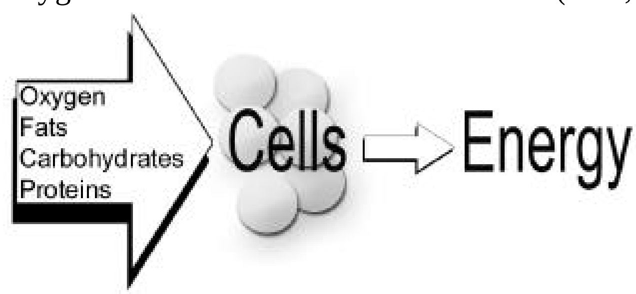
Background Information

Themes and required student background

With the exception of Module #1, these modules assume that students have already been introduced to the basic structures and functions of the cardiovascular and respiratory systems. Students should understand the pumping of the heart and the function of the blood vessels and capillaries in distributing blood to all of the tissues and cells of the body. Students should also understand that, by breathing, the lungs are able to provide oxygen and remove the carbon dioxide waste product. Students should know that cells need oxygen to be able to take nutrients (fats, proteins, and carbohydrates) and make



energy and that active cells (like those in exercising muscle) need more oxygen and nutrients than do less active cells. For both gas exchange at the lungs and gas exchange at the tissues, the size of the transfer surface area is important. There is a large surface area between the smallest air spaces (**alveoli**) in the lungs and the pulmonary capillaries that make the diffusion of oxygen into the blood and the diffusion of carbon dioxide into the exhaled air occur faster. In fact, the surface area of this blood-gas barrier in the lungs of one adult human is about the size of the playing surface on a tennis court!

What is the autonomic nervous system?

There is a part of the nervous system that is called the **autonomic nervous system**. “Autonomic” means that most of the time it acts by itself, without someone consciously trying to control it.

As an example, the autonomic nervous system determines how fast the heart beats (heart rate or pulse). If someone measured his or her heart rate at different times during the day, the values would vary. Sometimes heart rate is higher, while at other times, it is lower. For example, you may have noticed that your heart beats faster after you have just walked from one classroom to another, especially if you had to walk up some steps. You don’t have to think about raising your heart rate when you climb steps; the autonomic nervous system takes care of adjusting the rate.

There are areas in the central nervous system (the brain and the spinal cord) that determine how fast the heart should beat. There are also nerve connections going both ways between these areas and the heart. It is along these nerves that messages are sent to speed up or slow down the heart. These nerve connections are part of the autonomic nervous system. Not only the heart, but also all of the organs and blood vessels in the body receive messages from the brain and the spinal cord and send messages back along nerves that are part of the autonomic nervous system. The autonomic nervous system helps set the rate of breathing based on chemical detection of carbon dioxide and/or oxygen in the blood. After someone eats a meal, the stomach and intestines receive messages to begin working or to work harder so that the food can be digested and absorbed.

Autonomic reflexes
The **autonomic nervous system** is made up of the sympathetic and parasympathetic nervous systems. The **sympathetic nervous system** is involved in the **fight or flight response**, for example, getting the body ready to react to or run away from a grizzly bear. The **parasympathetic nervous system** controls the "housekeeping" functions of the body, such as regular breathing, resting heart rate, and digestion. Heart rate is one example of a body function that is controlled by both the sympathetic and parasympathetic nervous systems. How high the heart rate is at any particular time depends upon many factors. For example, how much oxygen the body needs and how nervous or how calm someone feels are factors that influence heart rate. Heart rate also plays a role in regulating blood pressure. When you visit a doctor, s/he or the nurse will almost always measure your blood pressure to make sure it is not too low or too high. It is very important that your blood pressure remain close to normal. If blood pressure suddenly falls, heart rate will quickly increase and the contraction of the heart will become stronger so that the heart pumps more blood and increases blood pressure until it is normal again. This response is an example of a reflex involving the autonomic nervous system called the **baroreceptor reflex**.

