle contraction is the diaphragm (fig. 1). If the diaphragm is relaxed, contraction of the abdominal muscles will thus result in a (passive) cranial displacement of the diaphragmatic dome into the thorax and, thereby, in a decrease in lung volume. In so doing, the abdominal muscles are powerful muscles of expiration and they play important roles in activities such as forced expiration, coughing, and defecation *.

In this connection, it is worth noting the role of the abdominal muscles in posture. This role has been reported by several investigators primarily interested in abdominal muscle electromyograms [5, 10, 17, 26] ; we illustrate it from our own studies in figure 2 [11]. In the supine posture, the abdominal muscles are usually silent in normal man breathing quietly. By contrast, during gradual tilting from supine to standing, a tonic electrical activity, unrelated to the phases of respiration, generally appears in the abdominal muscles, more markedly so in the lower than in the upper abdomen. This tonic activity appears to be related to the antigravitational function of the abdominal muscles : it is removed when the abdomen is immersed in a fluid and the effects of gravity are minimized [10].

The mechanism of this posture-related abdominal muscle activation is still unclear. Experiments in anesthetized rabbits have suggested that stimulation of slowly adapting stretch receptors in the airways by increases in end-expiratory lung volume might, via the vagus nerves, play an important role in eliciting tonic abdominal muscle contraction during head-up tilting [8]. However, vagal reflexes are weak in awake humans compared with anesthetized animals. In addition, it is hard to conceive how reflexes involving airways slowly adapting receptors alone could elicit a greater activation in the dependent (where the hydrostatic pressure is greater) than in the non-dependent portion of the abdominal muscles. Instead, the electrical observations shown in figure 2 suggest that the abdominal muscle activation which occurs in the vast majority of normal individuals when adopting the standing posture depends to a large extent on proprioceptive influences originating from the muscles themselves [11].

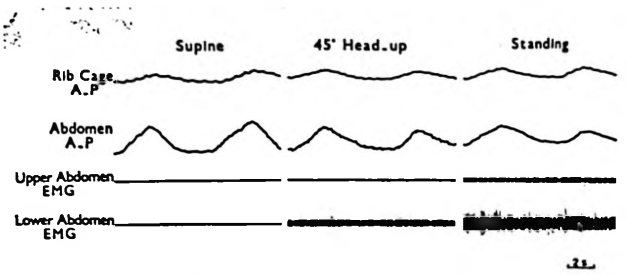


Fig. 2. — Electrical (EMG) activity of the upper and lower portions of the obliquus externus during quiet breathing in a representative normal individual in supine (left), 45° head-up (middle), and standing (right) positions. The changes in rib cage and abdomen anteroposterior (AP) diameters are also shown ; in these two recordings, upward deflections indicate an increase in diameter (inspiration). Reproduced, with permission, from A. De Troyer, *Resp. Physiol.*, 1983, **53**, 341-353.

Irrespective of its mechanism, this posture-related abdominal muscle activation plays a significant role in determining the pattern of thoracoabdominal motion during breathing [11, 22]. Figure 3 illustrates the pattern observed in the absence of any abdominal muscle activity. As can be seen, when the abdominal muscles remain silent, the tidal volume loop is superimposed upon the relaxed thoracoabdominal configuration and the spontaneous end-expiratory volume coincides with the relaxed functional residual capacity (FRC). This is not the case when the standing posture elicits tonic abdominal muscle activity. As illustrated by the representative example shown

