Chapter 42 Part III
The Respiratory System

Notes: In this section we will discuss the breathing system, also known as the respiratory system. This should not be confused with cellular respiration, or aerobic respiration (the breakdown of carbohydrates, and the generation of ATP) which was discussed earlier, and will be discussed again when we talk about Chapter 9.

Subjects:
I. Partial Pressure of Gasses in the Atmosphere and in the Blood
II. Respiratory Media: air vs. water breathers
III. Variations on Lungs I: Positive Pressure Breathing (amphibians) vs. Negative Air Breathing (mammals)
IV. Variations on Lungs II: Continuous Air Flow (birds) vs. In and Out Air Flow (Mammals)
V. Regulation of Carbon Dioxide Levels in Blood
VI. The Human Respiratory System
VII. Pathology of the Human Respiratory System

I Partial Pressure of Gasses in the Atmosphere and in the Blood.

The exchange of oxygen and carbon dioxide in our lungs can be explained by simple concentration gradients. Oxygen enters the blood at the lungs because the concentration of oxygen in the atmosphere is higher than it is in the blood. By the same token, carbon dioxide leaves the blood at the lungs because the concentration of carbon dioxide in blood is higher than it is in the atmosphere.

At sea level the total atmospheric pressure of all gasses is measured as 760mm (measured with a ‘barometer,’ that measures how many millimeters the atmospheric pressure will push a column of mercury up a tube). This is the total pressure of air, which is composed mostly of nitrogen, with a little bit of oxygen and carbon dioxide mixed in with it. Each of these different gasses exerts a ‘partial pressure,’ with all of them adding up to 760mm. The partial pressure of oxygen in air is 160mm (21% of air), and the partial pressure of carbon dioxide in air is very low, at 0.29mm (less than 0.04% of air). Thus, the concentration of oxygen in air is very high, and the concentration of carbon dioxide is very low. The concentration of oxygen in blood returning from the body to the lungs is much lower, and the concentration of carbon dioxide returning from the body to the lungs is much higher. It is because of this pressure and concentration difference that carbon dioxide leaves the blood at the lungs, and oxygen enters the blood at the lungs. A similar situation exists in water, allowing fish to breath.

Aerobic (Cellular) Respiration: Recall that there are three steps involved in aerobic respiration (breakdown of carbohydrates in order to generate energy): 1. Glycolysis, 2. The Krebs Cycle, and 3. The Electron Transport Chain. Carbon dioxide is a waste product of the Krebs Cycle, and
oxygen is required for the Electron Transport Chain. Thus cells are always consuming oxygen and producing carbon dioxide as a waste product. The waste carbon dioxide is released in the lungs during breathing, and new oxygen is acquired during breathing. The lungs are part of what is sometimes called the Respiratory System, but don’t confuse breathing with cellular respiration. Breathing is more accurately described as ‘ventilation’ (to be discussed later).

II Respiratory Media: Air vs. Water Breathers

For land animals, oxygen and carbon dioxide exchange happen for the blood in the lungs. The inner surfaces of lungs are kept moist because gas cannot cross a dry membrane. (This is the main reason for having our lungs inside, rather than breathing through the skin as amphibians do. Amphibians cannot move very far from the water, because their skin must be kept moist at all times.) In the case of insects (arthropods) oxygen exchange takes place via a Tracheal System, which is basically a long tube connected to holes in the exoskeleton (Figure 42.24). Organisms that live on land are fortunate that the concentration of oxygen in air (the ‘respiratory medium’ which they breathe) is so high (21%). Organisms that live in the water, and breath water (the ‘medium’ they breathe) are less fortunate in that the concentration of dissolved oxygen in water is much lower (approximately 0.5%), and they need to have a much more efficient gas exchange system.

For fish and other water-breathers, oxygen and carbon dioxide exchange occur in feathery ‘gills,’ which are sometimes protected by plates of cartilage (see Figure 42.23). Many variations on gills exist (see Figure 42.22), but they are all basically the same thing. They are all essentially thin appendages, with high surface areas, that are heavily lined with blood capillaries. The gill system of exchanging gasses is more efficient than the lung system for two reasons. First, water flows CONTINUOUSLY over the gills, as opposed to flowing in and then out again, the way it does in lungs. Second, blood flows through the gills in the opposite direction that water flows over them. This is called Countercurrent Exchange. Countercurrent exchange makes the most efficient use of the differences in oxygen partial pressure inside and outside the blood; guaranteeing that oxygen will always go into the blood by matching the most oxygen enriched blood with the most oxygen enriched water. This system makes sure that the oxygen concentration in the water is always higher than that in the blood, guaranteeing that oxygen will always move into the blood (see Figure 42.23).

