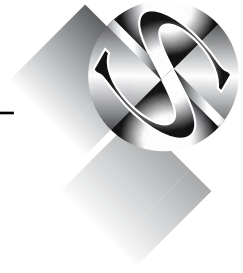# 4

The Anatomy and Physiology of the Diaphragm

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Aims

To describe development, anatomy and physiology of the diaphragm.

Anatomy

The Shape of the Diaphragm

The diaphragm is a musculo-fibrous sheet separating the thorax and the abdomen. It takes the shape of an elliptical cylindroid capped with a dome [1]. This short description of the shape of the diaphragm is not adequate to explain the way in which the structure and function are related, and a further expansion of this description is necessary. The use of the word dome in itself introduces a degree of inaccuracy, as it gives the impression that there is a curved structure rising equally from the sides to a central point, whereas a more accurate description is of a pair of cupolas either side of a central plateau.

This elliptical shape is determined by the thoracic outlet, which will also have an influence upon the function of the diaphragm, as it will determine the anatomical structure of it. This is because the thoracic outlet is set obliquely to the coronal plane, being superior anteriorly and inferior posteriorly.

The skeletal attachments of the diaphragm to the thoracic outlet commence at the xiphoid process and symphysis centrally, and, moving laterally, the ventral ends and costal cartilages of the seventh to twelfth ribs, the transverse processes of the first lumbar vertebra, and the bodies and symphyses of the first three lumbar vertebrae. As the periphery of the diaphragm is attached to the thoracic outlet anteriorly and laterally, and beyond it posteriorly, it will follow that the anterior portion of the diaphragm will be shorter than the lateral and posterior parts.

The presence of the viscera in the thorax and abdomen causes the part of the diaphragm separating them to be roughly horizontal, but will determine the shape of the unstressed dome. This may be considered as a separate zone from the other part of the diaphragm, and will be referred to as the diaphragmatic zone. The other part of the diaphragm will be referred to as the apposition zone, because it assumes a roughly vertical direction. It is also the area through which the rib cage is apposed to the abdominal contents and thus exposed to abdominal pressure (see below).

Diaphragmatic Attachments

The sternal part is attached by two slips to the back of the xiphoid process, although these slips may be absent (Figure 4.1). The costal part is attached to the internal surfaces of the lower six costal cartilages and their adjoining ribs, the vertical fibres of the diaphragm interdigitating with the horizontal fibres from the transversi abdominis. The lumbar part is attached to the aponeurotic medial and lateral arcuate
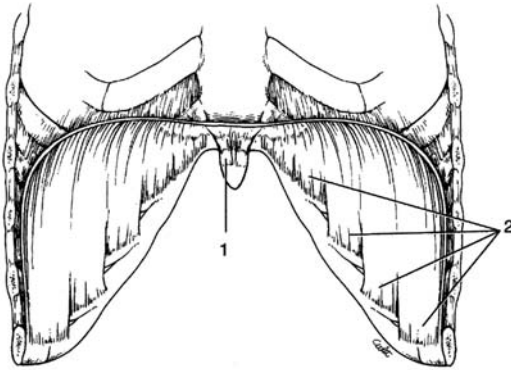
Figure 4.1. The inner anterior surface of the diaphragm. (Reproduced with permission from Gluzel P, Similowski T, Chartrand-Lefebvre C et al. Diaphragm and chest wall: assessment of the inspiratory pump with MR imaging – preliminary observations. Radiology 2000;215:574–83. Copyright Radiological Sciety of North America.)

ligaments (lumbocostal arches) and to the upper three lumbar vertebrae by crura. The sternocostal and lumbar portions are distinct developmentally and in 80% of the population are separated by a hiatus in the muscular sheet – the vertebrocostal trigone. This gap lies above the twelfth rib so that the upper pole of the kidney is separated from the pleura by loose areolar tissue only.

The lateral arcuate ligament is a thickened band in the fascia of quadratus lumborum, which arches across the muscle and is attached medially to the front of the first transverse process and laterally to the inferior margin of the twelfth near its midpoint.

The medial arcuate ligament is a thickened band in the fascia covering psoas major. Medially it blends with the lateral tendinous margin of the corresponding crus and is thus attached to the side of the first or second lumbar vertebrae. Laterally it is attached to the front of the first lumbar transverse process at the lateral margin of psoas. The arcuate ligaments allow the contraction of quadratus lumborum and psoas to occur without interfering with diaphragmatic activity.

The crura are tendinous at their attachments, blending with the anterior longitudinal vertebral ligament. The right crus is broader and longer and arises from the anterolateral aspect of the bodies and discs of the first three lumbar vertebrae, the left crus from the corresponding

parts of the upper two. As with the anterior longitudinal ligament, the main area of attachment is at the level of the intervertebral discs and the adjacent margins of the vertebral bodies. Between these attachments the upper lumbar arteries separate the fibres from the bodies of the vertebrae. The fibres ascend and run anteriorly to cross the aorta in a median arch, where the tendinous margins converge to form the median arcuate ligament. This ligament is often poorly defined, but when it occurs it is at the level of the thoracolumbar disc.

The fibres of the crura continue in their passage anteriorly and superiorly, but divide into medial and lateral bundles. The lateral fibres continue laterally to reach the central tendon. The medial fibres from the right crus ascend to the left of the oesophageal opening. Sometimes a muscular fasciculus from the medial side of the left crus crosses the aorta and runs obliquely through the fibres of the right crus towards the vena caval opening but does not approach the oesophageal opening. The right margin of the oesophageal opening is covered by the deeper medial right crural fibres. From part of the right crus near the oesophageal opening originates the suspensory muscle of the duodenum, which goes to connective tissue near the coeliac artery. Here it joins with a fibromuscular band of non-striated muscle originating along the third and fourth parts of the duodenum and the duodenojejunal flexure. The exact nature and function of this muscle has been the subject of discussion over many years, and will not be considered here.