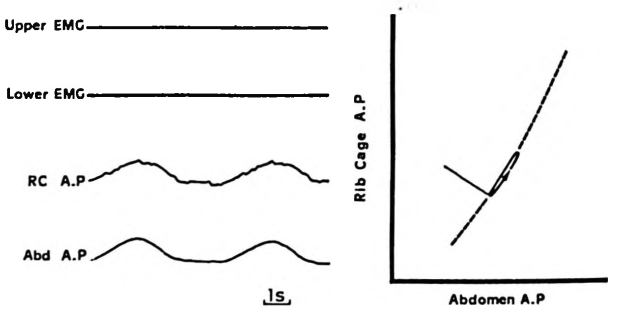


Fig. 3. — Pattern of thoracoabdominal motion during quiet breathing in a normal, trained subject who maintains the abdominal muscles silent in the standing posture. The broken line in the right panel represents the configuration of the thoracoabdominal system during voluntary relaxation, and the thin solid line represents the isovolume line obtained at relaxed FRC. The solid loop represents the tidal volume cycle ; the arrow on the loop marks the inspiratory phase and indicates the direction of the loop. See text for explanation.

* Evidence has been recently obtained in the dog that the pressure swings in the abdominal cavity, in fact, are not necessarily uniform [9]. In particular, during contractions of the abdominal muscles, the rises in intraabdominal pressure were found to be substantially smaller under the diaphragmatic dome than in the stomach or in the intestinal loops. This thus indicates that the amount of peritoneal fluid in which the abdominal viscera are floating is not sufficient to make the abdominal contents behaving as a mass of liquid. As a corollary, the hydraulic coupling between the ventral abdominal wall and the diaphragm is more complex than conventionally thought.

in figure 4, the abdomen is then smaller throughout the breath than during voluntary relaxation and the spontaneous end-expiratory volume, as judged from the isovolume line, is below the relaxed FRC by a volume equal to about 0.5 times the resting tidal volume. This indicates that, due to abdominal muscle contraction, quiet breathing does not occur on the chest wall relaxation characteristic in most normal humans standing at rest, and the end-expiratory lung volume is at least in part actively determined and maintained below the neutral position of the respiratory system. Otherwise stated : the majority of normal individuals recruit their abdominal muscles and thereby reduce the volume of the abdominal compartment of the respiratory system so as to minimize the increase in end-expiratory lung volume which normally occurs when adopting the standing posture.

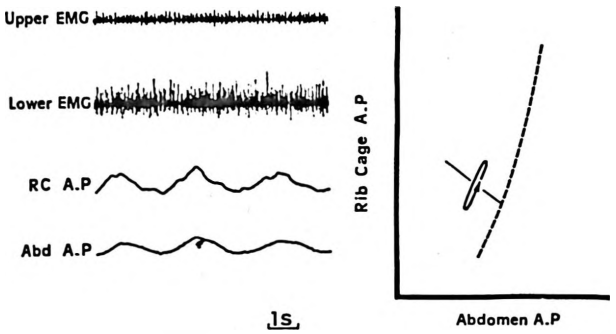


Fig. 4. — Pattern of thoracoabdominal motion during quiet breathing in a subject who has tonic abdominal muscle activity in the standing posture. Same legend as in figure 3. Note that the subject is here breathing to the left of the relaxed thoracoabdominal configuration (the abdomen is smaller) and that the spontaneous end-expiratory level is below the relaxed FRC. Reproduced, with permission, from A. De Troyer, *Resp. Physiol.*, 1983, **53**, 341-353.

The rise in intraabdominal pressure and the accompanying cranial displacement of the diaphragm that take place during abdominal muscle contraction account not only for most of the expiratory action of these muscles on the lung : this phenomenon also plays a predominant role in determining how these muscles act on the rib cage.

Action of the abdominal muscles on the rib cage

To the extent that the four muscles of the anterolateral wall of the abdomen insert cranially into the rib cage and caudally into the pubis and the iliac crests, one would anticipate that they all act to pull down the ventral portion of the rib cage (fig. 1). Because of the pump-and bucket-handle mobility of the ribs, one would, therefore, expect that they all tend to deflate the rib cage. Recent studies indicate, however, that any of a spectrum of changes in rib cage dimensions can be observed depending on the muscle stimulated [12].