How does the baroreceptor reflex work? Some large blood vessels near the heart contain blood pressure sensors that measure blood pressure. Physiologists call these sensors **baroreceptors** (**baro** means "passive"). The blood pressure signal is sent via nerves to an area of the brain where it is compared to a normal blood pressure. For example, if the blood pressure is too low, this area of the brain will send a message via sympathetic nerves back to the heart to increase the heart rate. In this way the blood pressure will be brought back up to normal. You can test the baroreflex yourself; see **"An experiment and its explanation"** – next page.

An experiment and its explanation

Two students should work together. First the subject lies down in a relaxed, inactive manner on the floor or a table for three minutes. Then the other person measures the subject's heart rate and records it. The subject stands upright, relaxed and inactive for three minutes. At the end of these three minutes, the other person measures the subject's heart rate and records it. The students compare the two heart rates.

After standing for three minutes, a person's heart rate will normally be higher than heart rate while lying down. The reason is that as a result of standing up, blood temporarily pools in the legs and therefore less blood is in the heart. If you looked at an x-ray you would see that the heart is actually smaller when a person stands up. As a result, the heart pumps less blood volume with every beat, causing the blood pressure to fall slightly. Thus, the baroreceptor reflex increases the heart rate to bring the blood pressure back to normal. That is why heart rate is higher when a person stands upright. The baroreceptor reflex can also help bring sudden increases in heart rate back down.

The cardiovascular system -- transport and mechanisms

The cardiovascular system is the integral link among oxygen transport across the blood-gas barrier of the lungs, oxygen delivery to the cells of the body by the blood vessels, and oxygen utilization by the cells for energy. The cardiovascular system is therefore essential for life in multicellular organisms. The heart plays an important role in moving blood loaded with oxygen throughout the body. This oxygen is then used by the cells and tissues to provide energy (known as **cellular respiration**). The response of the human body to exercise offers an excellent opportunity to observe and learn about the physiology of oxygen transport, and the utilization and integration of the cardiovascular and respiratory systems. In this module, students can observe the effects of exercise both on heart rate and respiration.

Oxygen transport

Oxygen is the fuel of life, and more oxygen is needed by cells during increased activity such as exercise. An important function of the cardiovascular and respiratory systems is to supply oxygen to metabolically active tissues, including: contracting muscles, including the heart, brains processing information, and kidneys actively pumping salts and waste products into and out of the blood. The total amount of oxygen in the blood is greatly enhanced by the protein molecules (**hemoglobin**) found in red blood cells. Oxygen is carried in the blood both as a physically dissolved gas (normally only 1.5 % of blood oxygen) and in chemical combination with the hemoglobin inside the red blood cells (normally 98.5 % of blood oxygen). **Cardiac output** (see below) is a measure of how much blood is available to the body every minute. If we had no hemoglobin in the blood, we would need a cardiac output of almost 1000 liters/minute to deliver enough physically dissolved oxygen to the muscles to support high rates of exercise! For a 90-pound middle school student, the normal *maximum* cardiac output is about 17.85 liters/min and the normal *resting* cardiac output is about 4.5 liters/min.

The chemical binding properties of oxygen with hemoglobin are advantageous for delivering oxygen to the cells of the tissues and organs in the body. As it leaves the lungs, hemoglobin in the arterial blood is about 97% saturated with oxygen, while in the venous blood entering the right side of the heart, hemoglobin is still about 70% saturated with oxygen. It is advantageous to keep capillary oxygen levels high because then more oxygen can leave the capillaries to enter cells by **diffusion**, that is, moving from a high concentration of oxygen in the blood to a low concentration of oxygen in active cells.

The heart as a pump

Many physiological transport systems involve muscular pumps. These include cardiac muscle in the heart, skeletal muscles for breathing, and smooth muscle in the stomach and intestine. The amount of materials these pumps can move depends upon: 1) how much **pressure** they can generate to pump materials; and 2) how much **resistance** to flow they must overcome in blood vessels, airways, etc.

