Respiratory System

Sub-Subjects: Physiology 4
Lecture: Pulmonary Ventilation & Circulation
Doctor: Nayef Al-Gharaibeh
Done By: Alaa Hani
What makes breathing easy?

The respiratory system has many functions; the most important one is respiration. This system is designed to make breathing energetically affordable which allows our body to utilize the rest in a more productive fashion. This is possible for a number of reasons:

1. High compliance
2. Pulmonary surfactants
3. Partial Inflation of the lungs
4. The unobstructed bronchial tree

For respiration to occur, the lungs must distend and recoil continuously. The elasticity of the lung is described in two ways: compliance and elastic recoil. The compliance of the lung measures how much change in lung volume results from a given change in the transmural pressure gradient. The lower the compliance the higher must be the difference between the pressures of the atmosphere and the thoracic cavity. Increasing the pressure gradient requires a more forceful contraction of the inspiratory muscles to expand the thoracic cavity. The higher the compliance the easier it is to fill the lungs with air. Elastic recoil measures how readily the lungs return to their pre-inspiratory size. This depends on two factors: a) highly elastic connective tissue b) alveolar surface tension. The alveolar surface tension is a result of the attraction of the particles in the thin liquid film lining the alveoli. If the alveoli were lined with water alone, the cohesive forces would exceed the stretching force of the transmural pressure gradient and the lungs would collapse. This tremendous force is counteracted by the pulmonary surfactants. The pulmonary surfactants intersperse between the water molecules and hence lower the surface tension (5-10 times) thereby increasing the lung’s compliance.

The hardest breath is the first one which is taken right after delivery. The situation is analogous to blowing up a new balloon. It takes more effort to blow in the first breath of air in a new balloon than to blow additional breaths into an already partially expanded balloon. When the newborn expires after its first breath, its lungs are left partially inflated by the residual and expiratory reserve volume. This partial inflation enables it to take in the tidal and inspiratory reserve volume.
The fourth reason as to why breathing is easy is the unobstructed bronchial tree. The conducting channels remain almost always open thanks to their cartilaginous make up. They are surrounded by muscles that can increase the diameter when needed. If obstruction occurs due to a pathologic condition (bronchial asthma), breathing becomes very difficult because of the increased airway resistance. The airway resistance increases as a result of the narrowed airway lumens. To take in the tidal volume, a more forceful muscle contraction is needed to overcome the increased resistance. In expiration, the bronchial tree reaches its collapsing point trapping contaminated air inside the respiratory tract, which can be detected by X-ray.

- **What keeps the alveoli open?**

  The surface tension must be distributed equally amongst the different-sized alveoli. If that wasn’t the case, the small alveoli would collapse and empty their content (air) into the larger ones causing them to rupture. This instability is prevented by the following safety factors. First, the alveoli are found in clusters called alveolar sacs. These alveoli share adjacent (septal) walls, so they are interdependent, that is, they depend on the expansion of neighboring alveoli to help them inflate. If an alveolus starts to collapse, surrounding alveoli are stretched and they apply expanding forces on the collapsing alveolus thus keeping it open. This is known as **alveolar interdependence**. The second safety factor is the presence of a large number of fiber units between the alveoli. Third, the surfactants secreted from type II alveolar cells. The concentration of surfactants is inversely proportional to the size of the alveolus. This is important to maintain alveolar stability.
Newborn Respiratory Distress Syndrome (RDS):

Surfactant-secreting alveolar cells develop during the 6th or 7th month in pregnancy. If the infant is born prematurely, not enough surfactants may be produced to reduce the alveolar surface tension to manageable levels. Moreover, the work of breathing is increased because the alveoli tend to almost completely collapse after each expiration. It is as though with every breath the infant must start blowing up a new balloon. Worse yet, the newborn’s muscles are still weak. This would result in the infant putting strenuous effort in order to inflate the poorly compliant lung. Breathing can become exhausting and inadequate to support sufficient gas exchange which may lead to death.