The Central Tendon of the Diaphragm

All the muscular fibres converge upon the central tendon of the diaphragm (Figure 4.2). The central tendon is a thin, strong aponeurosis of interwoven collagen fibres, with its anterior margin closer to the front of the diaphragm. This results in the longer fibres being lateral and posterior. The longest fibres of the diaphragm arise from the ninth costal cartilage.

Embryology

The diaphragm develops from four main structures, the septum transversum, the pleuroperi-
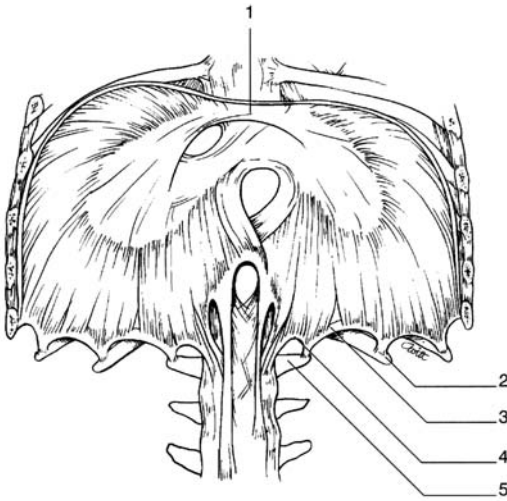
Figure 4.2. Inner posterior aspect of the diaphragm. 1, The central tendon. 2, Attachment of lateral arcuate ligament to end of the twelfth rib. 3, Lateral arcuate ligament. 4, Medial arcuate ligament. 5, Transverse process first lumbar vertebra. (Reproduced with permission from Gluzel P, Similowski T, Chartrand-Lefebvre C et al. Diaphragm and chest wall: assessment of the inspiratory pump with MR imaging – preliminary observations. Radiology 2000;215:574–83. Copyright Radiological Sciety of North America.)

toneal membranes, the dorsal oesophageal mesentery and the body wall.

The septum transversum forms the bulk of the diaphragm, namely the central tendon and the majority of centrally placed muscle. It starts off as a plate of mesoderm developing at the end of the fourth week of gestation in a position between the heart and the yolk sac. At this time the headfold and tailfolds form, and the heart and pericardial cavities move ventrally below the foregut. They open dorsally into the pericardioperitoneal canals, which lie above the septum transversum on each side of the foregut connecting the thoracic and abdominal portions of the intraembryonic coelom.

The septum transversum is initially at the level of the second cervical segment, but with the growth of the embryo it moves in a caudal direction, and at the level of the fourth cervical segment it receives the phrenic nerve and cells destined to differentiate into muscular tissue from the corresponding myotomes. It migrates caudally during flexion and comes to lie at the level of the junction between the thoracic and lumbar segments. At this site it forms a ventral

mass of tissue which then extends dorsally and medially towards the dorsal body wall, to meet the dorsal mesentery of the foregut. As it grows it leaves two dorsolateral gaps, which are the orifices of the pleuroperitoneal canals.

The pleuroperitoneal membranes are a pair of membranes which gradually separate the pleural and peritoneal cavities. They are attached dorsolaterally to the body wall with their free edge projecting into the caudal end of the pericardioperitoneal canals. At about the sixth week of gestation they grow medially and ventrally away from the body wall towards the septum transversum. By the end of that week they have come to fuse with the dorsal mesentery of the oesophagus and the septum transversum to separate the pleural and peritoneal cavities. The closure of the openings is further enhanced by the growth of the liver and muscle tissue extension into the membranes. The right pleuroperitoneal canal closes before the left one, the latter being the more common site of persistent communication between the pleural and peritoneal cavities. The pleuroperitoneal membranes are believed only to produce a small dorsolateral part of the diaphragm in adult life.

The dorsal mesentery of the oesophagus fuses with both the septum transversum and the pleuroperitoneal membranes. This mesentery forms the medial portion of the diaphragm. The crura of the diaphragm develop from muscle fibres that grow into the oesophageal mesentery.

The contribution of the muscular body wall to the diaphragm is the result of the expansion of the pleural cavities between the ninth and twelfth weeks of gestation. To expand, the pleural cavities extend into the mesoderm dorsal to the suprarenal glands, the gonads and the mesonephric ridges, causing somatopleuric mesoderm to be peeled away from the dorsal body wall to form a substantial area of the dorsolumbar part of the diaphragm. As a result of the extension of the pleural cavities into the body wall, the costodiaphragmatic recesses are formed.

It is described variously as trifoliate, trefoil or like the club in a pack of cards, the three parts being partly separated by slight indentations. This description does not seem to agree with the pictures that are reproduced in many textbooks, which make it look far more like a boomerang. There is a middle part, which is an equilateral triangle, its apex towards the xiphoid process.

This central area is beneath and partly blended with the pericardium above, and relates to the triangular ligament of the liver in the abdomen. The right and left parts posteriorly are longer and linguiform, curving posterolaterally, the left being the narrower. These are related to the parietal pleura above and the peritoneum below. In the central area can be recognised four diagonal bands, which expand from a thick node where decussation of compressed tendinous strands occurs in front of the oesophageal aperture and left of the vena caval opening.

The Diaphragmatic Apertures

As the diaphragm separates the abdominal and thoracic cavities, there are several structures which will either pass through it, or between it and the body wall including blood vessels, nerves and the oesophagus. There are various apertures to allow the passage of these, three of which are large and constant, and various others which are smaller and sometimes variable.

The aortic opening, the most inferior and posterior, lies at the level of the lower border of the twelfth thoracic vertebra and the thoracolumbar intervertebral disc, slightly to the left of the midline. This is not a true opening, rather it is a vertical osseo-aponeurotic and symphysio-aponeurotic channel between the crura laterally and the vertebral column posteriorly and the diaphragm anteriorly. Therefore it is actually behind the diaphragm or the median arcuate ligament. On occasions there are some tendinous crural fibres which pass behind the aorta, forming a fibrous ring. It transmits the aorta. Along with the aorta, generally to the right of the midline, runs the thoracic duct, posterolateral to which are the azygos vein on the right, and the hemi-azygos vein on the left. Sometimes the azygos and hemi-azygos veins will pass through the right and left crus respectively. Lymphatic trunks also descend through the opening from the lower posterior thoracic wall.