These experiments were done on supine, deeply anesthetized dogs made apneic by mechanical hyperventilation, and the four muscles of the anterolateral wall of the abdomen were separately stimulated at FRC by implanted electrodes. The results are illustrated in figure 5. Tetanic stimulation of the rectus abdominis always resulted in a decrease in lung volume, a rise in abdominal (gastric) pressure, and a reduction in both the anteroposterior and the transverse diameter of the lower rib cage. On the other hand, the other muscles of the abdominal wall, while also producing a fall in lung volume and a rise in abdominal pressure, did not deflate the rib cage. Stimulation of the obliquus internus and stimulation of the transversus abdominis (not shown in the figure) did not cause any noticeable change in rib cage diameters, and stimulation of the obliquus externus always caused an expansion, not a contraction, of the rib cage along its anteroposterior and transverse diameters. When the animal was eviscerated or had the abdomen open so that abdominal pressure could no longer rise, each of the abdominal muscles, including the obliquus externus, was expiratory for the rib cage, causing a decrease in its anteroposterior and transverse diameters. The axial displacements of the sternum and the ribs observed in these experiments were consistent with the changes in rib cage diameters, being caudal in direction when the rib cage was deflating and cranial when the rib cage was expanding [12].

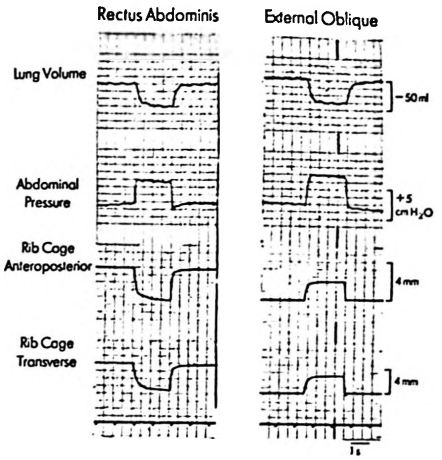


Fig. 5. — Effect of bilaterally stimulating the canine rectus abdominis (left) and obliquus externus (right) on the anteroposterior and transverse diameters of the lower rib cage. The changes in rib cage diameters were measured by small hooks screwed into the sternum and the 7th or 8th rib in the midaxillary line, respectively, and connected by inextensible threads to linear displacement transducers. In the present records, upward deflections indicate an increase in rib cage diameter, and downward deflections the reverse. Reproduced, with permission from A. De Troyer *et al.*, *J. appl. Physiol. : Resp. environm. Exercise Physiol.*, 1983, **54**, 465-469.

From these experiments, the conclusion thus emerges quite clearly that the abdominal muscles have two opposing effects on the lower rib cage when they contract. On the one hand, in relation to their anatomic attachments, they all tend to pull down the lower ribs and hence they all tend to deflate the rib cage. After evisceration or when the abdomen is widely open to atmosphere, this insertional, expira-

tory force is the only acting component. On the other hand, these muscles have an inspiratory action on the rib cage which adds to the effect of the rise in pleural pressure and is removed by evisceration or opening of the abdomen. Most clearly, this inspiratory action of the abdominal muscles on the rib cage is primarily related to the rise in abdominal pressure that takes place when they contract.

There are at least two mechanisms by which the rise in abdominal pressure can expand the lower rib cage during abdominal muscle contraction (fig. 6). First, there is a large zone where the diaphragm is

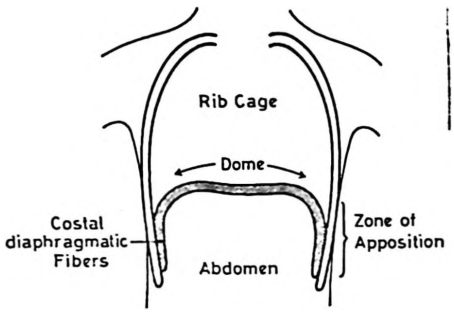


Fig. 6. — Frontal section of the respiratory system, illustrating the zone of apposition of the diaphragm to the rib cage and the orientation of costal diaphragmatic fibers. During abdominal muscle contraction, the rise in abdominal pressure acts through the zone of apposition and causes passive distention of the diaphragm. By these two mechanisms, abdominal pressure tends to inflate the lower rib cage during abdominal muscle contraction.

