2

HOW WE BREATHE

We breathe in. We breathe out. We do this on average 12 to 16 times a minute. Although we can consciously decide to take a breath, to breathe faster or slower, to hold our breath, or to take an extra-deep breath, the vast majority of the time we breathe without giving it a thought. And that's a good thing too! Right? Just imagine trying to get some sleep if you had to think about every breath.

So it's automatic when we need it to be, and yet we can have control when we want it. Our Creator thought of everything.

Now that we have examined the parts of the respiratory system, let's take a close look at how we breathe.

Breathing Basics

At first glance, breathing doesn't seem all that complicated. It has only two parts — in and out.

The first phase of breathing is called *inspiration* (or *inhalation*), when air is taken into the lungs. The second phase is called *expiration* (or *exhalation*), when air flows back out of the lungs. Air goes in, air goes out. Nothing to it.

But when you look closer at "how" and "why" the air moves the way it does, you begin to see the wonderful complexity. It's not simple at all.

We will begin by seeing how we get air in. (We'll get it back out later. . .)

Inspiration

Taking air into the lungs is known as inspiration. It is also called inhalation, inhaling, or just "breathing in." It is such a familiar thing, isn't it? You expand your chest and you feel the air move through your nose and down into your lungs.

Here is how it works.

Recall our discussion about blood flow. How does blood flow? It flows from higher pressure to lower pressure. The higher pressure in the larger arteries causes blood to flow to the smaller, lower pressure arteries downstream.

Air flow works pretty much the same way. Air moves from areas of higher pressure to areas of lower pressure. When the lungs expand or contract, the pressure in the airways changes. This results in air flowing into and out of the lungs.

Imagine the lungs at rest in the thoracic cavity. No inspiration or expiration happening. No pressure changes are occurring. No air is moving.

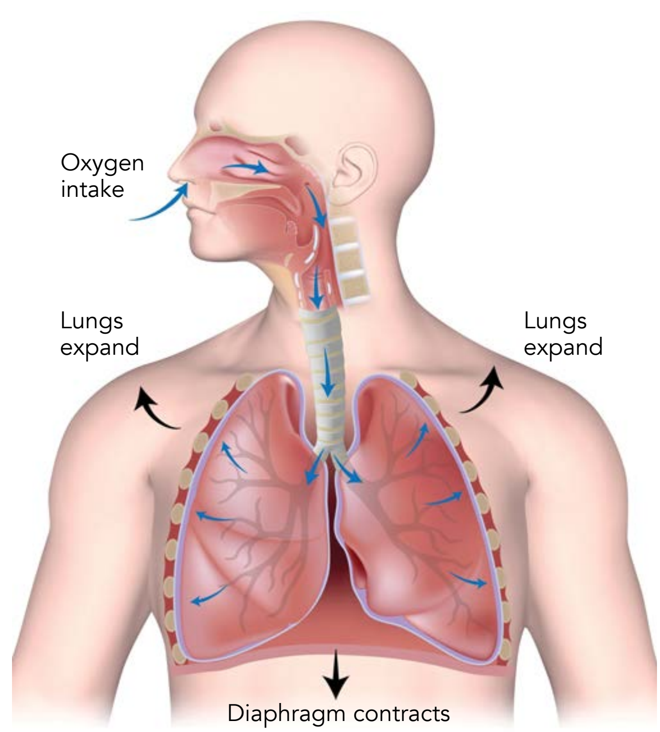
Now let's take a breath.

Inspiration begins with the contraction of the inspiratory muscles, the *diaphragm* and the intercostal muscles. The diaphragm is the large, dome-shaped muscle located below the lungs. The bases of the lungs rest on the diaphragm. When the diaphragm contracts, it flattens and loses much of its domed shape. As it contracts and flattens, the height of the thoracic cavity increases, making the space in the chest much larger. Air rushes into the enlarged thoracic cavity. Contraction of the diaphragm accounts for about 75 percent of the air movement in a typical breath.

The *intercostal muscles* are the muscles between the ribs. When these muscles contract, they elevate each

TAKING A CLOSER LOOK

Inspiration



rib like the handle on a bucket. This movement of the ribs causes an increase in the size of the thoracic cavity, not only front to back (anteroposteriorly) but also side to side (laterally). The reason for this has to do with how the ribcage was designed. The ribs are attached posteriorly to the vertebral bones and anteriorly to the sternum. When the intercostal muscles contract, the ribs move much in the same way that a bucket handle moves when it is lifted. It moves both up and out at the same time. About 25 percent of the air movement in a basic breath is due to intercostal muscle movement.

As the thoracic cavity enlarges, each lung expands. This happens because the pleura help the lungs "stick" to the chest wall. The parietal pleura is in contact with the chest wall and moves outward with it. Because there is a lot of surface tension between the parietal and visceral pleura, the visceral pleura and the attached lung expand too.