The oesophageal aperture is elliptical and lies at the level of the tenth thoracic vertebra, where its long axis lies obliquely, ascending to the left of the midline in the muscular part of the right crus which has by now crossed over the midline. Its lower end lies anterosuperior to the aortic opening, its upper end being further anterosuperior and a short distance to the left. It transmits the oesophagus, the trunks of the vagus nerves, and the oesophageal branches of the left gastric vessels and lymphatic vessels.

The muscle of the oesophageal wall and the diaphragm remain separate. However, the inferior diaphragmatic fascia, which is a thin areolar stratum rich in elastic fibres, lying between the diaphragm and the peritoneum, and continuous with the transversalis fascia, ascends through the opening. It does so like a flattened cone to blend with the oesophageal wall about 2 cm above the gastro-oesophageal junction. Some of the elastic fibres penetrate to the submucosa. This fascial expansion, which forms the phreno-oesophageal ligament, connects the oesophagus and the diaphragm in a flexible manner which allows some freedom of movement during breathing and swallowing.

The vena caval aperture is the highest of the three, and lies approximately at the level of the disc between the eighth and ninth thoracic vertebrae. It is quadrilateral and sited within the central tendon, at the junction of its right leaf with the central area. Therefore the margin is aponeurotic, to which the vena cava is adherent as it traverses the opening. With it run branches of the right phrenic nerve. The left phrenic nerve runs off the pericardium to pierce the muscular part of the diaphragm in the form of the left limb of the central tendon.

There are various minor apertures. Two lesser apertures in each crus transmit the greater and lesser splanchnic nerves. The ganglionated sympathetic trunks run from the thorax to the abdomen behind the medial end of the medial arcuate ligament. Posterior to the lateral arcuate ligament runs the subcostal nerve.

Between the sternal and costal margins of the diaphragm run the superior epigastric arteries and veins, prior to entering the rectus sheath, along with lymph vessels from the abdominal wall and liver. Similarly the musculophrenic artery and vein run between the attachments of the diaphragm to the seventh and eighth costal cartilages. The neurovascular bundles of the seventh to eleventh intercostal spaces pass between the digitations of transversus abdominis with the diaphragm into the neurovascular plane of the abdominal wall.

Extraperitoneal lymph vessels on the abdominal surface pass through the diaphragm to nodes lying on its thoracic surface, mainly in the posterior mediastinum. Finally, openings for small veins are frequent in the central tendon.

Nerve Supply

The diaphragm receives its nerve supply predominantly from the phrenic nerve. This arises mainly from the ventral root of the fourth cervical nerve, with contributions from the third and fifth cervical nerve roots. The intrathoracic course of these nerves will not be discussed here.

The right phrenic nerve reaches the diaphragm just lateral to the inferior vena cava (IVC). The left phrenic nerve joins the diaphragm just lateral to the border of the heart, in a slightly more anterior plane than the right phrenic nerve. The nerves divide at the level of the diaphragm, or just above it into several terminal branches, the right being the mirror of the left. Apart from small twigs to the serosa of the diaphragm, there are three main branches: a sternal or anterior branch, an anterolateral branch and a posterior branch which divides into a posterolateral branch and a crural branch that runs posteromedially to the region of the crus. They are usually deep within the muscle rather than lying exposed on the undersurface of the diaphragm [2,3].

The phrenic nerve provides the only motor supply to the diaphragm. The crural motor supply comes solely from the phrenic nerve, but all crural fibres (regardless of the side of origin) right or left of the oesophageal opening are supplied by the ipsilateral phrenic nerve. The phrenic nerve also supplies the majority of sensory fibres including muscle spindles [4]. There are some sensory fibres to the diaphragm from the lower six or seven intercostal nerves in the area where the diaphragm is attached to the ribs.

Blood Supply

The arterial supply varies above and below the diaphragm. The superior surface is supplied by the musculophrenic, pericardiacophrenic and superior epigastric arteries, all of which are branches of the internal thoracic mammary artery, and the phrenic branches of the lower thoracic aorta. There is also a supply from the lower five intercostal and subcostal arteries. The inferior surface is supplied by the inferior phrenic arteries, which are branches of the abdominal aorta, although sometimes they may be derivatives of the coeliac trunk.

The venous drainage mirrors the blood supply. The superior surface drains through the pericardiacophrenic veins, musculophrenic veins and superior epigastric veins which all drain into the internal thoracic vein. The inferior surface of the diaphragm drains through the inferior phrenic veins. The right drains to the IVC. The left is often double, the anterior branch going to the IVC, the posterior branch to the left renal vein or left suprarenal vein. The two veins may anastomose with each other.

Lymphatic Drainage

The diaphragmatic lymph nodes on the thoracic surface of the diaphragm form three groups. An anterior group comprises two or three small nodes posterior to the base of the xiphoid process draining the convex hepatic surface, and one or two nodes on each side near the junction of the seventh rib and cartilage which receive anterior lymph vessels from the diaphragm and drain to the parasternal nodes.

A lateral group on each half of the diaphragm comprises two or three nodes, close to the site at which the phrenic nerves enter the diaphragm, and on the right some of the nodes may lie anterior to the intrathoracic end of the IVC within the pericardium. They receive afferents from the central diaphragm (bilateral) and from the convex surface of the liver (right side), and send efferents to the parasternal, posterior mediastinal nodes, and brachiocephalic nodes.

A posterior group consists of a small number of nodes on the back of the crura, connected with the lateral aortic and the posterior mediastinal nodes.

Lymph Vessels of the Diaphragm

An extensive lymph plexus is present in each surface of the diaphragm, and the two plexuses are united by numerous vessels that pierce the diaphragm. The thoracic plexus unites with vessels of the mediastinal and costal pleura. Anterior efferents pass to the anterior diaphragmatic nodes near the junction of the seventh ribs and cartilages, the middle efferents to nodes on the oesophagus and around the inferior vena cava, and posterior efferents to nodes around the aorta as it leaves the thorax. The abdominal plexus anastomoses with hepatic lymphatics and with subperitoneal tissue peripherally.