III Variations on Lungs I: Positive Pressure Breathing (amphibians) vs. Negative Air Breathing (mammals)

The process of moving air in and out of the lungs is called ventilation. The process of moving blood through the lungs to exchange gasses is called perfusion. Breathing air in is also called inspiration, and breathing air out is also called expiration. There are two types of lungs: A) those that are ventilated using positive pressure, and B) those that are ventilated using negative pressure. In positive pressure breathing, air is literally pushed into the lungs mechanically. Many types of frogs do this by pushing air into their lungs using muscles in their mouth. Because lungs are elastic, once air is pushed in, it will go back out again when the inward
pressure is released, like deflating a balloon. This is called **elastic recoil**. In negative pressure breathing, the lungs are stretched from the inside to create suction, literally *sucking* air inside like a bellows. Humans do this by contracting the muscles in between their ribs (called **intercostal muscles**), and contracting their **diaphragm** (a large layer of muscle located below the lungs), which has the effect of increasing the size of the lungs, and pulling air inside (see Figure 42.28).

Thus, positive pressure breathers (ie-frogs) literally *push* air into their lungs, while negative pressure breathers (ie-humans) literally pull or suck air into their lungs. In both cases, the air is expelled again using elastic recoil. This is only true for air breathers. Fish and other water breathers have gills instead of lungs, and either wave these gills around in the water, or swim through the water to make sure water passes over their gills. (Thus, it is true that most fish cannot stop swimming, or they will die of suffocation. Does this mean that fish don’t sleep? Yes, most fish and other water-breathing organisms don’t sleep, at least not as we understand it.)

**IV. Variations on Lungs II: Continuous Air Flow (birds) vs. In and Out Air Flow (Mammals)**

Simple mammalian lungs are composed of many tiny inflatable sacks (called **alveoli**) that are surrounded by capillary beds, and which inflate and deflate. Human lungs are made up of approximately 300 million alveoli. Every time a human inhales, they bring fresh air (rich in needed oxygen) into the lungs, and every time they exhale they expel the old air (rich in waste carbon dioxide). This is actually quite inefficient compared to fish gills, which allow a *continuous* flow of water, and thus, continuous exchange of gasses. Birds actually do a variation of this, where air flows continuously through their lungs. A bird has a posterior air sack, which it fills with air prior to entering the lungs, and an anterior air sack which fills with air after the air has left the lungs (see Figure 42.27). By filling these air sacks in the proper sequence, birds are able to keep air flowing through structures in their lungs (called **parabronchi**) in one direction, continuously. This allows for greater ventilation, and a higher metabolic rate. As mentioned in previous lectures, birds also have nucleated erythrocytes, which live longer than mammalian erythrocytes. Thus, birds have a much more efficient respiratory system, and a higher metabolic rate than mammals, due to longer lived red blood cells, and a more efficient breathing system.

**V. Regulation of Carbon Dioxide Levels in Blood.**

Carbon Dioxide mixes with water in blood to form **carbonic acid**, which then ionizes to form **bicarbonate** ions and hydrogen ions (see page 922, and Figures 42.29 and 42.31). The carbonic acid to bicarbonate ratio acts as a **buffer** for the blood. Under normal breathing conditions this system buffers the blood at a **pH of between 7.2 and 7.4**. If you exert yourself with exercise, your cells will respire more, and generate more carbon dioxide. Increasing the output of carbon dioxide creates more carbonic acid, and lowers the **pH** of the blood. A structure in the brain, called the **Medulla Oblongata** measures the **pH** of the blood, and increases your breathing depth and breathing rate to raise the **pH** by removing more carbon dioxide from the blood at the lungs. Thus, breathing rate and breathing depth are regulated by the medulla oblongata in response to
changes in blood pH, and not changes in oxygen concentration, per se. Thus, while the actual purpose of increasing the breathing rate is to bring in more oxygen, and get rid of more carbon dioxide, it is the level of carbon dioxide in blood that controls the breathing rate. (This is why, if you get nervous and ‘hyperventilate’ [rapid, shallow breathing], a medical professional will get you to breathe temporarily into a paper bag. This will cause you to re-inhale the carbon dioxide you’ve just exhaled. Can you explain what the effect of this would be?) Signals regulating breathing are sent from the medulla oblongata to the diaphragm via a set of nerves called phrenic nerves, and to the intercostal muscles via nerves called intercostal nerves.

