Anatomy of the Respiratory System and the Respiratory Muscles

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Without oxygen, the human organism is not capable of living. It gains a major part of its energy from oxidative degradation of nutrients. The processes involved in this are called pulmonary respiration or external respiration. The carbon dioxide that is formed in the process of combustion has to be released. The gas exchange between air and blood takes place in the lung. When nutrients are degraded in order to gain energy, oxygen is consumed - a process that takes place in every individual cell of the body and is therefore called cell respiration or internal respiration. The detailed processes of cellular respiration are the subject of biochemistry and will not be discussed here.

Respiratory System: Structure and Function

The respiratory system is a series of organs that function as a whole to oxygenate the body by inhaling air and exhaling carbon dioxide. There are three major parts of the respiratory system: the airways, the lungs, and the muscles of respiration.
Respiratory muscles

The muscles of respiration are those muscles that are necessary in order to reverse the pressure relationships for inspiration and expiration. By means of contraction, they can actively increase the thoracic volume (inspiration) or decrease it (expiration) by passive relaxation. The diaphragm and the intercostal muscles drive respiration during quiet breathing.

Respiration

Respiration, in the narrower sense, usually refers to external respiration and is also called pulmonary respiration. Besides the actual gas exchange between the alveoli and lung capillaries, the term refers to the provision and removal of gases via blood and air; therefore, respiration consists of three components that span the whole process.

- **Ventilation** of the alveoli
- **Perfusion** of the capillaries
- **Diffusion**: gas transport and exchange via the membrane

For gas exchange, the air of the environment must be exchanged in the alveoli, which corresponds to the ventilation of the alveoli. This is accomplished by the alternating build-up of pressure differences between the surrounding air and the lungs so that respiratory air can flow in (**inspiration**) and out (**expiration**).

The lung follows the movements of the thoracic wall due to the negative pressure in the pleural cavity (**Donder's low pressure**). This pressure acts against the elastic retraction forces of the lung, which would contract otherwise.
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Inspiration

For inspiration, the fresh and oxygen-rich air from the surroundings is transported into the alveoli where gases are exchanged. The ‘sucking in’ of the air into the lungs is facilitated by the intrapleural pressure, which is lower compared to the surroundings. As mentioned above, the active forces of the respiratory muscles and the negative pressure in the pleural cavity are responsible for the generation of this negative pressure.

At inspiration, the thorax widens, the pressure decreases, the lungs expand, and air flows in.
More specifically, the following structures are part of inspiration:

1. **Respiratory muscles**: diaphragm (see below)
2. **External intercostal muscles**: These muscles obliquely run from one rib to the next rib in a ventral-to-caudal direction. Along with the internal intercostal muscles and the ribs, they form the chest wall. The contraction of the external rib muscles elevates the ribs and expands the thorax. These muscles support inspiration. The **external thoracic fascia** covers the muscles from the ventral direction.
3. **Accessory respiratory muscles**: There are three muscles associated with accessory inspiration function: sternocleidomastoid (elevates sternum), scalenes (elevates upper ribs), and *pectoralis minor*. 

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[Image: Intrapulmonary and intrapleural pressure relationships. By Phil Schatz. License: CC BY 4.0.]

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**Sternocleidomastoid muscle**

In its course, this muscle divides the neck into two triangles, the **posterior triangle of the neck** and the **anterior triangle of the neck**. The muscle is divided into a **lateral head** and a **medial head**. The origin of the lateral head is at the **clavicle**; the medial head originates from the **manubrium of the sternum**.

In the middle of the neck, the two heads form a thick, round muscle belly. The insertion of the *sternocleidomastoideus* muscle is at the lateral side of the **mastoid process** of the **temporal bone**. The innervation occurs via the accessory nerve and branches of the **cervical plexus** (C1–C3/4).

**Scalenus anterior muscle**

The origins of this muscle are the **anterior tubercles** of the **transverse processes** in the area of the third to sixth cervical vertebrae. It runs obliquely in the caudal direction...
and inserts at the tubercle of the **scalenus anterior muscle** of the first rib. The innervation occurs via the anterior branches of the spinal nerves in the area C5–C7.

When there is bilateral contraction and the cervical spine is fixed, the muscle elevates the first rib and therefore expands the thorax.