When the diaphragm and intercostal muscles contract, the thoracic cavity expands. As the thoracic cavity expands, the lungs expand as do the airways in the lungs. This lung expansion causes a decrease in the air pressure in the alveoli. When the pressure in the alveoli drops below the pressure in the surrounding environment (atmospheric pressure), air moves into the lungs. This is a simple inspiration.

In some circumstances, when a deeper or more forceful breath is required, there are so-called accessory muscles that come into play. These muscles are not important during normal inspiration, but are used, for example, during exercise. These accessory muscles include the sternocleidomastoid muscles, the scalene muscles, and the pectoralis minor muscles.

Expiration

Getting air back out of the lungs is called expiration, also known as exhalation, exhaling, or "breathing out."

Isn't expiration just the opposite of inspiration? That seems reasonable, but there is a significant difference. You see, expiration is not ordinarily an active process. It is a passive process.

At the end of inspiration, the diaphragm and intercostal muscles simply relax. As they relax, the diaphragm and ribs return to their original position. In addition, due to their natural elasticity, the lungs contract back to their original shape. As this recoil/relaxation takes place, the air pressure in the alveoli increases. When the pressure in the alveoli increases above the pressure in the surrounding environment, air moves out of the lungs. This is a simple expiration. As you see, no active muscle contraction is needed for breathing out.

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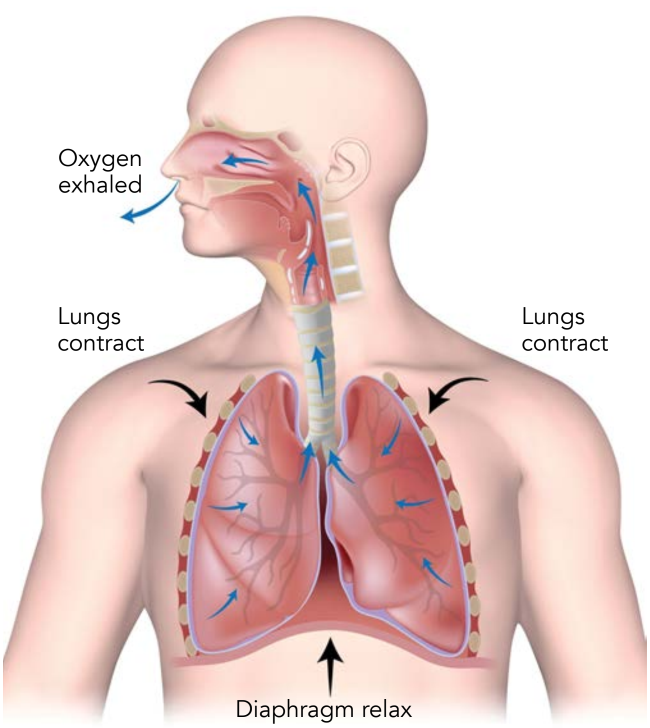
Expiration



There are times when we need a more forceful expiration, like when you are blowing up a balloon or playing the trumpet. In these situations, the abdominal wall muscles can assist expiration by contracting and pushing the abdominal organs upward against the diaphragm. The internal intercostal muscles can also help by pulling the rib cage downward.

Lung Volumes

The *total lung capacity* of an average male is around 6 liters. This is the total amount of air in the lungs at the end of a deep inspiration. We do not, however, move nearly that much air with each breath.

In an adult, a normal breath moves about 500 mL of air into the lungs during inspiration and back out during expiration. This is called the *tidal volume*. The tidal volume is the amount of air in one breath.

Fortunately, we do have the capacity to take in far more than just 500 mL of air in a breath. During heavy exertion we need to take in much more oxygen. We have a great deal of lung capacity in reserve. To see this for yourself, try this: take a normal breath, and stop. Don't exhale. Now start breathing in again. Breathe as deep as you can. The amount of air taken in *beyond* the normal tidal volume is called the *inspiratory reserve volume*.

Now again, take the deepest breath you can. Hold it for a second or two and then exhale as much air as you can. The amount of air you just exhaled is called the *vital capacity*. This is the maximum amount of air that can be exhaled after a maximum inspiration.

Now if you exhale as completely as possible, can you get all the air out of your lungs? Of course not. And it's a good thing too. There needs to be some air left in the lungs at the end of expiration or the alveoli in the lungs would collapse. The amount of air that remains in the lungs after a maximum expiration is called the *residual volume*.

The amount of air that is moved into and out of the lungs in one minute is called the *minute ventilation*.