Efferents on the right end up either in a group of nodes on the inferior phrenic artery or in the right lateral aortic nodes. Efferents on the right go to preaortic nodes, lateral aortic nodes and nodes at the lower end of the oesophagus.

Relations of the Diaphragm

Superiorly the diaphragm is associated with serous membranes. On either side is the pleura, which separates the diaphragm from the lung bases, and in the middle is pericardium separating it from the heart. The middle part of the central tendon is slightly lower, flatter and more horizontal than the other parts, which form rounded cupolas. The inferior surface is covered with peritoneum, that of the right cupola being in contact with the convex right lobe of the liver, the right kidney and suprarenal gland. The peritoneum of the left cupola is in contact with the left lobe of the liver, the gastric fundus, the spleen, left kidney and adrenal gland.

Physiology

The main function of the diaphragm is ventilation, but there is also a non-ventilatory role of the diaphragm. This will be considered at the end of this section. Prior to that, this section will concentrate upon the ventilatory function of the diaphragm, looking at three different areas, firstly the elastic properties of the diaphragm, then the effects of contraction, followed by an examination of the importance of relaxation in maintaining normal ventilation.

Elastic Properties of the Diaphragm

As the diaphragm is a composite structure the elasticity will vary with the type of tissue. The collagenous central tendon is relatively inelastic. The muscular component will vary in its elasticity dependent upon the state of expansion of the chest wall, as this will have an impact upon the resting length of the muscle groups.

Muscle is composed of a contractile component, and an elastic component. The elastic component can be divided into a series component and a parallel component. Elasticity of resting muscle is usually described in terms of its tensile properties, characterised by mea-surements of relationships between tension and muscle elongation. This relationship is non-linear, as a result of the muscle becoming stiffer as it is stretched, and is believed to represent a recruitment phenomenon within the muscle; that is, as the muscle is stretched, fibrous elements that are unstressed at low extension are progressively recruited, contributing their elasticity in parallel with increasing extension [5].

The collagenous central tendon is less extensible than the muscle. Collagen has a high modulus of elasticity, such that a high stress is necessary for a small amount of extension. It is believed that the central tendon has a function similar to that of a normal muscular tendon, namely transmitting the stress generated by the muscle, and allowing this to be converted into movement.

Contraction of the Diaphragm

During quiet breathing, the zone of apposition represents one-quarter to one-third of the total surface of the rib cage. In an average human in the upright position the axial extent of the zone of apposition from costal insertion to the diaphragmatic reflection increases from nearly 0 to 5 cm as the lung volume is reduced from total lung capacity to functional residual capacity, and increased further to 10 cm at residual volume [6].

When the diaphragmatic muscle shortens during inspiration, the axial length of the cylindrical portion diminishes and the dome descends relative to its costal insertions. The zone of apposition of the diaphragm cannot change shape during breathing, unless the shape of the rib cage does. The dome part of the diaphragm is able to change, but does not normally do so during quiet breathing.

During quiet breathing the decrease in axial length of the apposed diaphragm is about 2 cm, whereas the increase in sagittal and coronal diameters of the rib cage is only approximately 0.3 and 0.5 cm, respectively. Therefore the most important change in diaphragmatic shape, responsible for the majority of volume displacement during normal quiet breathing, is the piston-like axial displacement of the dome of the diaphragm by the contraction of the axial length of the zone of apposition.

The pressure difference across the diaphragm (the transdiaphragmatic pressure (Pdi)) is

related to the orthogonal tensions and radii of curvature by Laplace's law, but in the zone of apposition the radius of curvature in the axial direction is large, and so local Pdi would be related to circumferential tension and curvature. Pdi is therefore the total axial force developed by the apposed diaphragmatic fibres divided by the cross-sectional area at the zone of apposition. Because the number of fibres contracting is probably fairly consistent, the Pdi is directly related to the tension developed within the fibres and inversely related to the thoracic cross-sectional area. As recent radiological studies have shown that the area of the dome of the diaphragm varies very little between residual volume and functional residual capacity, this may not need to be considered in assessing the Pdi [7].

The shape of the dome does not vary significantly during quiet breathing as mentioned above, and therefore the radius of curvature of the diaphragmatic dome also does not need to be considered in assessing the Pdi. This is an advantage because the shape of the diaphragm is complex as described above, and has many radii of curvature, all of which will conspire to make estimates of Pdi from Laplace's law difficult.

The piston analogy breaks down when the diaphragm has shortened enough to eliminate the zone of apposition. Under these conditions the transdiaphragmatic pressure has to be analysed by considering the radii of curvature and the anisotropic (i.e. varying with position) tension within the muscular sheet of the diaphragm. A major variable for determining the force generated by the diaphragmatic muscle is the length–tension behaviour of the muscle. Generally the greater the initial length of the muscle fibre, the greater the force developed, and therefore the greater the transdiaphragmatic pressure. When considering the diaphragm, one of the determinants of fibre length will be the lung volume; the lesser the volume the greater the fibre length.

Effect of Diaphragmatic Contraction on Abdomen and Rib Cage

The descent of the dome of the diaphragm, which occurs during inspiration, will increase the subdiaphragmatic pressure and cause displacement of the abdominal viscera caudally.

As the contents of the abdomen are virtually incompressible (apart from a small amount of gas within the bowel), there must be an equal and outward displacement of the abdominal wall. In the human the abdomen is bounded by the lumbar spine posteriorly and pelvis inferiorly, which are not readily displaced, and by the rib cage, which nearly meets the iliac crest at the side. The free abdominal wall is therefore limited to the ventral abdominal wall, and contraction of the diaphragm should displace it. However, if the rib cage expands sufficiently the diaphragm may contract during inspiration without producing any abdominal displacement.