**Scalenus medius muscle**

From the origin at the transverse processes of the cervical vertebrae 3–7, the **scalenus medius** muscle runs to the first rib, occasionally also to the second rib. Innervation is provided by the spinal nerves of segments C4–C7. During bilateral contraction, the muscle elevates the upper ribs and expands the bony thorax this way.

**Scalenus posterior muscle**

This muscle originates from the **posterior tubercles** of the transverse processes of the cervical vertebrae 5–6. From this location, the muscle fibers run to the outer surface of the second rib or the third rib. Innervation occurs via the anterior branches of the spinal nerves of the segments C7 and C8. During bilateral contraction, this muscle also supports the elevation of the bony thorax.

**Pectoralis major muscle**

The strong, real ‘greater chest muscle’ lies on top of the **pectoralis minor muscle**. It is one of the chest muscles and connects the ventral shoulder girdle with the torso. Because of its large extensions, it is topographically divided into three parts, as follows:

1. **Clavicular part:** origin at the medial clavicle
2. **Sternocostal part:** origin at the ipsilateral edge of the sternum and the cartilage of the second to the sixth rib
3. **Abdominal part:** origin at the anterior sheet of the aponeurosis of the rectus abdominis muscle

The fibers of all three parts merge into a flat tendon, which inserts at the **crest of the major tubercle** of the humerus. The tendon consists of two twisted **laminae** (layers). At an elevation of the arm, this twist is reversed.

Innervation is provided by the **medial pectoral nerve** (C8-Th1) and the **lateral pectoral nerve** (C5–C7) of the **brachial plexus**. Along with the **minor pectoral muscle**, it serves as a supporting respiratory muscle.

**Pectoralis minor muscle**

The ‘lesser chest muscle’ originates from the ventral surfaces of the third to fifth rib and runs cranially and laterally. As a flat tendon, it inserts at the cranial surface of the **coracoid process** of the **scapula**.

It is innervated by the **medial pectoralis muscle** (C8–Th1) and the **lateral pectoral muscle** (C5–C7) of the **brachial plexus**. The fibers of the muscle serve as a supporting respiratory muscle.

**Superior posterior serratus muscle**

This muscle is part of the migrated back muscles, which are innervated by the **anterior**
**Rami** of the spinal nerves (Th2–Th5). It originates from the spinous processes of the sixth to seventh cervical vertebrae and those of the first and second thoracic vertebrae.

The serrated muscle fibers insert at the second/third to fifth ribs, lateral of the **costal angle**. The contraction elevates the ribs and thus supports inspiration.

**Inferior posterior serratus muscle**

As a migrated back muscle, it is also innervated by the **anterior rami** of the spinal nerves (Th11–L2). It originates from the spinous processes of the last two thoracic vertebrae and the first two lumbar vertebrae. They insert at the ninth to twelfth ribs.

In contrast to the **superior posterior serratus muscle**, the fibers run upward. Bilateral contraction moves the lower ribs dorsally and caudally, which leads to narrowing of the thorax and, thus, actually supports expiration.

Support of inspiration and expiration by the lower ribs is related to the contraction of the diaphragm. When the diaphragm contracts, the pleural pressure falls, exerting a caudal and inward force on the entire rib cage. However, the **diaphragm also exerts forces in the cranial and outward direction on the lower ribs**.

One of these forces, the ‘insertional force,’ is applied by the muscle at its attachments to the lower ribs. The second is called the ‘appositional force’ due to the transmission of abdominal pressure to the lower rib cage in the zone of apposition. The control condition at functional residual capacity (**FRC**) is the volume of air present in the lungs at the end of passive expiration, the balance state between inspiration and expiration when both forces are balanced at equal pressures.

The effects of these two forces on the lower ribs are nearly equal and outweigh the effect of pleural pressure, whereas, for the upper ribs, the effect of pleural pressure is greater. According to this, the lower ribs counter the cranial and ventral tension of the diaphragm, which would not be favorable for the expansion of the lungs.

**Anterior serratus muscle**

This muscle is part of the chest muscles and also connects the shoulder girdle to the torso. It is divided into three parts, as follows:

1. **Superior part**: The origin is at the first to second rib, and insertion is at the scapula, which is responsible for the elevation of the shoulder.
2. **Intermediate part**: The origin is at the second to third rib, and the insertion is at the medial edge of the scapula, which is the major part of the muscle and pulls the scapula ventrally.
3. **Inferior part**: The origin is at the fourth to ninth rib, and the insertion is at the medial edge and the inferior angle of the scapula, which allows the elevation of the arm.