The management of this syndrome usually begins as soon as the infant is born, sometimes in the delivery room. The physicians might hold the newborn upside down to rid the lungs of the excess fluid. If it continues to gasp, a tube is inserted in the trachea by a procedure called tracheal intubation. This tube is connected to a machine which creates a positive pressure that blows air into the respiratory tract overcoming the crushing force of surface tension. In addition to that, surfactant replacements and corticosteroids are given. The latter hastens the maturation process of the alveolar cells.

Work of breathing

Under normal conditions, the respiratory muscles perform “work” to cause inspiration but not to cause expiration because it is almost entirely a passive process caused by elastic recoil of the lungs and the chest cage. Work of breathing is defined as the energy expended to inhale a breathing gas. Despite the work put in the inhalation process, respiration remains energetically inexpensive. This is no longer true when the respiratory tract is suffering from a restrictive or obstructive condition. (More work has to be done in order to breathe). The work of inspiration can be divided into three fractions (in descending order):

1. that required to expand the lungs against the lung and chest elastic forces, called compliance work;
2. that required to overcome airway resistance to movement of air into the lungs, called airway resistance work;
3. that required to overcome the viscosity of lung and chest wall structures, called **tissue resistance work**.

This graph illustrates the work that has to be done in order to inspire. As you can tell, most of the work is done to overcome the elasticity of the lungs and minimal work is done to overcome the tissue resistance.

**Pulmonary and Alveolar Ventilation**

*Pulmonary ventilation* is the total amount of new air moved into the respiratory passages each minute. In other words, it is the volume of air breathed in and out in 1 minute. It is calculated by multiplying the tidal volume and the normal respiratory rate. The normal tidal volume is 0.5 L and the normal respiratory rate is 12 breaths per minute. Therefore, the minute respiratory rate is 6 L/min. Not all inspired air gets down to the site of gas exchange. Part remains in the anatomic dead space which averages to about 150 ml. This is why a new term is used to describe the volume of air used in gas exchange. *Alveolar ventilation* is defined as the volume of air exchanged between the
atmosphere and the alveoli. It is calculated using the following equation:

\[
\text{Alveolar ventilation} = (\text{tidal volume} - \text{dead space}) \times \text{respiratory rate}
\]

With average resulting values,

\[
\text{Alveolar ventilation} = (500 - 150) \times 12 = 4200 \text{ ml} = 4.2 \text{ L}
\]

**Effect of Breathing Patterns on Alveolar Ventilation**

To understand the effect of the dead space on the alveolar ventilation let’s take the following examples,

- If a person deliberately breaths **deeply** (TV= 1200ml) and **slowly** (5 breaths/min), the pulmonary ventilation rate is equal to 6 L/min, while the alveolar ventilation increases to 5250 ml/min.
- In contrast, if a person is breathing **shallowly** (TV= 150 ml) and **rapidly** (40 breaths/min), the pulmonary ventilation does not change. However, the alveolar ventilation rate is equal to 0 L/min. This person is drawing air in and out of the dead space without any atmospheric air being exchanged with the alveoli. The individual can maintain this breathing pattern for a few minutes before losing consciousness.

Notice that in all three cases (quiet breathing, deep and slow, shallow and rapid) the alveolar ventilation rate has changed, while the pulmonary ventilation rate hasn’t. In conclusion, it is more advantageous to have a greater increase in tidal volume than in respiratory rate because of the anatomic dead space.
The following table summarizes the three cases,

<table>
<thead>
<tr>
<th>TABLE 12.2</th>
<th>Effect of Different Breathing Patterns on Alveolar Ventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td>BREATHING PATTERN</td>
<td>TIDAL VOLUME (ml/breath)</td>
</tr>
<tr>
<td>Quiet breathing at rest</td>
<td>500</td>
</tr>
<tr>
<td>Deep, slow breathing</td>
<td>1,200</td>
</tr>
<tr>
<td>Shallow, rapid breathing</td>
<td>150</td>
</tr>
</tbody>
</table>

*Equals tidal volume × respiratory rate.
**Equals tidal volume − dead space volume) × respiratory rate.