There is evidence in humans to demonstrate that there are changes in the rib cage that occur as a result of diaphragmatic activity. This work has been done by studying the breathing patterns in patients who have had transections of the cervical spine, so that there is an active phrenic nerve, but no intercostal muscle activity [8]. Measurements were made in sitting subjects at the third and seventh costal interfaces, and demonstrated a difference between the two parts of the rib cage. During inspiration the abdominal wall moves out, associated with an increase in the sagittal and coronal diameters of the lower rib cage. In contrast, at the upper rib cage the movement in both planes is inward.

Thus the contraction of the diaphragm appears to have two actions on the rib cage. Firstly, the decrease in pleural pressure that it produces would tend to displace the rib cage inwards. This is an effect predominantly on the upper ribs, although in the non-tetraplegic patient the scalene and intercostal muscles tend to prevent this. Secondly, it also has an inspiratory action, which tends to affect the lower ribs. The inspiratory action has two components to it, one being related to the force developed through the insertion into the ribs (insertional component), the second being the force exerted through the zone of apposition by the increase in abdominal pressure that occurs during diaphragmatic contraction (appositional component). The net action of the diaphragm at this level will depend upon the balance between the insertional and appositional inspiratory forces and the expiratory force generated by the fall in pleural pressure. In general inspiration is the greater force.

The insertional component of the inspiratory action of the diaphragm relates to the manner of insertion of the costal fibres, namely into the lower ribs. As these fibres are directed upwards and parallel to the rib cage axis, their contraction exerts a force that tends to raise the ribs, and therefore move them outwards. This is dependent upon forces resisting the descent of the diaphragm. Part of this resistance is provided by the abdominal pressure, as well as by the solid elements in the abdomen, the latter providing resistance by resisting displacement, which is not reflected in the abdominal pressure. That the abdominal viscera provide a fulcrum on which the diaphragm acts to raise the lower ribs has been confirmed in canine experiments, which demonstrate that evisceration of the animal causes the costal fibres of the diaphragm to contract rather than to expand the rib cage [9].

The appositional component of lower rib cage expansion relates to changes in abdominal pressure. This increase in abdominal pressure that occurs during diaphragmatic contraction will act through the zone of apposition. There are several variables that will affect the appositional component, the main two being the abdominal pressure and the size of the zone of apposition, but the compliance of the abdominal wall will also have an impact upon it.

If there is a large zone of apposition, the increase in abdominal pressure will be transmitted to the rib cage over a large area, and will act by causing outward movement of the ribs. This will be greater if the abdominal compliance is low. This is the situation occurring during normal tidal breathing. However, if the zone of apposition is greatly reduced, which occurs at lung volumes approaching vital capacity, the pressure generated upon the abdominal contents will not have such a great inspirational component.

Influence of Posture

In normal upright subjects quiet breathing occurs in such a manner that with inspiration there is an increase in the anteroposterior diameters of both the abdomen and the rib cage which is reversed on expiration. In the supine subject there is a greater increase in the abdominal component than the rib cage during inspiration. Although the effect of diaphragmatic contraction on the rib cage has been discussed above, the situation in the normal subject is complicated by the fact that there are inspiratory muscles other than the diaphragm, including the intercostals and scalenes. These appear to be automatically brought into play with the diaphragm.

However, even when these are taken into consideration, it has been demonstrated that the diaphragm expands the lower rib cage less in the supine position than the erect. This evidence comes from tetraplegic patients, in whom, during inspiration in the upright posture, the lower rib cage moves outwards [10]. However, in the supine position, during inspiration the lower rib cage moves inwards, whilst the abdominal diameter increases. The rib cage then moves outwards during expiration. Thus the diaphragm has an inspiratory activity in the erect posture, but expiratory effect in the supine position.

The explanation for the mechanism behind these differences in posture is not fully elucidated. Whatever the position of the body, the effect of diaphragmatic contraction is to cause a fall in pleural pressure, and therefore for the same increase in lung volume the expiratory force of the rib cage would be assumed to be equal. Thus the differences in rib cage movement between supine and erect posture are considered to be related to differences in appositional and/or insertional forces. The zone of apposition is known to vary between erect and supine posture, both in shape and size, the dorsal component being greater when supine, the ventral component being less. In transferring between the upright and horizontal position the abdominal contents are displaced cephalad and the lung volume at functional residual capacity is reduced by approximately 15% of the vital capacity. The diaphragmatic muscles are lengthened and develop appreciable passive tensions at relatively higher lung volumes. Also, the diaphragmatic dome is subject to varying transmural pressures, increasing from the uppermost to the lower surfaces, as a result of gravitational effects. The gradient of pleural pressure is probably less than that of the abdominal side, and in humans the difference in transmural pressure between the upper and lower surfaces is about $10\,cmH_2O$. This will give the dome an increase in curvature in the direction of gravity.

The latter may have an impact upon the insertional component of the ventral part of the diaphragm, possibly as a result of converting the axial tension, which would be created in the erect posture, to a radial tension, which would cause the ribs to be drawn in. On top of this there will be an increase in abdominal compliance in the supine position, which will also cause the ribs to move inwards, the opposite to the changes occurring in the erect posture.

The effects of diaphragmatic contraction on the upper part of the rib cage are unrelated to posture. When the rib cage muscles are inactive the diaphragm causes the upper rib cage to move inwards in both erect and supine postures. This has been demonstrated not only in tetraplegic patients [8] but also in normal subjects during rapid-eye-movement sleep [11], when there is a reduction of electrical activity in the parasternal area, allowing a paradoxical movement of the rib cage with inspiration.

Influence of Lung Volume

Lung volume will have a marked influence on the action of the diaphragm on the rib cage. As lung volume decreases below functional residual capacity the zone of apposition will increase. Thus the area of the rib cage exposed to abdominal pressure will increase while the area exposed to the pleural pressure decreases. Conversely, with an increase in lung volume, there will be a reduction in the zone of apposition. From this it will be seen that there is a reduction in the diaphragm's inspiratory activity with increasing lung volumes. Furthermore, when the lung volume approaches total lung capacity, the zone of apposition disappears completely, and the muscle fibres at their insertion into the ribs are orientated radially towards the body axis rather than axially along the body axis. The insertional component then enhances rather than opposes the expiratory force related to a fall in pleural pressure, and contraction of the diaphragm therefore deflates the lower rib cage.