The innervation of all three parts is ensured by the **long thoracic nerve** of the **supraclavicular part** out of the **brachial plexus** (C5–C7). If the arm is fixed, it serves as a supporting muscle for inspiration.
The diaphragm accounts for nearly 75% of the muscular contribution for respiratory function. Topographically, the 5-mm thick dome-shaped muscle plate is located between the thorax and the abdomen.

The muscle originates from the lumbar spine, the sternum, and the ribs. The two domes reach into the thorax and are covered by connective tissue. In the thorax, the diaphragm is additionally covered by pleura and, in the abdomen, by peritoneum. The right dome protrudes 1–2 cm (0.4–0.8 in) higher into the thorax than the left dome. This morphology determines its asymmetric appearance.

Anatomy of the diaphragm

The diaphragm is located at the inferior-most aspect of the rib cage, filling the inferior thoracic aperture. It acts as the floor of the thoracic cavity and the abdominal cavity. It has three attachments, as follows:

- Lumbar vertebrae and arcuate ligaments
- Costal cartilages of ribs 7-10 (attach directly to ribs 11-12)
- Xiphoid process of the sternum
- **Esophageal hiatus (hiatus esophagus):** The esophagus, vagal nerve (anterior/posterior vagal trunks), left gastric artery and vein, and lymphatic vessels run through this orifice. Surrounded by muscles, this orifice is narrowed at inspiration (a contraction of the muscle), a motion that inhibits the occurrence of reflux.

- **Caval opening (foramen vena cavae):** In the shape of a firm ring of connective tissue, the vena cava is grown together with the diaphragm. This way, it is not compressed when the diaphragm contracts. Besides the inferior vena cava, the right phrenic nerve also runs through this orifice.

- **Aortic hiatus (hiatus aorticus):** Again, a firm tendinous arch for stabilization of the opening inhibits narrowing at inspiration. The aortic hiatus also contains the thoracic duct and the azygos vein.

The major and minor splanchnic nerves, the **superior epigastric vein**, the **left phrenic nerve**, the **hemiazygos vein**, and the sympathetic trunk run through the minor orifices.

The following structures take care of the provision of nutrients and nervous control:

- **Arteries:** abdominal aorta, internal thoracic arteries, left and right phrenic arteries
- **Veins:** left suprarenal vein and azygos system
- **Nerves:** phrenic nerve with origin in the cervical segment (cervical plexus C3–C5)

**Diaphragmatic respiration**

The muscle contracts for inspiration; for expiration, it relaxes. This is controlled by the autonomic nervous system via the respiratory centers in the medulla oblongata and pons and occurs involuntarily.
During inspiration, the lungs expand, and the volume of the thorax increases at the expense of the abdominal volume. The diaphragm becomes flatter, lowers in the caudal direction, and also pushes the abdominal organs caudally. The abdominal space protrudes.

The tidal volume during relaxed inspiration is roughly 500 mL. Expiration is accompanied by the relaxation of the diaphragm. During this process, the diaphragm elevates, the air leaves the lungs, and the protruded belly flattens and returns to its original dome shape.

The diaphragm does not only manage the major part of the respiratory performance, but it also acts as the abdominal press in collaboration with the abdominal muscles. This press is necessary for the processes of birth and defecation.

**Diseases and conditions of the diaphragm**

Following are possible diseases and conditions of the diaphragm:

- **Side stitches**: A side stitch is an intense stabbing pain under the lower edge of the rib cage that occurs while exercising. This is believed to occur because this is a referred site of pain for the diaphragm via the phrenic nerve. Mostly, they occur in the initial phases of physical performance. They result from overloading and simultaneous oxygen deficiency.

- **Diaphragmatic hernia**: This condition is usually congenital and manifests as a cranial shifting of abdominal organs into the thoracic space. Symptoms such as bloating, dyspnea, and nausea can be caused by the condition. In most cases, it can be treated surgically.

- **Diaphragmatic elevation**: Impaired inspiration, in combination with protrusion of the diaphragm into the thorax, indicates diaphragmatic elevation. It is often caused by abnormal changes in the abdominal space or lung.
diseases. The paralysis of a hemidiaphragm, caused by damage to one of the phrenic nerves, may lead to dyspnea and respiratory failure.