The circulatory system works to provide cells throughout the body with the oxygen they need to function. How can we estimate how much oxygen is used by the body's cells? One analogy is how much money you use during a trip. At the beginning of the trip, you put $20 in your pocket. At the end of the day you have $3 left in your pocket. Therefore, you know your trip required $17. Similarly, if we want to know how much oxygen a group of cells (tissue) used, we would look at the difference between the amount of oxygen entering the tissues with the arterial blood and the amount of oxygen leaving the tissue with the venous blood. How does the body control the supply of oxygen to the cells in our body's tissues? The important variables for supplying oxygen to the tissues are the **cardiac output** (pump output) and the **arterial-venous oxygen concentration difference** (input-output difference).

Most physiological pumps like the heart can increase the rate of delivery (or output) by increasing the frequency of contractions and/or by increasing the volume pumped with each contraction. In the cardiovascular system, **cardiac output** (or blood flow to the body) depends upon two variables: **heart rate** (number of beats/min) and **stroke volume** (ml/beat of volume of blood pumped by one ventricle during a contraction). A balance between nervous inputs from the sympathetic and parasympathetic branches of the autonomic nervous system sets the heart rate. The volume of blood in the ventricle before contraction and the strength of the heart muscle contraction determine the stroke volume. Increasing blood returning to the heart (**venous return**) so that there is more blood in the ventricle before contraction both increases the volume that can be pumped and changes the mechanical properties of the heart muscle fibers. Thus, the heart can contract more forcefully during subsequent contractions.

In addition, the sympathetic branch of the autonomic nervous system and the epinephrine it releases from the adrenal glands into the blood can increase the force of the heart's contractions. Cardiac output may increase more or less than the increase in heart rate, because stroke volume may increase more or less. For example, during exercise, stroke volume increases progressively until about 60% of the maximum rate for oxygen utilization and further increases in cardiac output are achieved mainly by increasing the heart rate.

Therefore:

Cardiac output = (heart rate) *times* (stroke volume)

A typical resting cardiac output would be 4.5 liters/minute for middle school students and their typical resting heart rate would be 60-100 beats/minute. Therefore, a typical stroke volume in a middle school student would be:

Cardiac output = (heart rate) x (stroke volume)

$$\frac{4.5 \text{ liters}}{\text{minute}} = \frac{80 \text{ beats}}{\text{minute}} \times \text{stroke volume}$$

$$\frac{4.5 \text{ liters}}{\text{minute}} \times \frac{\text{minute}}{80 \text{ beats}} = \text{stroke volume}$$

$$\frac{.056 \text{ liters}}{\text{beat}} = \text{stroke volume}$$

$$\frac{56 \text{ ml}}{\text{beat}} = \text{stroke volume}$$

A resting adult average heart rate is about 72 beats/minute, about 50 beats/minute in trained athletes, and > 125 beats/minute in someone who is excited or anxious. Children generally have higher average heart rates than adults do. The adult normal stroke volume is 70 ml/beat. Therefore, an average adult would have a resting cardiac output of about 5 liters/minute (72 beats/minute x 70 ml/beat = 5040 ml/minute = 5.04 liters/minute), and a maximum cardiac output of about 35 liters/minute.

The flow of blood

The flow of blood through the blood vessels is similar to the flow of current in an electrical system and follows the same principle known as Ohm's Law:

In an electrical system:

voltage = (current) *times* (resistance)

For fluid flowing through a tube:

pressure difference = (flow) *times* (resistance)

Several factors contribute to the resistance to flow in such a system, including the **radius** (half of the diameter) of the tube, the **length** of the tube, and the **viscosity** (thickness) of the fluid in the tube.

Fluid viscosity can be understood by thinking of some common fluids:

More Viscous → **Less Viscous**

Gelatin | **Honey** | **Pancake Syrup** | **Water**

Factors Contributing to Resistance to Flow	
Flow through a tube **increases** when:	the pressure difference from one end of the tube to the other **increases; and** when
	the radius of the tube **increases**.
Flow through a tube will **decrease** when:	the length of the tube **increases,** or
	when the viscosity of the fluid in the tube **increases**.

