

Gas Exchange Physiology

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Physiology is the nuts and bolts of how organisms work. Typically it involves a quantitative approach to figuring out what organisms can and can't do. Physiology is critical in medicine, where things like oxygen concentration are matters of life and death. Quantitative approaches are also informative in **comparative physiology**, in which biologists compare different species in order to figure out general principles that apply to all kinds of organisms.

This lab is an introduction to quantitative physiology, emphasizing gas exchange and circulation. You'll be given some background information and some equations, and asked to solve some problems. There's only a little bit of math. **Answer the questions during lab. Choose the one best answer for each question. You may discuss your answers with other students in the class, and you may use your textbook.** When you're done, put all your answers on a Scantron sheet and turn it in. Each person should turn in a Scantron. Please write "Gas Exchange" in the subject area of the Scantron.

BASIC PRINCIPLES OF GASES

The two gases we're concerned with here are carbon dioxide (CO₂) and oxygen (O₂). The basic problem that heterotrophic organisms need to solve is to have O₂ diffuse into the body and CO₂ diffuse out of it. The efficiency of this gas exchange is limited by some basic physical and chemical principles.

Concentration. Concentration is the amount of a substance in a particular volume. In chemistry, the units of concentration are often moles/liter. In gas exchange physiology, we're often looking at molecules that go from gas (in the air) to dissolved in liquid (in the blood). It's common to use units such as ml O₂/100 ml blood; ml O₂ refers to the milliliters of pure oxygen at standard temperature and pressure (1 atm, room temperature). A liter of air, if it contains 20% O₂, would contain 200 ml O₂.

Partial pressure. Air at sea level has a pressure of approximately 1 atmosphere (atm). That pressure comes from about 80% nitrogen and 20% oxygen, so the partial pressure of nitrogen (P_{N₂}) is 0.8 atm and P_{O₂}=0.2 atm.

Partial pressure can also refer to dissolved gases. If the P_{O₂} in a glass of water is 0.2 atm, then the oxygen level in the glass is at equilibrium with the environment.

Solubility. Solubility refers to the amount of a particular chemical that will dissolve in a particular solvent under specified conditions. This is important in gas exchange physiology in a couple of ways:

- CO₂ is more soluble in water than is O₂. (CO₂ is a polar molecule; O₂ is not.) While there is much more oxygen than carbon dioxide in the air, there is much more carbon dioxide than oxygen in water.
- Oxygen solubility is higher in cold water. (That's why trout, which need a lot of oxygen, can only live in cold water.)

CO₂ and pH. When CO₂ dissolves in water (or blood), it makes the solution more acidic. In solution, carbon dioxide can react with water to form carbonic acid (H₂CO₃) or bicarbonate (HCO₃⁻):



All these forms are present at equilibrium. The more CO₂ is added, the more the equilibrium will be shifted toward H⁺ (acid) production. More acid means lower pH. This equilibrium depends on an enzyme (carbonic anhydrase) that starts the conversion of CO₂ to carbonic acid. Oxygen does not have a significant effect on pH.

SOME EQUATIONS AND DATA

Diffusion rate for gases (Fick's law of diffusion):

$$R=DA(\Delta p/d).$$

This is simpler than it looks.

R: the amount of gas diffusing in a given amount of time

D: the diffusion constant

A: the area over which diffusion takes place

Δp : the difference in partial pressure (e.g., from air to blood)

d: the distance across which diffusion takes place

Composition of air:

O₂: 20.95%

CO₂: 0.03%

N₂: 78.09%

Argon: 0.93%

Total: 100.00% (give or take a few minor constituents)

Note: the composition above is true for dry air; air may also contain varying amounts of water vapor.

Solubility of O₂ in seawater at 20°: 5.3 ml O₂ per liter seawater when the seawater is in equilibrium with the atmosphere.

Pressure from being underwater: if you go underwater, you're subject to pressure from the water above; the deeper you go, the greater the pressure. Ten meters of water above you adds an extra 1 atmosphere to the 1 atmosphere normal air pressure that you'd feel at the surface. Your whole body will experience the pressure – including the air in your lungs. The air in your lungs at sea level is at approximately 1 atm; at 10 meters underwater, the air in your lungs would be at about 2 atm. It's not possible for the air in your lungs to stay at a pressure that is significantly different from the environment.