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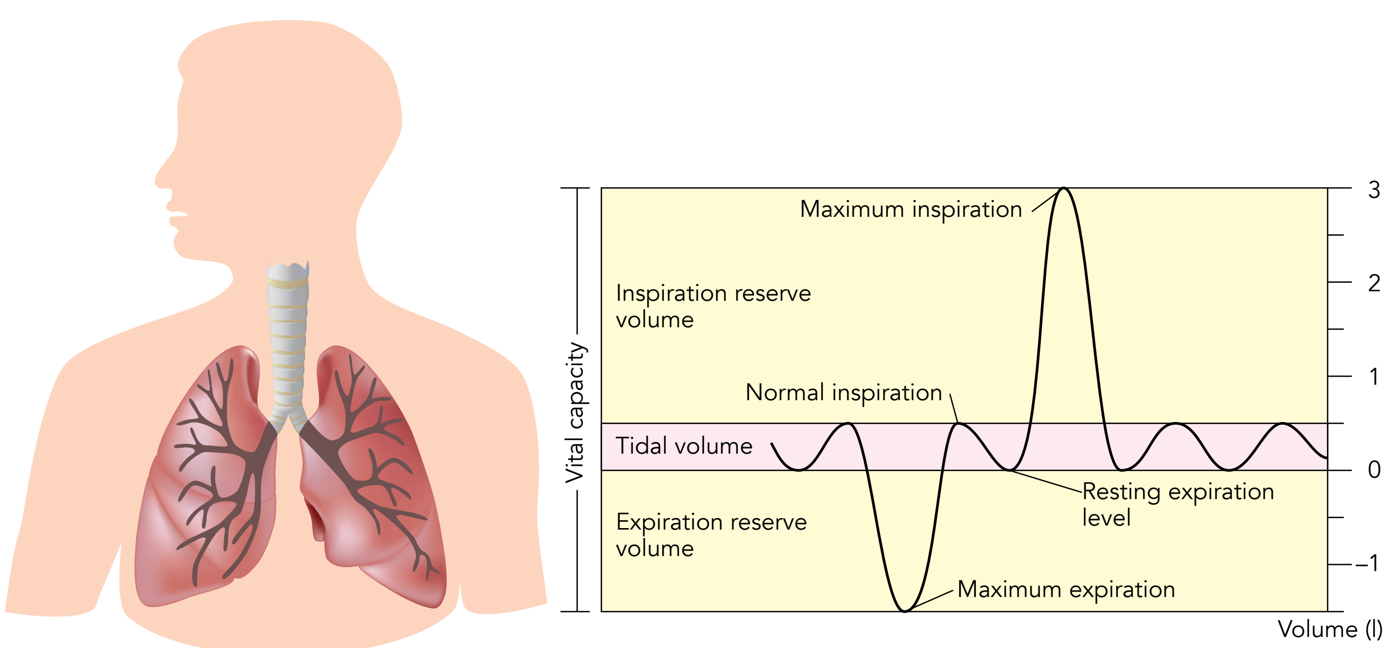
Lung Volume



It is easy to calculate. If a person at rest has a tidal volume of 500 mL and breathes 14 times a minute, what do you think the minute ventilation is?

500 mL/breath X 14 breaths/minute

7000 mL/minute

Minute ventilation = 7 liters/minute

This is a calculation of minute ventilation at rest. During exertion, the minute ventilation will be much, much higher.

One other measurement that is often quite helpful is called the *forced expiratory volume in 1 second* (or FEV_1). This is, as it would seem, the amount of air that can be forced out of the lungs in one second after a maximal inhalation. Patients with asthma or chronic obstructive pulmonary disease (COPD) often have an abnormal FEV_1 and its assessment can be helpful in treating those patients.

Gas Exchange

The ultimate purpose of the respiratory system is to get oxygen into the bloodstream so that it can be delivered to the body's tissues and to remove the carbon dioxide generated by the body tissues and expel it from the body. Even as incredible as the anatomy of the respiratory system is, it would be a very poor design if it didn't accomplish its mission. But it does work. It works very well indeed!

Oxygenated blood is pumped from the left ventricle out to the body. When its gets to the capillary beds, the oxygen in the blood moves into the tissues where it is used in metabolic processes. As a consequence of these metabolic activities, carbon dioxide is produced. Carbon dioxide is a waste product and would do serious harm to cells if it were allowed to accumulate. Fortunately, the carbon dioxide that is produced in the tissues moves into the blood in the capillaries to be taken away and disposed of.

The blood leaving the capillary beds has a lower oxygen content than the blood entering the capillary beds. This blood is said to be deoxygenated.

Deoxygenated blood returns to the right atrium and is sent to the right ventricle. The right ventricle pumps the deoxygenated blood to the lungs via the pulmonary artery. This blood makes its way to the capillary beds adjacent to alveoli in the lungs.