**Diaphragmatic paralysis:** This is caused by an interruption in the diaphragm’s nerve supply due to damage caused by mechanical trauma, compression by a tumor inside the chest cavity, myasthenia gravis, and diabetic neuropathy. It is generally asymptomatic in cases of unilateral diaphragmatic paralysis. It may lead to dyspnea and fatigue.

A special case is that of the **hiccups.**

Mostly, hiccups occur suddenly and unexpectedly. They are the involuntary cramp-like contractions of the diaphragm caused by an irritation of the **phrenic nerve.** Inspiration is abruptly interrupted by the closure of the vocal folds, which causes the characteristic inspiration sound (‘hics’). Prolonged attacks are serious and associated with morbidity and can even cause death.

The purpose of this strong inspiration movement remains unknown. Often, hiccups are the consequence of eating too quickly, smoking, nervousness, and hot or cold beverages.

Besides these harmless triggers, there also are pathologic causes that lead to chronic hiccups. They can be a sign of other diseases, such as disorders of the central nervous system (CNS) (**subarachnoid hemorrhages**, tumors, and **encephalitis**), impairments of the **phrenic nerve** (cardiac infarction), and/or impairments of the diaphragm (stomach ulcer, **pleuritis**, **gastroesophageal reflux diseases**, and **pancreatitis**). The treatment is usually symptomatic.

**Expiration**

In the process of expiration, deoxygenated air that has been loaded with carbon dioxide and deprived of oxygen in the gas exchange that occurred in the alveoli is released to the outside. As the lung becomes smaller and higher, surrounding pressure builds up. Thus, air flows out.

Expiration involves the diaphragm, the intercostal muscles, and the accessory respiratory muscles, as follows:

1. **Diaphragm:** It elastically collapses and allows for the recoil of the lungs.
2. **Intercostal muscles:** The **internal intercostal muscles** contract, lower, and reduce the diameter of the thorax.
3. **Accessory expiration muscles:** These include the internal intercostals, the quadratus lumborum, and the abdominal musculature (these all work to pull the ribs down).
**Rectus abdominis muscle**

This paired, long skeletal muscle runs vertically and belongs to the abdominal muscles. Its origin is at the anterior surface of the fifth, sixth, and seventh ribs. The right and left muscles meet at the white line (linea alba) and insert at the superior ramus of the pubic bone and ligaments of the pelvic symphysis. A particularity is the fact that the rectus abdominis muscles are completely divided by three intermittent tendons (intersectiones tendineae) and partially by a fourth one. These tendons divide the muscle into segments.

Two broad tendinous sheaths surround the muscle completely on both ventral and dorsal sides, forming the rectus sheath. In athletic persons with little subcutaneous fat tissue, the muscle relief can be seen on the body surface as the notorious ‘six-pack.’

The innervation of this muscle is supplied by the anterior rami of the seventh to twelfth thoracic or intercostal nerves (Th7–Th12) and the first and second lumbar nerves (L1–L2). The arterial supply is provided by the superior epigastric artery and the inferior epigastric artery.

The rectus abdominis muscle increases the tension of the abdominal wall, and together with the pelvic floor muscles and the diaphragm, it increases the pressure in the abdomen.

**Transversus abdominis muscle**

The fibers of this innermost muscle run mostly horizontally and originate from the inner surface of the 11th and 12th ribs, the iliac crest, the inguinal ligament, the thoracolumbar fascia (deep sheet), and the superior anterior iliac spine.

The muscle inserts at the white line and the pubic bone; its aponeurosis forms a part of the rectus sheath. A particularity of this muscle is that it joins the internal oblique muscle to form the cremaster muscle and attaches to the spermatic cord. The equivalent in women is the teres uteri ligament.
Innervation is provided by the **intercostal nerves** (Th7–Th11), as well as the **ilioinguinal nerve**, the **genitofemoral nerve**, the **iliohypogastric nerve**, and the **subcostal nerve** (Th12). During bilateral contraction, the abdominal organs are pushed inward, which contributes to the abdominal press during expiration.

**External oblique muscle**

From the outer surface of the 5th–12th rib, this outermost abdominal muscle runs in the caudal and medial direction and perpendicular to the **internal oblique muscle**. The muscle shares its points of origin with the insertion spikes of the **anterior serratus muscle**. In athletic persons, a serrated line is clearly visible.