CRAB IN A BUCKET

Suppose you find an interesting crab in the ocean, and you want to bring it in to show the biology class. You want to make sure it stays alive, but you're concerned that it might not get enough oxygen. The crab uses oxygen at about 5 ml/hour. You're going to carry it in a straight-sided bucket with some seawater in it. The bucket can hold up to 10 liters, and the surface area of the water in it is 1000 cm². The crab will have to be in the bucket overnight, and you don't have a bubbler to put more oxygen into the water.

1. Should you fill the bucket with water, or use only a little water? Why?

- A. A lot of water; the 10 liters of water will hold enough oxygen to keep the crab alive.
- B. A small amount of water; the water can't possibly hold enough oxygen to keep the crab alive, so the crab will depend on oxygen diffusing into the water from the air. A smaller volume of water will allow the oxygen to diffuse in faster.

GAS EXCHANGE & MOUNTAINEERING

Suppose you want to climb a mountain that is 19,000 feet tall. The air at that altitude has a total pressure of about half an atmosphere. The chemical composition of the air is the same as at sea level. Suppose you want to breathe the same partial pressure of oxygen that you normally would breathe at sea level – no more and no less. You decide to breathe bottled air from a tank, and adjust the composition of the air in the tank so you get the same P_{O_2} that you'd normally get at sea level.

2. What should the composition of the air in your tank be?

- A. 21% O_2 , the same as at sea level.
- B. 10.5% O_2 .
- C. 42% O_2 .
- D. It depends on the pressure in the tank. The higher the pressure, the lower the O_2 concentration should be.

PARTIAL PRESSURES & DISSOLVED GASES

Suppose you open a bottle of Pepsi. Sodas like Pepsi have bubbles because they contain a lot of CO_2 ; they are packed with pressurized CO_2 .

3. What happens to the air in the top of the bottle at the moment when you open it?

- A. The P_{CO_2} of the air in the top of the bottle suddenly increases.
- B. The P_{CO_2} of the air in the top of the bottle suddenly decreases.

4. What happens to the partial pressure gradient of CO_2 between the air in the bottle and the Pepsi at the moment when you open the bottle?

- A. The partial pressure gradient increases suddenly, causing bubbles to form.
- B. The partial pressure gradient decreases suddenly, causing bubbles to form.

5. What happens to the P_{CO_2} of the soda itself after the bottle has been open for a couple of hours?

- A. The P_{CO_2} of the soda gradually increases as bubbles form.
- B. The P_{CO_2} of the soda gradually decreases as bubbles form.

A DIVING BELL

A diving bell is an old-fashioned way of allowing people to breathe underwater. It is a big container, shaped roughly like a bell, closed on top and open on the bottom. With air trapped inside, it can be lowered down into the ocean. The air can't escape, but it is in contact with the water at the bottom. A person can stay in the diving bell, breathing the trapped air.

For the following questions, assume that you are in a diving bell that is lowered from the surface to a depth of 40 meters. There is no air supply to the diving bell, so you only have the air that's trapped in the bell.

6. What would the air pressure in the bell be immediately after it was submerged to 40 meters?

- A. 0.1 atmosphere
- B. 1/4 atmosphere
- C. 1 atmosphere
- D. 4 atmospheres
- E. 5 atmospheres

7. What would the partial pressure of O₂ be in the bell immediately after it was submerged to 40 meters? (Assume you haven't used any of the oxygen yet.)

- A. 0.2 atmosphere
- B. 0.8 atmosphere
- C. 1 atmosphere
- D. 2 atmosphere
- E. 4 atmospheres

8. If the diving bell contained 1000 liters of air at the surface, what volume of air would it contain after it was submerged to 40 meters?