The ability of the diaphragm to generate pressure is also strongly dependent upon lung volume. As lung volume increases, the transdiaphragmatic pressure created for a given stimulation of the phrenic nerve decreases almost linearly. This relationship, demonstrated in humans [10], is related to the force length characteristic of the diaphragmatic fibres, the greater the lung volume, the lesser the length of the muscle fibre, placing them on a less advantageous portion of the length/tension curve. It has also been shown that for a given electrical stimulation of the phrenic nerve, the transdiaphragmatic pressure increases as the abdominal anteroposterior diameter decreases (i.e. as the diaphragm is more cephalad with its fibres longer). At high lung volumes when the zone of apposition has disappeared and the muscles are no longer inserting into the ribs tangentially, the transdiaphragmatic pressure will be less because of the increasing radius of curvature of the diaphragm (Laplace's law). Finally, near total lung capacity phrenic nerve stimulation is expiratory to the lungs, as a result of both the rib cage constricting activity of the diaphragm at high lung volumes and the inability of the flattened dome to expand the abdomen.

Relaxation of the Diaphragm

Muscle relaxation is the process by which the muscle actively returns, after contraction, to its initial conditions of length and load. The diaphragm contracts and relaxes continuously throughout life, and must return to a relatively constant resting position at the end of each contraction–relaxation cycle. There is evidence to support the hypothesis that rapid and complete relaxation of the diaphragm plays an important role in adaptation to changes in respiration load and breathing frequency [12]. Relaxation abnormalities may contribute, in part, to impaired contractile performance. This may occur at various levels from the molecular level upwards.

Molecular Aspects of Relaxation in Diaphragm Muscle

There is a complex interplay between inactivation (mainly at the molecular and cellular level) and loading conditions (forces affecting muscle length and tension). The rate of inactivation is limited by various mechanisms, which will be described below.

Firstly there is active Ca^{2+} pumping by the sarcoplasmic reticulum (SR). The SR is a specialised form of agranular endoplasmic reticulum, which forms a plexus of anastomosing membranous channels filling much of the space between the myofibrils. The arrival of the action

potential causing contraction is responsible for the release of large amounts of calcium from the SR, which triggers the development of actin–myosin cross-bridges and hence muscle contraction. The reverse is essential for relaxation, the cytosolic Ca^{2+} being transported into the SR, an active process assisted by Mg^{2+}- Ca^{2+}-activated ATPase. Thus the rate of uptake will be a function of the number of pumping sites and the rate at which they operate.

There are variations in the SR of the different muscle types described elsewhere in this chapter. There is a higher capacity of SR Ca^{2+} uptake in fast- compared with slow-twitch fibres, which is mirrored by the higher relaxation rate. This is related to differences in the density of active pumping sites. There are also molecular differences, particularly in the sarco(endo)-plasmic reticulum Ca^{2+}-ATPase (SERCA), of which two isoforms have been found in the human diaphragm, namely SERCA1 and SERCA2a. SERCA1 is found only in fast-twitch skeletal fibres, whereas SERCA2a is expressed in slow-twitch skeletal fibres as well as in cardiac and smooth muscles.

It should also be noted that there are age-associated changes within the muscle fibres, as an age-related decline in SR Ca^{2+} pump function has been described in skeletal muscles. This decline, presumably due to impaired coupling between ATP hydrolysis and Ca^{2+} transport into the SR, may contribute to the slowing of the diaphragm relaxation rate in older persons.

Secondly there is Ca^{2+} removal from troponin C (TnC). The binding of Ca^{2+} to TnC acts as a switch to allow cross-bridge formation, hence contraction of the muscle, whilst removal inhibits cross-bridge attachment and hence relaxation. The movement will depend in part on the affinity of Ca^{2+} for TnC, which increases with sarcomere length and decreases with a decline in intracellular pH. Thus the capacity of TnC to release Ca^{2+} and the SR to reuptake it explains the length dependence of relaxation in the diaphragm. At heavy load sarcomere shortening is moderated so that the high affinity of TnC for Ca^{2+} impedes Ca^{2+} removal from the myofibrils, whilst at short sarcomere length and/or low load, the low affinity of TnC to Ca^{2+} promotes the dissociation of the two. Therefore as long as the Ca^{2+} can be sequestered into the SR, relaxation is faster as the sarcomere shortening increases.

Thirdly there are other mechanisms which may be relevant. It has been suggested that parvalbumin, a high affinity Ca^{2+}-binding protein, may modulate the relaxation rate of skeletal muscle by facilitating Ca^{2+} transport from the myofibrils to the SR. In mammalian skeletal muscle the relaxation rate has been found to correlate with the parvalbumin concentration.

Another possibility is that changes in membranous ionic conductances play a role in the slowing of relaxation in fatigued diaphragm by slowing of action potential repolarisation.

Mechanical Aspects of Relaxation in Diaphragm Muscle

Although much work has been done on relaxation of the diaphragm after isometric contraction, and has demonstrated that there are various factors which can impair the relaxation rate, such as ageing, maturation, denervation, malnutrition, cardiomyopathy and fatigue, this is not the normal situation, as the in vivo diaphragm contracts and relaxes against various levels of load. During afterloaded contraction, the muscle relaxation phase classically consists of isotonic lengthening, followed by isometric tension decay.

Isotonic relaxation is an increase in length at constant tension. It has been shown that the maximum extent of muscle shortening, ΔL is the main mechanical determinant of peak lengthening velocity [13]. Peak lengthening velocity (VL) physiologically increases with the extent of muscle shortening, irrespective of initial muscle length and of the load imposed on the muscle during the lengthening process. The slope of the VL–ΔL relationship is lower in twitch than in sustained mode and/or when the lengthening process is delayed. In myopathic models, VL is slowed and the overall duration of isotonic lengthening is prolonged. The myopathic process modifies the coupling between ΔL and VL.