**Hemoglobin** is the main protein which carries oxygen around to the body in most mammals. Significantly, the affinity of hemoglobin for oxygen differs with pH. The affinity of hemoglobin for oxygen is lower at lower pH. Recall that the pH of the blood is lower if it has more carbon dioxide dissolved in it, and the level of carbon dioxide dissolved in the blood will be higher in areas where the cells are respiring more. The result of this is that more oxygen will be ‘unloaded’ by hemoglobin at cells that are respiring more, and generating more carbon dioxide. This makes sense, as your cells will require more oxygen when they are respiring more, in response to exercise or exertion, for example. Thus, if you are running, the pH of the blood bathing your leg muscles will be lower, and in response to this, more oxygen will be released in these areas.

**VI. The Human Respiratory System.**

Air enters the upper respiratory tract via the nose and mouth. The area where the oral cavity branches out into either the esophagus (leading to the stomach) or the trachea (leading to the lungs) is called the larynx. The larynx includes the epiglottis, a flap of tissue that covers and closes off the trachea when you swallow, to prevent food and liquid from going down into the lungs. The trachea is lined with rings of cartilage to prevent it from collapsing (like a vacuum cleaner hose lined with a spring, and for the same reason). The trachea then bifurcates into a left and right mainstem bronchus (collectively referred to as bronchi), which lead to a left and right bronchial tree. Note that human lungs are not symmetrical. The right lung has three lobes while the left only has two, meaning that three branch networks are required for the right lung, and only two are required for the left. Each tree then branches out into smaller tubes called bronchioles, each of which is attached to many microscopic air sacks called alveoli (singular: alveolus). The alveoli are separated by capillary networks by only one or two layers of simple squamous epithelium, allowing gasses to exchange easily.

The lungs and heart are enclosed in a membrane-lined compartment called the plural cavity, and sit atop a large, thick layer of muscle called the diaphragm. When relaxed the diaphragm in convex (bent upwards), but moves downwards when the diaphragm muscles are contracted. This has the effect of pulling the lungs downwards, and pulling them open in the process, and sucking air inside. Muscles located in between the ribs, called intercostal muscles, pull the rib cage upwards when contracted, opening the lungs even more, and sucking more air inside. Signals are sent from the medulla oblongata to the diaphragm to contract via nerves called phrenic nerves, and signals are sent to the intercostal muscles via intercostal nerves. Contracting the muscles of
the diaphragm and intercostals causes the lungs to inflate, and takes effort. Relaxing the muscles allows the lungs to deflate spontaneously, due to elastic recoil.

Human lungs contain approximately 300 million alveoli, which are the main structures where gas exchange takes place. The alveoli are not lined with cartilage, and are not rigid. They are therefore able to expand and contract with each breath. The alveoli have thin walls (one or two layers of squamous epithelium, and a thin layer of connective tissue) to allow gas exchange, and are extensively lined with capillary beds. They are elastic (a property of the connective tissue, which contains elastin), so that once they have been inflated they will deflate again via elastic recoil.

The squamous epithelial cells that form the lung membrane are classified as either Type I or Type II alveolar cells. Type I cells constitute the majority, and are only structural in nature. By contrast, Type II alveolar cells actively secrete a fluid called surfactant, which coats the side of the membrane that is exposed to air. This fluid serves two purposes. First, it helps to keep the lung membranes moist (as oxygen and carbon dioxide won’t cross a dry membrane, and must first dissolve in water). Second, the surfactant prevents the lungs from collapsing, and the inner surfaces from sticking to one another. The lung membranes are coated with a large amount of water. If the walls of an alveolus ever came close enough together to touch one another, they would probably stick together, and be held together by surface tension. The surfactant secreted by Type II cells is rich in lipids that are able to lower the surface tension of the liquid lining the lungs, making the alveolar sack easier to re-inflate if they should ever collapse and stick together. (Premature babies have not yet started to produce lung surfactant, making the danger of lung collapse, and the inability to re-inflate the lung quite severe. When this happens it is called Infant Respiratory Distress Syndrome [discussed below]).