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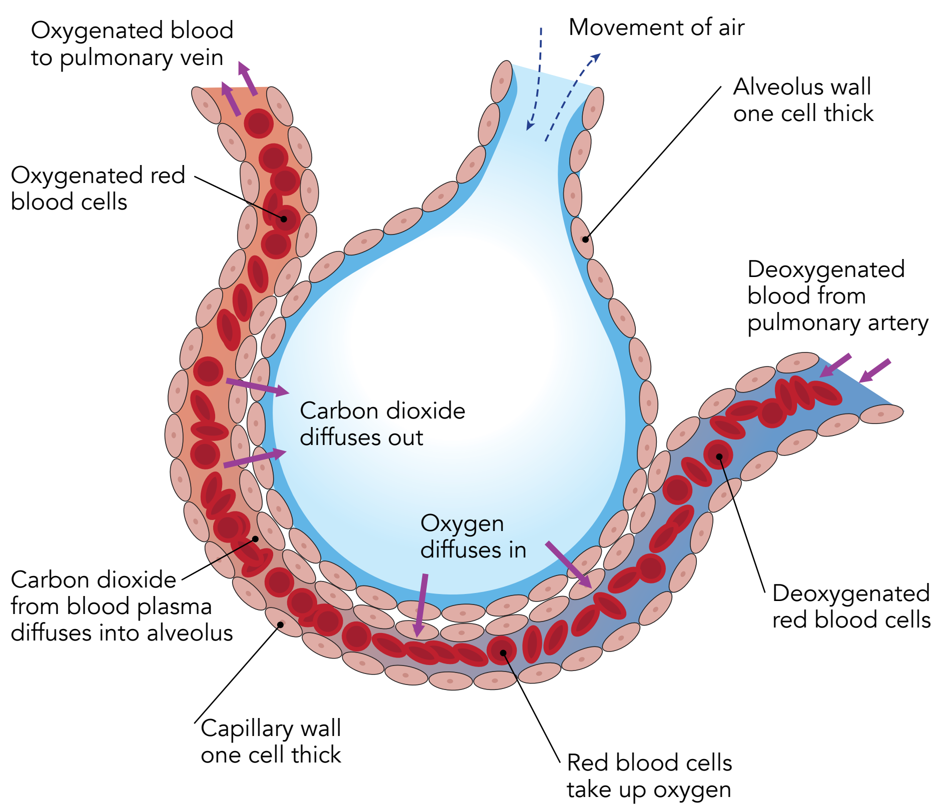
Alveolar Gas Exchange



The alveolus, as we said before, is where gas exchange takes place, and this is the ideal place for this process to occur. The very thin wall of the alveolar cell, adjacent to the thin wall of the capillary, makes a perfect environment to promote the movement of gases into and out of the blood.

After all, it makes sense that it's easier for gases to diffuse through something thin than something thick, right? That is why there is no gas exchange farther back up the bronchial tree. Those structures (bronchi and bronchioles) are too thick to allow for proper gas exchange. The alveoli are perfectly designed for gas exchange.

The total surface area for gas exchange provided by the alveoli is staggering! With at least 300 million alveoli in our lungs, if you spread all the alveoli out on a flat surface, it would cover an area a little more than 750 square feet! That is a lot of area for gases to diffuse through. This is another evidence of the amazing design of the human body. It didn't just happen by accident.

Oxygen Transport

Step one of gas exchange is to get the oxygen in the alveoli into the blood in the alveolar capillaries. In other words, the "deoxygenated" blood needs to be "oxygenated." Seems simple, but how does it work?

Well, doesn't the oxygen in the alveoli just move into the blood on its own? After all, we said these membranes were thin enough for the oxygen to move through them easily. That's true enough, but as usual, there's more to it than that.

When oxygen reaches the blood in the capillaries, it doesn't just dissolve in the blood plasma and get carried away to the tissues. In fact, when you look closely, you will find that blood plasma does not make a very good carrier of oxygen. You see, oxygen does not dissolve well in water. Blood plasma only carries about 2 percent of the oxygen found in the bloodstream — so there must be something else in the blood to "do the heavy lifting," so to speak. There must be something in the blood that can carry oxygen efficiently. And that thing is called hemoglobin.

The erythrocytes (red blood cells) in the blood contain a protein called hemoglobin. Hemoglobin is composed of four polypeptide chains and four heme groups. Each of the four heme groups contains an iron atom. Each iron atom in the hemoglobin molecule can bind to one oxygen molecule, so every hemoglobin molecule can bind with a maximum of four oxygen molecules.

Hemoglobin binds oxygen molecules very efficiently, and the vast majority of the oxygen in the blood (98 percent or so) is bound to hemoglobin. When hemoglobin is bound to one or more oxygen molecules, it is called *oxyhemoglobin*. When the hemoglobin is not bound to any oxygen molecules, it is called *deoxyhemoglobin*.