Changes with exercise

The body's response to exercise involves simultaneous coordination of multiple systems in the body. Obviously, **chemical sensing** of the oxygen and carbon dioxide in the blood is important for increasing breathing. In addition, a cardiovascular control center in the brain uses the sympathetic nervous system to increase heart rate and reset the baroreceptors to a higher level; they sense a higher blood pressure than the normal blood pressure. Also, changes in oxygen or other chemicals cause the blood vessels to dilate (**increase in diameter**), in the active muscle, thereby decreasing the resistance and enhancing blood flow to that muscle. With more intense exercise, the sympathetic nervous system further increases cardiac output by increasing heart rate and contractility (force of contraction) of the heart and by redirecting blood flow to essential systems (the brain, the heart, or the working skeletal muscle). Blood vessels that serve nonessential systems **constrict** (decrease in diameter), leading to reduced blood flow (and an increase in vascular resistance) during exercise in some vascular beds. For, example, the gut, which is not needed in the **"fight or flight"** response, has decreased blood flow during exercise.

The exact stimuli sensed by the body to cause all of the changes in each of the various systems of the body during exercise are not yet known. Interestingly, changes in the cardiovascular and respiratory systems actually begin **before the exercise has begun and, thus, before the sensors can detect any changes**. Therefore, the body anticipates the coming exercise. If we think of the brain as a computer, it seems that a brain "software package" called *exercise* is inserted into the disk drive whenever someone plans to exercise.

Acute (immediate) cardiovascular responses to exercise include:

- increased blood flow to the working muscles (especially the skeletal muscles);
- increased blood flow to the heart muscle (increased coronary artery blood flow);
- increased heart rate (# beats/minute);
- increased stroke volume (volume of blood pumped with each heartbeat);
- increased cardiac output (volume of blood pumped each minute); and
- increased blood pressure.

Acute (immediate) respiratory responses to exercise include:

- increased rate of breathing (# breaths/minute);
- increased depth of breathing (tidal volume or volume of gas in with each breath);
- increased total ventilation (the volume of gas breathed each minute)

- increased blood flow to the lungs (increased pulmonary artery blood flow); and
- increased surface area for gas exchange in the lungs (due to recruitment of new pulmonary capillaries so that more oxygen can diffuse into the blood and more carbon dioxide can diffuse into the air).

Thus, the effects of exercise on the cardiovascular and respiratory systems are complex and varied. For example, an average middle school student can increase his/her heart rate from about 80 to 210 beats/minute with extreme exercise. He can also increase the stroke volume from a low of about 25 ml/beat to 85 ml/beat. Thus, the student's cardiac output can change from an average of about 4.48 liters/minute to 17.85 liters/minute. This is an increase of about four-fold (four times).

Simultaneously during exercise, the student can increase **tidal volume** (volume of gas inhaled or exhaled by the lungs per breath) from about 0.2 ml/breath to two liters/breath. They can also increase **rate of breathing** from about 12 breaths/minute to 40 breaths/minute. Thus, **total ventilation** (the volume of air moved in and out of the lungs each minute) can increase from about 2.46 liters/minute to 80 liters/minute during heavy exercise.
Therefore, since the respiratory system can work up to 32.5 times better during exercise and the cardiovascular system can only work about four times better during exercise, it must be the cardiovascular system that limits how much exercise a human is able to perform. *(See Table on the **Effects of Exercise** below)*

Total ventilation (volume/min) = **rate of breathing** (breaths/minute) ***times*** **tidal volume** (volume/breath)

[Resting adult average breathing rate is about 12-20 breaths/min. The adult average tidal volume is 0.5 liter/breath with a possible maximal breath of 3.5 liters/breath. Therefore, an average adult would have resting total ventilation of about six liters/minute (12 breaths/minute x 0.5 liters/breath).]