Isometric relaxation is a falling tension at constant length. When tension decay occurs at initial length, the peak rate of tension decline is mainly determined by the afterload, and except at approximately isometric load levels an increase in afterload linearly accelerates the peak rate of tension decline [14].

Relaxation of the diaphragm, like the heart, is load sensitive, that is, the overall time course of

relaxation is strongly affected by the afterload level. A contraction loaded with light or moderate load terminates earlier than a full isometric contraction, so that a muscle that is allowed to shorten has a shorter contraction–relaxation cycle. This is a manifestation of the shortening-induced deactivation phenomenon described above.

Although the muscle appears to relax in two stages, sarcomeres relax auxotonically, i.e. changes in sarcomere length and tension occur simultaneously. Because loading conditions have opposite effects on isotonic and isometric relaxation rates, it has been suggested that different intracellular mechanisms regulate the diaphragmatic muscle-lengthening rate on the one hand, and the isometric relaxation rate on the other [14]. It may be that the sarcomere length (SL) at the start of the relaxation phase is important.

As has been observed in cardiac muscle, sarcomere relaxation in the afterloaded diaphragm displays two consecutive phases: an initial phase of rapid sarcomere lengthening corresponding to the isotonic relaxation phase followed by a second, slower relaxation phase corresponding to the isometric relaxation phase [15]. It has also been shown, in studies that have examined both muscle length and SL, that as the load level increases, isotonic muscle lengthening occurs at progressively longer SL, which will correspond to the SL at peak shortening. In contrast, at the end of the isotonic phase, when the muscle has finished shortening, the sarcomere has not yet returned to its resting length. At that stage isometric contraction begins, and it is demonstrated that the SL is constant at that time, regardless of the external load.

Thus there is a complex equilibrium modulated by the capacity of TnC to liberate Ca^{2+} and SR to recapture Ca^{2+} and by length-dependent changes in myofilament lattice spacing, which may help to explain why relaxation occurs earlier and faster at low loads than it does at heavy loads. Provided SR is efficient, length-dependent changes in the affinity of TnC and in myofilament lattice spacing may favour rapid and early muscle lengthening when the muscle length is notably shortened (i.e. at low loads).

Relaxation of the Diaphragm In Vivo

Although much is learnt about the function of the diaphragm from in vitro studies, it is only when applied in vivo that it starts to have clinical relevance. As mentioned above, it is known that changes in relaxation occur with fatigue of the diaphragm, and that a suitable means to measure this clinically would be an advantage. Various means have been tried, which involve deriving the relaxation rate from various pressure curves, measuring either the transdiaphragmatic pressure (Pdi) oesophageal, mouth or nasal pressures. These rely on the assumption that the chest wall and lungs will not have a significant effect upon the pressure curves, and that the pressure decay coincides with the start of diaphragmatic relaxation. The latter may not be true, as studies have demonstrated that the diaphragm continues to receive motor output during the early part of expiration [16].

Two main measures have been derived from the pressure decay curves. The first is the maximum relaxation rate (MRR), which is the negative peak of the pressure derivative as a function of time, and measures the initial part of the pressure decay. The latter portion of the curve is described in terms of its time constant, as it is normally a mono-exponential curve. The MRR varies with Pdi, such that relaxation is accelerated when Pdi increases.

It has been shown in the in vivo diaphragm that respiratory muscle fatigue slows the relaxation rate, as demonstrated by an increase in the time constant and/or a decrease in the MRR. Slowing of relaxation is an early signal of the onset of fatigue as it precedes failure of the diaphragm to generate a previously attainable Pdi. A slowing of relaxation has been shown in normal subjects who have undergone fatiguing contractions of the diaphragm, and in patients with chronic obstructive airways disease walked to dyspnoea. Slowing of inspiratory muscle relaxation has been proposed as a predictive index of weaning failure in mechanically ventilated patients.

New techniques have enabled measurements to be made in intact animals, and it has been demonstrated that the decay of pleural pressure ends before the crural and costal parts of the diaphragm have returned to their initial muscle length [17]. Thus pleural pressure swings during relaxation do not totally coincide with diaphragm muscle relaxation. Also it is noted in supine animals that the peak lengthening velocity of the crural diaphragm, which has a greater extent of shortening, exceeds that

of the costal part, suggesting that VL is related to ∆L in vivo as well as in vitro.

Role of Diaphragm Relaxation in Respiratory Function

The ventilatory performance of the diaphragm depends upon its resting length, which also depends upon the relaxation and compliance of the muscle. The optimal resting length (L_o) of the diaphragm is at or slightly below functional residual capacity (FRC) [18]. During inspiration between FRC and total lung capacity the human diaphragm will shorten by 25–35% L_o. It is necessary for the diaphragm length to return to L_o by the end of expiration. If this does not occur, due to incomplete or delayed relaxation, there will be incomplete expiration to FRC. This will cause multiple problems, as the lungs will move up the lung compliance curve, potentially increasing the work of breathing, while the diaphragm moves down its passive length–tension relation, is placed at a mechanical disadvantage for optimal force generation, and its inspiratory shortening capacity is curtailed. This will increase the risk of ventilatory failure.

As in other skeletal muscle, contractile performance is dependent upon adequate energy supplies, hence an adequate blood supply. The relaxation phase is responsible for accommodating most of the changes in blood perfusion brought about by increased diaphragmatic work. Diaphragmatic blood flow is reduced during inspiration and can be completely abolished during forceful contractions [19]. Blood flow restriction has been attributed to intramuscular pressure acting on the blood vessels between muscle fibres. The pressure in turn depends upon the load to which the diaphragm is subjected and the degree of muscle shortening. However, the zone of apposition is known to increase greatly in thickness during inspiration, which may have a beneficial effect upon the regional blood flow by minimising the pressure surrounding the microvasculature [20]. During relaxation intramuscular pressure declines to baseline, thus allowing diaphragmatic perfusion to occur. At a low respiratory rate the duration of relaxation is long and the blood flow can increase to meet the metabolic demands. At higher rates the relaxation period may be insufficient to meet diaphragmatic oxygen requirements. Thus delayed or slowed relaxation may

further limit diaphragmatic perfusion, especially at high breathing frequencies [21].