When four molecules of oxygen are bound, the oxyhemoglobin is "fully saturated." If one, two, or

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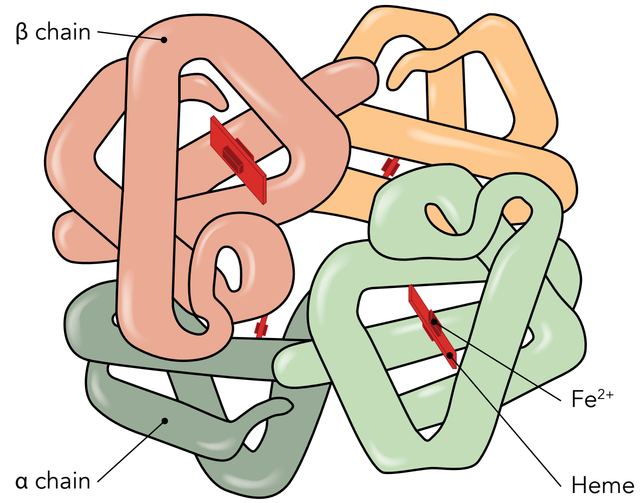
Hemoglobin



Structure of the hemoglobin molecule showing alpha (a) and beta (β) chains, heme groups (Heme), and iron atoms (Fe^{2+}).

three oxygen molecules are bound, the oxyhemoglobin is only "partially saturated."

The presence of hemoglobin is the reason that our blood is red. Oxyhemoglobin is bright red in color. Deoxyhemoglobin is a much duller shade of red. This is why arterial blood (oxygenated) looks redder than venous (deoxygenated) blood.

Each red blood cell contains around 270 million hemoglobin molecules. So, at maximum saturation, every red blood cell can carry one billion oxygen molecules! That's a LOT of oxygen molecules.

Oxygen contained in inspired air is delivered to the alveoli, and it moves into the alveolar capillaries where it is binds to hemoglobin. In yet another testimony to our Creator, hemoglobin has an incredible property. After the first oxygen molecule binds to hemoglobin, the hemoglobin molecule alters its shape slightly to enhance the binding of other oxygen molecules! (No way that happened by chance. Our Creator thought of everything!) This is a very efficient system.

The now-oxygenated blood is carried back to the left side of the heart by the pulmonary veins. The left side of the heart then sends it out to the body's tissues. Upon arrival in the capillary beds of the body's tissues, the oxygenated blood finds itself in an entirely different situation. Whereas in the alveoli the oxygen level was relatively high, oxygen levels in the tissues surrounding the capillaries are relatively low. So what happens to the oxyhemoglobin

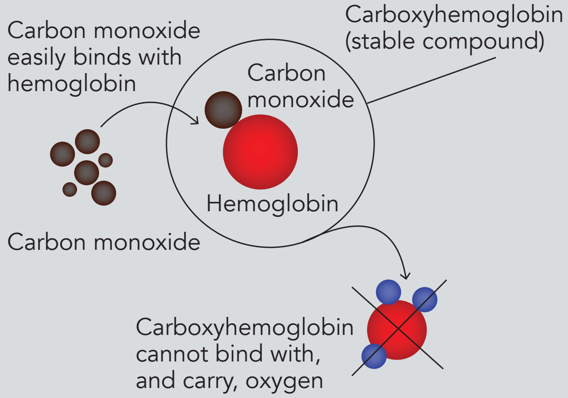
Carbon Monoxide Poisoning

Carbon monoxide is a colorless, odorless gas that consists of one carbon atom and one oxygen atom. It is generated by the burning of carbon-based substances like wood, coal, and gasoline.

People can be poisoned by exposure to carbon monoxide, and a number of deaths are caused each year by this type of poisoning. This can occur when combustion of things like wood or gasoline takes place in poorly ventilated areas. In circumstances like these, people may not realize they are being exposed until significant symptoms develop. Symptoms can include headache, shortness of breath, and nausea. If exposure continues, more severe symptoms can follow, such as confusion, vomiting, and loss of consciousness. In the worst cases, death can occur.

Many homes contain carbon monoxide detectors to alert sleeping people about carbon monoxide leaks in the home. Since carbon monoxide poisoning makes people sleepy, people would not awaken to save themselves without this sort of warning. In a house with a carbon monoxide furnace leak, such a detector can save the lives of everyone in the home.

Carbon monoxide binds very effectively to hemoglobin. In fact, it binds to hemoglobin much more efficiently than oxygen. Carbon monoxide is particularly dangerous because it competes with oxygen for binding sites in the heme group. Plus, hemoglobin's binding to carbon monoxide is 200 times greater than for oxygen.



People exposed to carbon monoxide require prompt medical attention. Treatment for those patients is therapy with 100 percent oxygen until the carbon monoxide clears from the body.

here? If you think it now releases its bound oxygen molecules, you are correct! The released oxygen molecules then move out of the capillaries and enter the body tissue cells where they are needed.