Effects of Exercise on the Cardiovascular and Respiratory Systems of an Average Middle School Student				
System		**Before Exercise**	**After Extreme Exercise**	**Operation Efficiency**
Cardiovascular	**Heart Rate**	**80 beats/min**	**210 beats/min**	**Works 4 times**
	Stroke Volume	**25 ml/beat**	**85 ml/beat**	

	Cardiac Output	**4.48 liters/min**	**17.85 liters/min**	**better**
Respiratory	**Tidal Volume**	**0.2 liters/breath**	**2 liters/breath**	**Can work up to 32.5 times better**
	Rate of Breathing	**12 breaths/min**	**40 breaths/min**	
	Total Ventilation	**2.46 liters/min**	**80 liters/min**	

While exercising, trained athletes, compared to sedentary people, tend to increase stroke volume more and heart rate less and increase tidal volume more and rate of breathing less. This training and conditioning occurs by long-term regular aerobic exercise. With training, an individual can increase the maximal level of oxygen available to the cells of the body due to an increase in maximal cardiac output by decreasing resting heart rate, increasing resting stroke volume, and/or increasing total blood volume. Skeletal muscles can also become more efficient in their use of oxygen. The strength and endurance of the respiratory system may also increase slightly.

Medical focus

Heart disease will **decrease exercise capacity** because it decreases the efficiency of the pump. A **heart attack** may damage cardiac muscle so that stroke volume is diminished. However, cardiovascular disease frequently starts in the blood vessels outside the heart (peripheral circulation), such as, **atherosclerosis**, or clogging of the arteries with cholesterol and fat. This serves to increase resistance to flow through the arteries, similar to a clog in a drain. Chronic increases in vascular resistance, termed high-blood pressure (**hypertension**), can eventually lead to heart failure.

Interestingly, the heart may actually **hypertrophy** (become larger) in an attempt to pump through the vessels that have greater resistance, but the heart actually becomes less efficient and ultimately fails from such enlargement. A weak heart cannot pump blood effectively so that blood backs-up in the circuit, causing blood pressure to increase in the veins. This can lead to leakage of fluid out of the capillaries into the air spaces of the lungs (**pulmonary edema**) or into the body tissues (**tissue edema**, like the swelling of the ankles in the elderly or during pregnancy). This increase in blood volume also stretches the heart and increases the length of the individual heart muscle cells, making them less efficient, and can lead to **congestive heart failure**. High salt intake can cause water retention and also increase blood volume, which can further stretch the heart muscle.

The most common cause of increased blood viscosity is an increased **hematocrit**, that is, increased percentage of the blood cells in the blood.

Increased production of red blood cells by the bone marrow (**erythropoiesis**) occurs in response to low levels of oxygen in the blood. Increased production of red blood cells occurs normally when the body is adjusting to the lower oxygen levels at high altitudes. It also occurs in patients with lung diseases, often caused by smoking. It is also one of the adverse side effects of **blood doping**, that is, attempts by athletes to increase their hematocrit quickly before a race. This can temporarily increase their oxygen supply to exercising muscle.

Biological and experimental variability

Finally, it is important to note that **biological variability** between different individuals and **experimental variability** due to imperfect measurement techniques, contributes to differences in measurement of heart rate, blood pressure, etc. **Biological variability** includes gender differences, genetic differences, and differences due to training. This is the kind of difference you look for when you grade tests on a normal curve. **Experimental variability** can occur, for example, when different periods of time are used to count heart rate.

Consider what would happen if you only counted heart rate for one second. Sometimes you'd get a beat, but other times you may not, and your calculated heart rate could vary from 0/minute to the true value (usually 50-70 beats/minute)! The longer the time period for data collection, the more likely one is to obtain an accurate measurement. A normal-shaped curve usually describes random variation of an experimental nature, too. This is known as the Gaussian curve, named after the astronomer and mathematician, Gauss. He noticed that the coordinates of stars on sequential nights seemed to fit a normal-shaped curve, and he explained this as a result of imperfections in his telescope sighting methods.