- The doctor mentioned that you can increase the dead space by blowing into a tube. Breathing through it becomes exhausting after a while because little or no air is available for gas exchange.

A colleague asked about the difference between deep and forceful inspiration. The term “deep” refers to the volume of the inhaled air, while “forceful” refers to the muscle contraction. A forceful inspiration is not always deep, especially if the pattern is rapid.

*Clinical note: when measuring the respiratory rate, trick the patient into thinking that you’re measuring their heart rate. This would ensure a more accurate result.

- **Pulmonary Circulation**

The lung has two circulations:

1. **Low-pressure, high-flow circulation:**

   It is the one that is somewhat familiar to us. We took in CVS that we have 2 circulations in general; a larger one and a smaller one (the systemic and pulmonary circulation). The larger circulation being the oxygenated blood leaving the left ventricle under a very high blood pressure (120/80 mmHg) and feeding all of the body parts.

   The smaller circulation is different. As the body was fed with oxygenated blood, the deoxygenated blood then enters the right atrium. This then flows into the right ventricle and leaves through the pulmonary
artery which branches into two arteries of the lungs which then further branch into arterioles, capillaries and eventually forms the venous structures which will be oxygenated. Of course as we know, this is an exception since venous structures normally have deoxygenated blood. Here however, the whole target of sending this blood to the lungs is to oxygenate the blood (it picks up oxygen, and gets rid of CO2).

The pulmonary circulation has different characteristics to that of systemic circulation. First of which is that the pulmonary artery and its branches (smaller arteries and arterioles) are shorter and have thinner walls. They also have larger diameters compared to their counterparts in the systemic circulation. All of these factors combined give the pulmonary arterial tree a large compliance of almost 7 ml/mmHg (larger than that in systemic circulation). This is due to the fact that the pulmonary arterial tree needs to accommodate the same CO (which is 5L/min) to that of the left side of the heart. Having a large compliance makes this possible.

Let’s clear out one point though. We said that the compliance of the pulmonary circulation is higher than that of the systemic one. Pulmonary circulation is a lot smaller structure-wise compared to the systemic one, so logically it should have a lower compliance, but because of the factors we mentioned, it has a larger compliance. The overall compliance however, is the same.

2. High-pressure, low-flow circulation

Bronchial artery supplies the trachea, bronchial tree and supporting tissues of the lungs (with the exception of the alveoli) with systemic atrial blood. It originates from the thoracic aorta and branches with the bronchi. Once the oxygenated blood passes the lungs and the supporting tissues, it empties into the pulmonary vein, rather than the bronchial vein. As a consequence, blood returning to the left heart is slightly less oxygenated than blood found at the level of the pulmonary capillary bed.

This is known as a low-flow circulation because the volume of blood flowing through this bronchial tree is almost only 1-2% of the total cardiac output. If you follow the blood volume throughout this, you will notice that there is a difference of 1-2% between the volumes of blood
entering the left atrium to that leaving the right ventricle. Hence, the left ventricle ends up pumping an extra of 1-2% of blood.

❖ Lymphatics

A part of pulmonary circulation is the lymphatic vessels in the chest region. The chest region is rich with lymphatics which are very important in protecting against pulmonary edema, a dangerous situation which we will talk about later on.