As efficiently as it binds oxygen in conditions of high oxygen concentration, hemoglobin is equally efficient at releasing its oxygen when the surrounding oxygen levels are low. Even at that, not all the oxygen is released from all the hemoglobin molecules in the systemic capillaries. That would not work well at all. Here's why.

When we are at rest, the hemoglobin is almost completely saturated. In fact, it is around 98 percent saturated. That means the hemoglobin in oxygenated blood carries 98 percent of the maximum amount of oxygen it could theoretically hold. After the blood passes through the systemic capillaries we call it "deoxygenated," yet the hemoglobin is still 70 to 75 percent saturated! You see, the hemoglobin doesn't give up all its oxygen on every trip through the body. There's still plenty in reserve. And that's as it should be.

Under normal conditions while at rest, the body only uses about 25 percent of the available oxygen in the blood. But we are not always at rest, are we? During periods of exertion, the body's tissues need much more oxygen to meet their metabolic needs. In situations like this, the body is able to obtain a higher percentage of the oxygen bound to the hemoglobin than it does at rest. But wait a minute, how does hemoglobin release more oxygen at some times and less at others? Hemoglobin can't "know" anything. It doesn't "know" when someone is exercising. It's merely a molecule in the blood. The answer is that there are conditions in the body itself that can cause hemoglobin to release oxygen more readily.

First of all, tissues that are metabolically very active, such as muscles during exertion, can produce acids as a byproduct of that activity. As a result, the acidity of the blood in the region near these tissues increases. Tissues at rest produce far less of these substances, and thus the acid level in the blood near resting tissues is lower. Hemoglobin releases oxygen more readily in a more acidic environment. So the higher the tissue activity, the higher the acidity near these tissues, and ultimately, the more oxygen released to these active tissues.

Second, active tissues produce more carbon dioxide than tissues at rest. Carbon dioxide also binds to hemoglobin, and when it does, it causes the hemoglobin to unload its oxygen more easily. So again, the conditions near active tissues induce hemoglobin to give up its oxygen.

Third, higher temperatures cause hemoglobin to release oxygen. Again, this is another of the conditions found near active tissues. The more active the tissues are, the more heat is generated, and then, the higher the temperature in the capillary beds serving these tissues. So once again, here is a condition expected near tissues requiring more oxygen that leads to more oxygen being released.

It seems almost unfair to say that the respiratory system is designed to deliver oxygen to the tissues. It is really over-designed when you think about it. There are so many features working so well together: the design of the alveoli, the hemoglobin molecule itself, and the ability of hemoglobin to alter its binding to oxygen in response to the precise conditions produced by active tissues. It makes no sense to think these things could all be some sort of chemical accident occurring over millions of years.

The entire process of oxygen delivery speaks to the abilities of the Master Designer.

Carbon Dioxide Transport

Not only does the respiratory system take oxygen to the tissues, it has to remove the carbon dioxide produced by these same tissues. There are three main ways that carbon dioxide is carried by the blood.

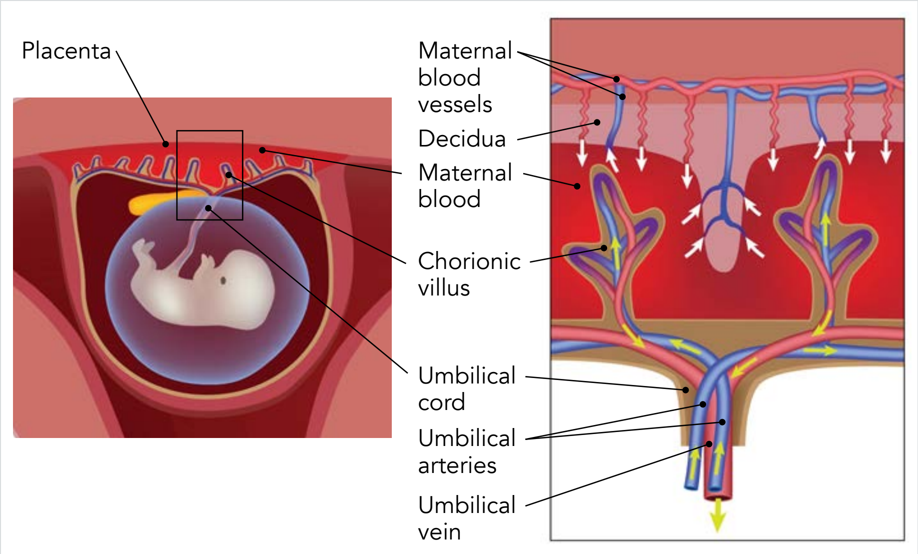
Carbon dioxide can dissolve in the blood plasma. It dissolves in plasma much better than oxygen does. About 10 percent of the carbon dioxide in the blood is carried in this fashion.