Non-ventilatory Properties of the Diaphragm

The concept that the diaphragm had functions other than that of ventilating the lungs originated in the work of Bartelink [22]. This study looked at the load placed upon the lumbar intervertebral discs when lifting heavy objects, and calculated that the load applied to the discs would be greater than that required to rupture them (as measured in vitro). Thus there must be some form of protective mechanism available to the body. Bartelink further demonstrated that the intra-abdominal pressure increased with lifting heavy weights, but also that the pressure was much greater as the trunk was flexed, in comparison with the erect position. He postulated that the abdominal contents acted as a fluid ball, surrounded by muscles, namely the diaphragm, the transverse abdominal muscles and the muscles of the pelvic floor. He suggested that if there were such a ball present between the costal margin and the pelvis, the lumbar spine could be removed, and the body would not collapse as a result thereof. In the presence of the lumbar spine, the increase in intra-abdominal pressure will serve to unload the spine and increase trunk stability.

It was recognised that the abdominal and thoracic cavities upon which the diaphragm acts are involved with the stability of the trunk and postural control [23]. Other respiratory muscles acting upon the rib cage and abdomen perform a postural function which is integrated with their respiratory role, for example the intercostal muscles stabilise the rib cage [24]. Contraction of the abdominal muscles contributes to trunk stability prior to and during movement of the limbs, an action which is increased when respiratory demands increase [25].

Contraction of the pelvic floor muscles and abdominal muscles, in particular transversus abdominis, correlates closely with the increase in intra-abdominal pressure in a variety of postural tasks [23]. When the stability of the trunk is challenged by reactive forces due to limb movement, transversus abdominis contracts before the agonist limb muscle, which

suggests that the response might be pre-programmed by the central nervous system [25,26].

More recent studies have demonstrated that the diaphragm contributes to the increased intra-abdominal pressure prior to the initiation of movements of large segments of the upper limb. This contraction is independent of the phase of respiration [24]. This evidence suggests that the diaphragm has a function in the maintenance of the postural control of the human trunk. The same paper also showed that the preparatory contraction of the diaphragm is associated with initial shortening of its muscle fibres and occurs simultaneously with activation of transversus abdominis.

The argument in favour of this conclusion relates to the fact that any movement of a limb is associated with reactive forces imposed upon the trunk which are equal and opposite to those producing the movement, and that the diaphragm in itself is unable to move the trunk directly to oppose these forces.

Moreover, the contraction of the diaphragm increases pressure within the abdominal cavity, which may contribute to trunk stability. Also, diaphragmatic contraction could increase stability of the trunk by minimising displacement of the abdominal contents into the thorax, maintaining the hoop-like geometry of the abdominal muscles, which could then increase spinal stability through tension in the thoracolumbar fascia. This study also demonstrated that there was co-activation of the costal and crural portions of the diaphragm [24], which suggests that for postural reasons the two parts of the diaphragm may function together, although there have been previous studies which demonstrate that the two portions of the diaphragm may function independently [27].

Unlike other muscles that are involved with the maintenance of posture, the diaphragm has to continue to act in its primary role as a muscle of ventilation. That it is able to do so is demonstrated in studies looking at the activity of the diaphragm during repetitive arm activity [28]. This modifies diaphragmatic activity in two ways unrelated to ventilation. First, unlike breathing at rest, the diaphragm contracted tonically throughout the respiratory cycle. If this were accompanied by abdominal muscle activity, the intra-abdominal pressure would be elevated. As well as this, phasic modulation of diaphragm activity at the frequency of limb

movement was superimposed on its ventilatory and tonic activation. Therefore ventilation can continue uncompromised by the activity of other muscle groups whilst the diaphragm is acting as a spinal support.

Further studies of a similar nature have demonstrated that there is a reciprocal activity of transversus abdominis with the diaphragm during breathing under conditions of repetitive arm action. With the initiation of movement the diaphragm and abdominal muscles contract simultaneously to increase abdominal pressure. Breathing is facilitated by the relaxation of transversus abdominis during diaphragmatic contraction, to allow displacement of the abdominal contents, and vice versa during expiration [29].

That the diaphragm acts tonically with activity in other parts of the body is consistent with earlier findings, which demonstrate the sustained elevation of transdiaphragmatic pressure during lifting [30]. More recent studies have demonstrated that the greatest increase in transdiaphragmatic pressure is seen during sit-ups and power lifts, and studies in weight-lifters has demonstrated an increase in the diaphragmatic mass in these people [31]. This is further evidence to support the proposition that the diaphragm is recruited in non-ventilatory activities. As well as supporting the spine, it is important in maintaining ventilation. With lifting of heavy objects, or even upper limb movement, there is an increase in intra-abdominal pressure. If there were no diaphragmatic recruitment, the elevated intra-abdominal pressure would be transmitted to the thorax, provoking the unwanted effects of raised intrathoracic pressure (raised central venous, intracranial and systemic blood pressures).

In patients with phrenic nerve paralysis there is often a difficulty in breathing with bending or lifting. Measurements made within such patients [31] demonstrate that there is a rise in intra-abdominal pressure with lifting, but there is no transdiaphragmatic pressure, i.e. the pressure in the abdomen is transmitted directly to the thorax. Thus these patients become dyspnoeic on exertion, as they are only able to breathe in between bouts of activity, unlike the normal person who is able to breathe and lift or move at the same time.

It will be apparent from this section that there is still a great deal of uncertainty about the

complete function of the diaphragm, and that there is a lot of work ongoing investigating the activity of the diaphragm in health and disease, utilising newer and more sophisticated techniques. It will be interesting to see what more will be learned about this fascinating organ in the coming years.

Questions

1. Which structures pass through the diaphragm?
2. Describe the nerve supply.
3. What is the function of the diaphragm?

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