directly apposed to the inner aspect of the lower rib cage [24]. This zone of apposition represents about 30 percent of the total rib cage surface area at FRC and allows abdominal pressure to be transmitted, though perhaps incompletely, to the lower rib cage. By acting over that zone, the rise in abdominal pressure that occurs when the abdominal muscles contract will thus be expected to have an inflating action on the lower rib cage [14, 24]. Second, the costal diaphragmatic fibres are inserted into the lower ribs and are directed cranially, parallel to the rib cage axis (fig. 6). Consequently, they must exert a force which tends to lift the lower ribs and hence expand the lower rib cage whenever they come under tension [13, 14]. To the extent that the rise in abdominal pressure is associated with a cephalic displacement of the diaphragm, contraction of the abdominal muscles thus causes passive tension within the diaphragmatic muscle fibres and thereby opposes the expiratory force that these muscles exert on the ribs by way of their insertions [12]. In the intact animal, therefore, the net action of the abdominal muscles on the rib cage depends on the balance between the insertional force, that tends to deflate the rib cage, and the rise in abdominal pressure which, operating by way of the zone of apposition and passive distention of the diaphragm, tends to inflate the lower rib cage.

The reason why the different muscles of the abdominal wall displace the rib cage differently is probably related to their anatomy. These muscles all cause a rise in abdominal pressure when they contract. Consequently, for a given rise in abdominal pressure, the inspiratory force they exert on the rib cage is presumably equal. One must conclude, therefore, that the differences in rib cage displacements produced by the different muscles result from differences in insertional force, and these appear to be largely attributable to differences in fibre orientation and site of rib cage attachment [12]. To the extent that the ribs move primarily through a rotation around the axis defined by the ribs' articulations with the vertebral bodies and the transverse processes [20, 21], the insertional force of the abdominal muscles will depend upon three variables : tension in the muscle fibres, orientation of the muscle fibres, and distance between the site of muscle insertion on the ribs and the axis of rotation of the ribs (fig. 7). Clearly, for a given muscle tension, the vector acting on the lower ribs, tending to lower them, is greater when the muscle fibres are oriented more axially and when the costal insertions of the muscle are more distant from the axis of rotation of the ribs (fig. 7).

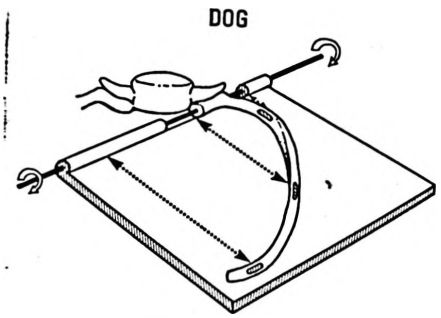


Fig. 7. — Diagram illustrating how the site of muscle insertion on the ribs may be a major determinant of the action of the abdominal muscles on the rib cage. Due to the shape of the canine rib cage, a muscle that inserts into the ventral end of the ribs will be more distant from the axis of rotation of the ribs. As a result, it will have a greater tendency to lower the ribs (to deflate the rib cage) than a muscle similarly oriented but inserted into the medial portion of the ribs.