The insertion points can be divided into a **medial crus** and a **lateral crus**. The medial crus forms the rectus sheath and radiates into the **white line**. The lateral crus inserts at the **iliac crest** and the **pubic tubercle**. Between the two crura, there is a fissure that forms the outer ring of the inguinal canal.

The **anterior rami** of the spinal nerves Th5–Th12 innervates this muscle. It supports the abdominal press for expiration.

**Internal oblique muscle**

This skeletal muscle belonging to the abdominal muscles originates from the **deep lamina** of the **thoracolumbar fascia**, the lateral half of the **inguinal ligament**, and the **superior anterior iliac spine**. After its cranial–medial course, it inserts at the inferior edge of the rib cartilages 9–2.

Furthermore, the muscle participates in the formation of the rectus sheath. As mentioned above in the section on the **external oblique muscle**, their fiber bundles form together with the **cremaster muscle**.

The innervation of this muscle is supplied by the **anterior rami** of the spinal nerves Th8–Th12, as well as the **ilioinguinal nerve**, the **iliohypogastric nerve**, and the **genitofemoral nerve**. Among other things, this muscle plays a role in the abdominal press and expiration.

**Erector spinae muscle**

This large back muscle group, lying on the vertebral column, belongs to the intrinsic back muscles. These intrinsic (or autochthonous) back muscles are divided into a medial and a lateral part, which will not be described in more detail at this point.

It receives innervation from dorsal ramus of the spinal nerves: The medial part is innervated by the medial **rami**, the lateral part by the lateral **rami**.

**Quadratus lumborum muscle**

This deep abdominal muscle originates from the **iliac crest** and the **iliolumbar ligament**, and inserts at the inferior edge of the 12th rib and the **costal processes** of the lumbar vertebrae 1–4.

The innervation is provided by **anterior rami** from Th12–L3. In forced expiration, this muscle fixes the free ribs.

**Note:** Inspiration is an active process, expiration is passive. The alveolar pressure
describes the pressure difference between the atmosphere and the pleural space. During inspiration, the alveolar pressure becomes negative; the air is sucked into the alveolar space from the outside. When the inspiratory muscles relax, the lungs recoil and this creates a positive alveolar pressure, which expels the air out of the lungs (expiration). During inspiration, the diaphragm and external intercostal muscles contract, causing the rib cage to expand and move outward and expanding the thoracic cavity and lung volume. This creates a lower pressure within the lung than that of the atmosphere, causing air to be drawn into the lungs. During exhalation, the internal intercostal and abdominal muscles may be involved in forcing air out of the lungs. In cases of narrowing of the airways, such as asthma, inspiration and expiration are impaired, which may result in a whistling sound (stridor). Because the respiratory bronchioles are the narrowest airways of the conducting zone of the lungs and because they lack cartilage for support, the bronchioles can constrict more under expiration because of the increased surrounding pressure. This causes expiratory wheezing.

Patients frequently ask

What is a normal respiratory rate?

The normal respiratory rate for a healthy adult at rest is 12–18/min. Average resting respiratory rates by age are as shown in the following table:

<table>
<thead>
<tr>
<th>Age category</th>
<th>Respiratory rate</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neonates</td>
<td>30–40</td>
<td>Neonates and smaller children have smaller organs that have to function faster to achieve the same level of metabolic clearance as older children. Also, they have a higher basal metabolic rate and thus their bodies need more oxygen to carry out these functions. Thirdly, the neonate’s lungs and rib cage are almost equal in size and thus lack an area to completely expand. This is compensated through rapid breathing.</td>
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<tr>
<td>Infant</td>
<td>25–40</td>
<td></td>
</tr>
<tr>
<td>1–5 years</td>
<td>20–30</td>
<td></td>
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<tr>
<td>5 years–adulthood</td>
<td>16–24</td>
<td>They have an average metabolic rate, with a maximum growth of the thoracic cavity; therefore, they can maintain the lowest respiratory rate as the lungs expand to the maximum volume and are required to supply oxygen moderately.</td>
</tr>
<tr>
<td>Adulthood (65–80 years)</td>
<td>12–28</td>
<td></td>
</tr>
<tr>
<td>Adulthood (&gt; 80 years)</td>
<td>10–30</td>
<td>There is an increased metabolic rate in this population but the rib cage is adequate for maximum expansion of the lungs; therefore, they respire faster than, but not as fast as, neonates.</td>
</tr>
</tbody>
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References