VII Pathologies Associated With The Human Respiratory System

The following is only a small sample of some of the problems that can be associated with the human respiratory system.

**Infant Respiratory Distress Syndrome:** The Type II alveolar cells of developing babies only start to produce lung surfactant after approximately 20 weeks of development. Premature babies, therefore, are in danger of having their lungs collapse (called atelectasis). Without surfactant, re-inflating the lungs is difficult because the surface tension of the liquid lining the lungs is too high. (You can demonstrate how this works with a party balloon. Try blowing up the balloon when it is dry. Then add some water to the inside of the balloon, and see how much harder it is to blow up. Then, finally, add a bit of dish washing liquid to the wet balloon and see how it becomes easy again. The dish washing liquid is doing the job that surfactant does in lungs.) When this happens it is called Infant Respiratory Distress Syndrome (IRDS), and it is often fatal.

**Chronic Bronchitis:** A condition where the bronchial tubes are constantly inflamed or irritated (often due to allergies, or cigarette smoking), and generate excess mucus that blocks breathing.
Chronic bronchitis is one of a class of conditions collectively referred to as **Chronic Obstructive Pulmonary Disease (COPD)**.

**Emphysema:** A condition where the elasticity of the alveoli has been lost, and once inflated, they will not deflate again as easily, due to **loss of elastic recoil**. The old, carbon dioxide saturated air has trouble getting back out again, making it difficult to breath, and causing the blood to be too acidic. Emphysema can be caused by many things, but the most common cause is cigarette smoking.

**Cardiogenic Pulmonary Edema:** ‘Pulmonary edema’ refers to having excess fluid in the lungs. Pulmonary edema can have several causes, but we’ll only discuss one of them here. Recall that if you increase the **hydrostatic pressure** in a capillary bed, you will literally force plasma out of the blood into the interstitial spaces. In lungs, the interstitial space is inside the alveoli themselves. For people who have a weakened left side of the heart (relative to the right side), the right side is able to pump blood into the lungs, but there is a ‘traffic jam’ in the left side of the heart, and the left side is not able to pump it back out to the body fast enough. The backup of blood in the left side of the heart creates a back pressure in the capillary beds of the lungs, forcing plasma into the alveoli. Having fluid in the lungs makes it difficult to breathe. Breathing difficulty is called **dyspnea**. People with pulmonary edema often have dyspnea, and typically have more difficulty breathing when they’re lying down. Difficulty breathing when you are lying down is called **orthopnea** (or sometimes ‘sleep orthopnea’). People with **left ventricle insufficiency** (a weak left ventricle) often have to sleep sitting up because breathing is too difficult otherwise.

**PRACTICE QUESTIONS:**

**Short Answer Questions:**
1. Air is composed mainly of oxygen, nitrogen and carbon dioxide. Place these three things in order of the most abundant to the least abundant. (3 points)
2. What is the approximate concentration of oxygen in air (as a percentage)?
3. Do humans use positive pressure breathing or negative pressure breathing?
4. Do frogs use positive pressure breathing or negative pressure breathing?
5. List the two main muscle systems of the human respiratory system responsible for expanding the lungs to draw in air. (2 points)
6. Which part of aerobic respiration generates carbon dioxide as a waste product?
7. Which part of aerobic respiration consumes oxygen, and converts it to water?
8. What is the technical term used to describe moving air in and out of the lungs?
9. What is the technical term used to describe moving blood through the pulmonary capillary beds in order to re-oxygenate it?
10. What is the single largest anatomical structure responsible for inflating human lungs?
11. Which part of the brain is responsible for regulating your breathing rate, and breathing depth, and what is it responding to when it does so? (3 points)
12. Name for the nerves that transmit breathing signals from the **medulla oblongata** to the **diaphragm**?
13. Does the affinity of hemoglobin for oxygen increase or decrease as blood pH is lowered?
14. Would you expect the concentration of carbon dioxide in the blood to be higher in the left side of the heart or the right side?
15. Would you expect the pH of blood to be higher in right side of the heart or the left side?
16. Would you expect the pH of blood to be lower in the right side of the heart or the left side?
17. How many lobes does the human right lung have?
18. How many lobes does the left human lung have?
19. Technical term for difficulty breathing, or shortness of breath?
20. Technical term for difficulty breathing while laying down or sleeping.
21. Name for the body cavity that the lungs and heart are contained in.