Both of these conditions hold in the case of the rectus abdominis and, on this basis, one can understand why the insertional force of this muscle prevails over the effect of abdominal pressure when it contracts alone. The insertional force of the obliquus internus and that of the transversus abdominis must be smaller since their muscle fibres insert more closely to the axis of rotation of the ribs and run obliquely (obliquus internus) or circumferentially (transversus). It is conceivable, therefore, that abdominal pressure counterbalances the insertional force of these muscles. That abdominal pressure may have the mechanical advantage over the insertional force of the canine obliquus externus in its action on the rib cage is equally conceivable since, among the muscles of the abdominal wall, this muscle has the closest costal insertions relative to the axis of rotation of the ribs. It is obvious that, if one abdominal muscle were to insert on the neck of the ribs and to run circumferentially, its insertional force would be nil and the muscle would have a pure inspiratory action on the rib cage. Such a muscle, however, does not exist, at least in mammals.

Whether or not the different abdominal muscles displace the rib cage in humans as they do in the dog remains unknown. Undoubtedly, abdominal muscle action on the rib cage in man will obey the same principle ; that is, it will depend on the balance between the muscle's insertional force and the rise in abdominal pressure. Also, the sites of rib cage attachments and fibre orientations of the abdominal muscles are closely similar in the two species, thus suggesting that the different muscles displace differently the human rib cage as well. However, that isolated contraction of the obliqui externi expands the rib cage in man is not obvious at all, since this depends upon the effectiveness of abdominal pressure in inflating the rib cage which, in turn, depends among other things upon the stability of the rib cage. The greater stability of the human rib cage, although not sufficient to ensure a unitary behaviour [2, 7, 25], would thus be anticipated to make abdominal pressure less effective and thereby the obliqui externi less susceptible to expand the rib cage. In addition, the rib cage shape in man substantially differs from that in small animals. Although not previously considered [12], this factor may in fact be of crucial importance in relation to the action of the abdominal muscles on the rib cage. In the dog as in many animal species, the rib cage at FRC is smaller in its transverse than in its dorso-ventral dimension, while in normal man the opposite is true (fig. 8). This implies that the costal insertions of the obliquus externus in man may be more, not less, distant from the axis of rotation of the ribs than those of the rectus and the transversus abdominis. It may well be, therefore, that the insertional force of the obliquus externus in man is greater than that of the transversus abdominis and, consequently, that the human rib cage deflates least during contraction of this latter muscle. This prediction, however, has yet to be tested.

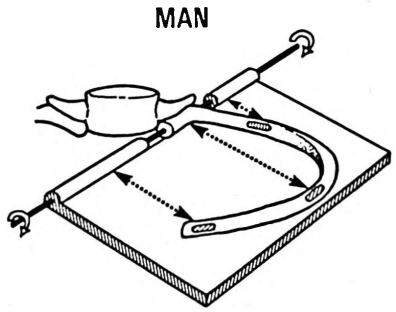


Fig. 8. — Diagram illustrating the difference in shape between the human and the canine rib cage (compare with fig. 7). Due to the particular shape of the human rib cage, a muscle that inserts into the ventral end of the ribs may be less, not more, distant from the axis of rotation of the ribs than a muscle inserted into the medial portion of the ribs. Its insertional force, accordingly, may be smaller.

Action of the abdominal muscles on the inspiratory muscles

Even though the abdominal muscles are expiratory to the lungs, they may play an important role in inspiration as well. This is particularly true when hyperpnea is induced by exercise or CO_2 rebreathing [19] and during breathing against inspiratory mechanical loads [23]. Under these circumstances, the coordinated use of abdominal muscles appears indeed to be organized to facilitate inspiration.

There are several mechanisms by which facilitation of inspiration may take place. The first is the coordinated use of abdominal and other expiratory muscles to increase expiratory airflow and prolong expiration so as to reduce end-expiratory lung volume. By initiating inspiration from a lower volume, the elastic recoil of the respiratory system contributes to the inspiratory work of breathing and a portion of the work of the inspiratory muscles is thus taken on by the expiratory muscles. The second mechanism of facilitation results from the elongation of the diaphragm by abdominal muscle contraction. Since the abdominal muscles displace the diaphragm into the thorax when they contract (fig. 1), they indeed lengthen its muscle fibres and place them on a more advantageous portion of their length-tension curve [18]. By contracting during expiration, the abdominal muscles thus make the subsequent inspiration to start at a longer length of the diaphragm so that its ability to generate pressure is increased. To the extent that the contraction of the diaphragm is coordinated with the relaxation of the abdominal muscles early in inspiration, the excursion of abdominal pressure is minimized despite rapid and substantial outward movement of the abdominal wall. It is remarkable that, during exercise or CO_2 induced hyperventilation, such a phasic expiratory activation of the abdominal muscles enables the abdominal diameter and, with it, the diaphragmatic length at end-inspiration to remain fairly constant regardless of the level of ventilation [19]. On this basis, the abdominal muscles can be considered as accessory muscles of inspiration.