Hemoglobin not only transports oxygen, it can also transport carbon dioxide. However, the carbon

The Placenta

We mentioned earlier that a baby in the womb does not have to use its lungs to breathe. Yet a baby of course needs to get oxygen into his or her blood cells and to release carbon dioxide to be carried away. God designed a wonderful way for a baby's gas exchange to take place. He designed a placenta. In the placenta, the mother's blood flows through capillaries right next to capillaries containing the baby's blood. The baby's blood is carried there in the umbilical cord and, once oxygenated, returns to the baby the same way. The mother's and baby's blood do not mix. Instead, oxygen is released from the hemoglobin in the mother's red blood cells. The oxygen crosses from the capillaries containing the mother's blood into the capillaries containing the baby's blood. There, the baby's hemoglobin molecules grab the oxygen molecules and carry it back to the baby.

You might wonder, since the mother's and the baby's blood both contain hemoglobin, how the mother's hemoglobin "knows" to release oxygen for the baby's hemoglobin to pick up. Here God designed a particularly wonderful system. He made a special kind of hemoglobin just for unborn babies. Fetal hemoglobin has an even greater affinity (attraction) for oxygen than ordinary hemoglobin. The unborn baby's hemoglobin is able to overcome the attraction of the mother's hemoglobin and carry away all the oxygen the baby needs from the placenta. Once a baby is born, red blood cells begin to be made with adult hemoglobin, and generally by about six months of age the fetal hemoglobin has been replaced.



dioxide carried by hemoglobin is not bound to iron but instead is attached to amino acids. These amino acids are part of the polypeptide chains that make up the globin part of hemoglobin. When hemoglobin is carrying carbon dioxide it is called *carbaminohemoglobin*. Approximately 20 percent of the carbon dioxide in the blood is transported by hemoglobin.

The remaining 70 percent of the carbon dioxide is transported in the blood plasma as bicarbonate ions (HCO_{3^-}). After carbon dioxide enters the plasma, it soon finds its way to the red blood cells. Once inside the RBC, the carbon dioxide combines with water and is turned into carbonic acid. This reaction occurs very rapidly due to the presence of a special enzyme called *carbonic anhydrase*. The carbonic acid quickly breaks down into a hydrogen ion and a bicarbonate ion. The bicarbonate ion is the form in which the carbon dioxide is carried to the lungs.

In the systemic capillaries where the carbon dioxide levels are high, the tendency is for more carbonic acid to be produced and then, ultimately, more bicarbonate ions. The bicarbonate ions are then carried to the lungs by the blood. In the lungs, the levels of carbon dioxide are relatively low, so the reaction here is reversed. The bicarbonate combines with the hydrogen ions to again form carbonic acid. Then, with the help of the carbonic anhydrase enzyme, the carbonic acid is broken down into carbon dioxide and water. The carbon dioxide then diffuses out of the blood and into the alveoli. It is then taken away with the expired air!

Control of Respiration

We breathe in and out, in and out. Thousands of times a day. And we really never give it a thought. It just happens. Automatically.

But stop and think a minute. We do have control over our breathing — a lot of control when we need it. If we didn't have the ability to voluntarily hold our breath, we could not go swimming. If we could not precisely control our respiratory system on command, we would not be able to talk or shout or sing.

The respiratory system has both involuntary and involuntary controls. And that's a very, very good thing.

The primary control of respiration takes place in the brain, in the medulla oblongata. There are two locations in the medulla that make up what is known as the medullary respiratory center. The first of these is the ventral respiratory group (VRG), and the second is the dorsal respiratory group (DRG). From these two centers, nerve signals are sent to the intercostal muscles and the diaphragm to stimulate them to contract. The contraction of these muscles (as you should recall) triggers inspiration. These impulses are generated for about two seconds, and then they cease. When the nerve signals stop, the intercostal muscles and the diaphragm relax. The natural recoil of these structures leads to expiration. Remember, expiration is generally a passive process. The cessation of nerve stimulation lasts 2–3 seconds, and then stimulation occurs again.

Inspiration is triggered by impulses from both the VRG and the DRG. However, the VRG does have another function. There are times when more forceful expirations are needed. In these circumstances, the VRG sends nerve impulses to the internal intercostal muscles and the muscles of the abdominal wall. Contraction of these muscles helps decrease the size of the thoracic cavity and assists with a forceful expiration.

Another important area is the pneumotaxic area located in the pons. It is sometimes referred to as the pontine respiratory group (PRG). The pneumotaxic area coordinates the switch between inspiration and expiration. The PRG helps regulate how much air is taken in with each breath. It can send signals to turn off the VRG and DRG to help limit inspiration. This can keep the lungs from getting too full of air.

The operation of the respiratory centers is regulated by many inputs from the body.