Essay Questions:
1. Explain two ways in which the fish Gill System of exchanging blood gasses is more efficient than the mammalian Lung System. (10 points)
2. Explain two ways in which the bird bronchial breathing system is more efficient than the mammalian bronchial breathing system. (10 points)
3. Explain how the affinity of hemoglobin for oxygen changes in response to increasing or decreasing the pH of blood. (10 points)
4. Would you expect the pH of blood to be higher in the right side of the heart or the left side? Explain your reasons for thinking so. (20 points)
5. Explain how positive pressure breathing (in amphibians) differs from negative pressure breathing (in mammals). (20 points)

Definitions: Define the following terms. If the term describes a pathology, explain the cause. (this is why some of these descriptions are worth so many points.)
1. Plural cavity (5 points)
2. Left ventricle insufficiency (5 points)
3. Positive Pressure Breathing. (5 points)
4. Negative Pressure Breathing. (5 points) Orthopnea
5. Emphysema (10 points)
6. Dyspnea (10 points)
7. Infant Respiratory Distress Syndrome (IRDS; 10 points)
8. Sleep Orthopnea (20 points)
9. Chronic Bronchitis (10 points)
10. Cardiogenic Pulmonary Edema (20 points)
11. Atelectasis (10 points)
12. Chronic Obstructive Pulmonary Disease (COPD; 10 points)
Extended Matching: Match the term to the definition.

A. Alveoli
B. Atelectasis
C. Bronchi
D. Bronchitis
E. Countercurrent
F. Diaphragm
G. Dyspnea
H. Emphysema
I. Epiglottis
J. Expiration
K. Gills
L. Inspiration
M. Intercostal
N. Larynx
O. Medulla Oblongata
P. Orthopnea
Q. Parabronchi
R. Perfusion
S. Phrenic
T. Plural
U. Terminal Bronchioles
V. Trachea
W. Ventilation

1. Technical term which refers to getting air into the lungs (2 answers).
2. Name for the body cavity that the lungs and heart are contained in.
3. Technical term for difficulty breathing, or shortness of breath.
4. Technical term for the collapsing of a lung or alveoli. (When walls of alveoli touch each other, and have trouble coming apart again.)
5. Lung pathology, where lungs have lost their elasticity, making it difficult for air to get out.
6. Name for the organs that aquatic animals use (instead of lungs) to breathe.
7. Technical name for exhaling air out of the lungs.
8. Condition where the bronchial tubes are chronically irritated, causing blockage by mucus.
9. Technical term used to describe difficulty breathing when one is lying down, or sleeping.
10. Name for the microscopic air sacks that make up the lungs.
11. Name for the muscles in between ribs that, when contracted, cause the lungs to expand.
12. Flap of tissue that covers the entrance to the trachea when you swallow.
13. Name for the large, cartilage-lined tube that brings air to the lungs.
14. Name for the smaller, cartilage-lined tubes that bring air to the left and right lungs after bifurcating from a larger tube.
15. A part of the brain that regulates breathing rate and breathing depth in response to changes in pH.
16. The smallest cartilage-lined tubes in the lungs, that are directly attached to the microscopic air sacks of the lungs where gas exchange takes place.
17. Area where the oral cavity diverges into the trachea and esophagus.
18. Technical term for circulating blood through the lungs.
19. A structure found in the lungs of birds that allows for continuous, unidirectional ventilation.
20. A sheet of skeletal muscle just underneath the lungs.
21. Term used to describe the way a fish circulates blood through its gills in the direction opposite water flow.
22. The largest anatomical structure responsible for inflating human lungs.
23. Name for the muscles in between ribs that expand the rib cage and lungs when contracted.
24. Name for the nerves that carry breathing impulses from the medulla oblongata to the diaphragm.

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