The abdominal muscles improve not only the ability of the diaphragm to generate pressure, but also its ability to expand the rib cage. Understanding this interaction between the abdominal muscles and the diaphragm requires clear understanding of how the diaphragm functions and how it displaces the rib cage when it contracts.

In relation to its function, the human diaphragm can be considered as an elliptical cylindroid capped by a dome (fig. 6). The cylindrical portion of the diaphragm corresponds to the portion directly apposed to the inner aspect of the lower rib cage (zone of apposition). The dome of the diaphragm corresponds mainly to the central tendon. Its shape and size are relatively constant during breathing [4] and, because it has no direct attachment to any solid structure, its motion mainly depends upon the relative resistance to motion of the abdominal contents and the lower ribs. When the diaphragmatic muscle fibres shorten during inspiration, the axial length of the apposed portion diminishes and the dome of the diaphragm descends relative to its costal insertions. The most important change in diaphragmatic shape, the one responsible for most of the volume displacement, is thus a piston-like axial displacement of the

diaphragmatic dome related to the shortening of the axial length of the apposed diaphragm. This phenomenon has three major consequences : 1) it decreases the intrathoracic pressure and, depending on whether the airways are open or closed, it increases lung volume or decreases the alveolar pressure ; 2) it pushes the abdominal contents caudally, causes a rise in intraabdominal pressure and expands the ventral abdominal wall ; and 3) it displaces the rib cage.

There are three forces acting on the rib cage when the diaphragm contracts alone (fig. 9). The first is related to the decrease in pleural pressure associated with the descent of the diaphragmatic dome ; this force tends to reduce the rib cage size. The second force by which the diaphragm displaces the rib cage is related to the rise in abdominal pressure [13, 14].

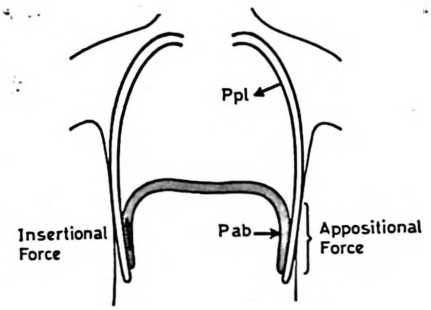


Fig. 9. — Frontal section of the respiratory system illustrating the three forces through which the diaphragm acts on the rib cage. See text for explanation.