First of all, we do have significant voluntary control over the respiratory system. This is possible because there are nerve pathways connecting the cerebral cortex to the respiratory centers. This gives us the ability to alter our inspiration and expiration. Of course, this control is within limits. For example, we cannot hold our breath for extended periods of time. Usually, after a minute or so, involuntary control of the respiratory system takes over and causes us to breathe whether we want to or not. These involuntary controls help protect the body and maintain proper levels of oxygen and carbon dioxide.

Further control of the respiratory system is based on input from special sensory cells called chemoreceptors. These special cells are sensitive to changes in the levels of certain chemicals or substances in the body. There are two main groups of chemoreceptors that regulate the respiratory system — the central chemoreceptors that are located in the brain stem, and the peripheral chemoreceptors found in the arch of the aorta and the carotid arteries. These cells help monitor blood levels of oxygen and carbon dioxide, as well as the acidity of the blood itself.

What is the most important thing that the respiratory system does? If you said that taking in oxygen and getting it into the bloodstream is most

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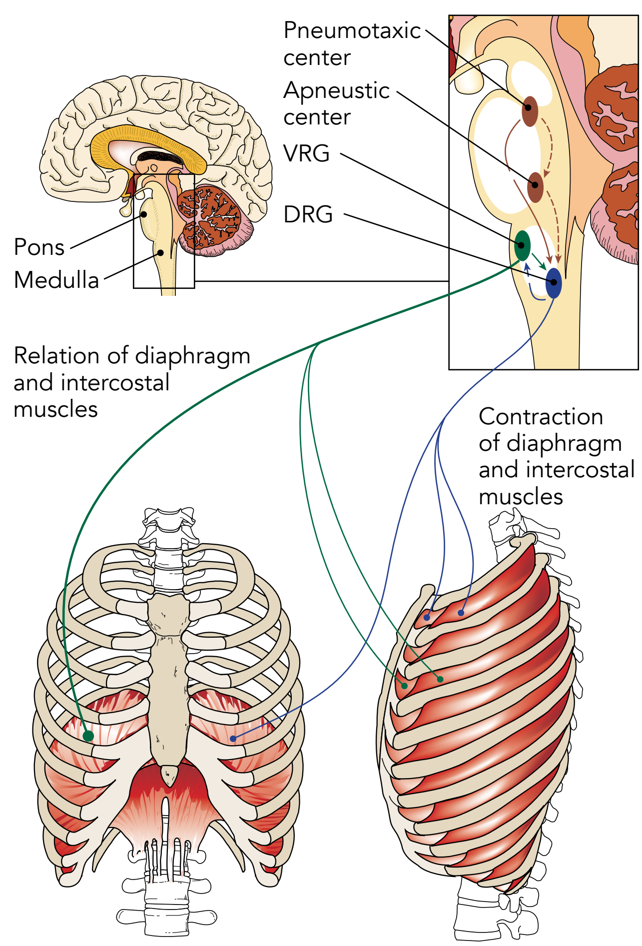
The Medulla Oblongata



important, you would be correct. Oxygen is the most important thing. A person can live only a few minutes without oxygen, so it is vital to keeping our bodies alive.

From this fact, you probably would assume that the primary thing that the chemoreceptors monitor is oxygen, right? Well, as it happens, that's not the case. The chemical in the body that has the most influence on respiration is actually carbon dioxide, not oxygen! And this makes sense when you give it some thought. Recall that the body uses only about 25 percent of the oxygen bound by hemoglobin, so under normal circumstances, there is plenty of oxygen in reserve. If the chemoreceptors primarily checked for oxygen, then we would have little stimulus to breathe because there is always so much oxygen in the blood. Our brains wouldn't signal the need to breathe until we were nearly out of oxygen with no reserve. If mindless evolutionary processes "designed" us we might have been made that way, but God is far wiser. He designed us to breathe before we become in desperate need of oxygen to survive.

It makes much more sense to monitor the levels of carbon dioxide, and this is what the central chemoreceptors do. They monitor the levels of carbon dioxide (in addition to monitoring the acidity of the blood). When the receptors sense the levels of carbon dioxide going up, what do you think happens? Correct! The chemoreceptors send signals to the respiratory center to increase respiration and remove the excess carbon dioxide. The opposite occurs when the level of carbon dioxide gets a little too low. The chemoreceptors trigger the respiratory center to slow respiration and allow the carbon dioxide level to return to normal. This control mechanism is very precise. It not only maintains control of the respiratory system, it also helps keep the level of carbon dioxide within very tight limits.

The level of acidity in the blood is also monitored by the central chemoreceptors. An increase in acid levels is usually accompanied by an increase in respiration.

While oxygen is not the primary controller of respiration, its level is also monitored by chemoreceptors. The peripheral chemoreceptors keep a close watch on the oxygen level in the blood. However, the oxygen level has to get very low before the peripheral chemoreceptors trigger an increase in respiration. It is very unusual for the peripheral chemoreceptors to be the primary stimulus for respiration.