- **Pressures in the Pulmonary Systems**
  o The systolic pressure of the right ventricle averages to about 25 mmHg whilst the diastolic averages to about 0 to 1 mmHg, values that are only one-fifth those of the left ventricle. The low diastolic pressure is actually normal since it is required for blood to flow into the ventricles from the atria.
  o During systole, the pressure in the pulmonary artery is essentially equal to the pressure in the right ventricle. The diastolic pressure is about 8 mmHg. The mean pressure is equal to 15 mmHg.
  o The mean pulmonary capillary pressure is about 7 mmHg which is less than that of the systemic capillaries that has a systolic pressure of 30 mmHg and diastolic pressure of 10 mmHg.
  o The mean pressure in the left atrium and the major pulmonary veins averages about 2 mmHg. It is difficult to measure the left atrial pressure using a direct measuring device, so it is estimated by measuring the pulmonary wedge pressure. Wedge pressure measurements can be used to clinically study changes in pulmonary capillary pressure and left atrial pressure in patients with congestive heart failure.

* (Pulmonary wedge pressure was not discussed in the lecture, but it is worth mentioning.)

Overall, the pulmonary circulation is a low pressure system compared to the systemic circulation. This is due to the fact that it extends to a shorter distance and has a lower resistance to blood flow.
• **Blood Volume in the Lungs**
  The blood volume in the lungs is about 450 milliliters, about 9% of the total blood volume. The rest is traveling through the systemic circulation. This has its advantages and disadvantages. Under various pathological and physiological conditions, the lungs serve as blood reservoirs. For instance, when a person blows out air so hard that high pressure is built up in the lungs as much as 250 milliliters of blood can be expelled from the pulmonary circulation into the systemic circulatory system. Also, loss of blood from the systemic circulation by hemorrhage can be partly compensated for by the automatic redirection of blood flow from the lungs into the systemic vessels.
  A change in the volume of blood has a greater effect on the pulmonary circulation than the systemic circulation. This is highlighted by the seriousness of the pathologic conditions that shift the blood flow to the pulmonary circulation. Failure of the left side of the heart or increased resistance due to mitral stenosis/regurgitation increases the pulmonary blood volume and causes a large increase in the blood pressure which has a serious impact on our body. The systemic circulation, on the other hand, can handle a shift in blood flow better because it accommodates nine times the blood volume.

❖ **Effect of Hypoxia on The Pulmonary and Systemic Blood Vessels**
  The alveolar capillaries are 5µm wide and cover a surface area of 70m². The diameter of the red blood cell is slightly larger than that of the capillary which forces it to squeeze into the vessel. This, combined with the fact that the capillaries accommodate only 70ml of blood, saturates the red blood cell after crossing only a third of the distance. When the concentration of oxygen decreases below 70%, the adjacent blood vessels constrict, with the vascular resistance increasing more than five-fold. The constriction of the local vessels redirects the blood flow to properly ventilated alveoli to ensure adequate aeration of the blood. Vasoconstriction is promoted by a yet undiscovered vasoconstrictor substance released from the endothelial lining of the alveolar capillary. This is the opposite of the effect observed in systemic circulation, which dilate
the vessels rather than constrict in response to low oxygen. The importance of the vasodilation in systemic capillaries is to increase the flow of oxygenated blood to the hypoxic organ.

- **Effect of hydrostatic pressure**
  *(the doctor continued this concept in the next lecture so don’t worry if you don’t understand it well)*

Alveoli actually surround pulmonary capillaries and not the opposite since we have 300 million alveoli.
Pressure in the capillaries is 8mmHg and in the alveoli it ranges from -1 to +1mmHg.
Blood circulation in the lungs has different zones depending on pressure in the alveoli and capillaries.
Let’s take two alveoli with a capillary in between. If pressure in the alveoli is greater than in the capillary, there won’t be any flow, however if the opposite happens, then there will be blood flowing through the capillary.

---

**Notes:**

1- I apologize profoundly for the delay.
2- Do not listen to the record while studying the sheet.
3- Credit goes to Salam Mustafa, my savior, for helping me with the sheet.

{Note from editor: She needed no savior; she did it on her own, lots of love chickaa}

Edited by: Salam Mustafa