The rise in abdominal pressure that takes place when the diaphragm contracts acts over the zone of apposition and thereby exerts an inflating action on the lower rib cage (« appositional » force) in the same way that it does when the abdominal muscles contract (see above). The third force which enables the diaphragm to displace the rib cage relates to its costal insertions (« insertional » force) [13, 14]. Since the costal diaphragmatic fibres insert into the lower ribs and are directed cranially, parallel to the rib cage axis, their contraction must exert a force that tends to elevate the lower ribs and hence move them outward. This insertional force clearly depends on solid structures which can resist displacement and thereby provide a resistance to diaphragmatic descent. Early work in this controversial area has focused on the nature of these solid structures which enable the diaphragm to expand the rib cage by way of its insertions. BEAU and MAISSIAT [3] believed that restraining of the diaphragmatic dome by the pericardium was sufficient to produce this effect. On the other hand, MAGENDIE and DUCHENNE [15] concluded that the abdominal viscera provided the solid « fulcrum » against which the contracting diaphragm pushed to elevate the ribs. This latter mechanism has since been convincingly confirmed. DE TROYER *et al.* [14] have demonstrated in the dog that removing the abdominal viscera from the abdominal cavity indeed caused the diaphragm to contract, rather than to expand, the lower rib cage, whereas sectioning the pericardial attachments of the diaphragmatic dome did not affect the rib cage expanding action of the diaphragm. In addition, D'ANGELO and SANT'AMBROGIO [6] have reported that the rib cage deflating action of the diaphragm seen in eviscerated rabbits was reversed into an expanding one when the diaphragmatic dome was prevented from descending by mechanical means. This thus clearly indicates that the abdominal contents provide the solid fulcrum through which the diaphragmatic insertions on the ribs can operate to elevate the lower ribs.

For anatomical reasons, it is obvious that the appositional and insertional forces developed by the diaphragm do not apply, or only to a limited extent, to the upper portion of the rib cage. Consequently, the upper rib cage is mainly driven by the fall in pleural pressure and when the intercostal muscles are inactive, as in tetraplegic subjects, it moves paradoxically inward during inspiration [7, 25]. By contrast, the action of the diaphragm on the lower rib cage will depend upon the balance between the fall in pleural pressure, which tends to deflate the rib cage, and the appositional and insertional forces, which both tend to expand the rib cage. To the extent that the magnitude of these two rib cage expanding forces depends upon the effectiveness with which the abdominal fulcrum opposes the descent of the diaphragmatic dome, the lower rib cage displacement associated with a given diaphragmatic contraction will be determined by the compliance of the abdominal compartment. Clearly, if the abdomen is very compliant, the dome of the diaphragm descends easily during inspiration and, at the same time, abdominal pressure rises little. Under those circumstances, the insertional and appositional forces are small and barely compensate for the effect of pleural pressure in its action on the lower rib cage. Hence, the lower rib cage expands little, if any. Conversely, if the abdominal muscles contract so as to markedly reduce abdominal compliance and fix the diaphragmatic dome, then shortening of the apposed diaphragmatic muscle fibres has a greater tendency to lift the lower ribs (greater insertional force) and is associated with a greater rise in abdominal pressure (greater appositional force). As a result, the rib cage expanding action of the diaphragm is increased.

A dramatic example of this action of the abdominal muscles is provided by tetraplegic subjects given an external abdominal compression. In such subjects, in whom the abdominal muscles are paralysed and the diaphragm is the only muscle active during quiet inspiration, quiet breathing in the seated posture does not occur on the chest wall relaxation characteristic. The upper rib cage moves paradoxically inward during inspiration and the abdominal expansion predominates over the lower rib cage expansion relative to the relaxed thoracoabdominal configuration [7, 25]. These distortions are markedly reduced with a passive, mechanical support to the abdomen [7]. Exerting a pressure on the abdomen via a pneumatic cuff or an elastic binder (so as to mimic tonic abdominal muscle contraction) indeed aids the diaphragm in expanding the lower rib cage and causes the chest wall tidal volume loop to be closer to the relaxed thoracoabdominal configuration, presu-

mably minimizing the elastic work of breathing. So, in a very real sense, the abdominal muscles can be considered as accessory muscles of inspiration.

Summary

The abdominal muscles, by causing a rise in abdominal pressure and a cranial displacement of the diaphragm,

1 — deflate the lungs (minimize the increase in FRC which normally occurs when adopting the standing posture),

2 — exert an expanding force on the lower rib cage, which may counterbalance or even dominate the insertional (expiratory) force they exert on the lower ribs by way of their insertions,

3 — improve the pressure-generating ability of the diaphragm. In addition, because they prevent the diaphragmatic dome from descending during inspiration, they also improve the rib cage expanding action of the diaphragm.

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