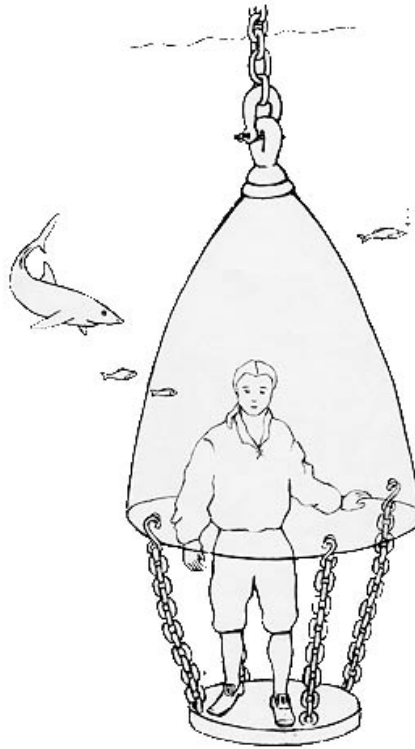
- A. less than 250 liters
- B. 250 liters
- C. 1000 liters
- D. 4000 liters
- E. more than 4000 liters

9. Suppose you spend some time in the diving bell, breathing the air, and then you decide to leave the bell and swim to the surface. What would happen to the partial pressure of oxygen in your lungs as you rapidly ascend? (Assume that your body is using very little oxygen.)

- A. The P_{O₂} in your lungs would decrease as you ascend.
- B. The P_{O₂} in your lungs would increase as you ascend.

10. What would happen to the volume of air in your lungs as you ascend, assuming you don't allow any air to escape your lungs?

- A. The air in your lungs would expand, dangerously stretching your lungs to several times their normal size.
- B. The air in your lungs would expand somewhat. Since the volume of air in the lungs started out smaller than normal (due to the high pressure), your lungs would expand to approximately normal size as you approach the surface.
- C. The air in your lungs would shrink due to increasing pressure.
- D. The air in your lungs would not change in volume.



11. Now suppose your friend starts at the surface and dives down to where the diving bell is, at 40 meters depth, and then immediately swims back to the surface. She holds her breath the whole time and doesn't breathe from the diving bell. What would happen to the volume of air in her lungs as she *descended*?

- A. The air in her lungs would expand, stretching her lungs to several times their normal size, and her lungs might burst like a balloon.
- B. The air in her lungs would shrink due to increasing pressure.
- C. The air in her lungs would not change in volume.

12. In the scenario described in question 11, what would happen to the volume of air in your friend's lungs as she *ascended*?

- A. The air in her lungs would expand, stretching her lungs to several times their normal size, and her lungs might burst like a balloon.
- B. The air in her lungs would expand somewhat. Since the volume of air in the lungs started out smaller than normal (due to the high pressure), her lungs would expand to approximately normal size as she approaches the surface.
- C. The air in her lungs would shrink due to increasing pressure.
- D. The air in her lungs would not change in volume.

GAS EXCHANGE AND CIRCULATION

The following questions refer to normal breathing in sea-level air.

13. Where would the P_{CO_2} be highest?

- A. The air you exhale.
- B. The air in the alveoli of your lungs.
- C. The blood entering your alveolar capillaries.

14. Where would the P_{O_2} be the highest?

- A. The air you exhale.
- B. The air in the alveoli of your lungs.
- C. The blood leaving your alveolar capillaries.

15. In a normal person, will the P_{O_2} in active muscles be higher or lower than the P_{O_2} in the blood that flows through the capillaries supplying the muscles?

- A. Higher.
- B. Lower.

OXYGEN-CARRYING PIGMENTS: HEMOGLOBIN

Hemoglobin carries oxygen in mammalian blood. Very little O_2 would dissolve in blood without it. If human blood for some reason lacked hemoglobin, it could carry only about 0.3 ml O_2 /100 ml blood. With hemoglobin, blood carries about 20 ml O_2 /100 ml blood – a 70-fold increase. Hemoglobin is found in red blood cells; it's red when it's bound to oxygen, blue when it's not. Normally, when you breathe, the blood flowing through your lungs becomes almost completely saturated with oxygen – nearly all the hemoglobin molecules are carrying all the oxygen they can hold.

16. Suppose you come upon an unconscious person, and his skin looks bluish because his blood has little oxygen. Is the pH of his blood likely to be higher than normal, lower than normal, or unchanged?

- A. Higher pH than normal.
- B. Lower pH than normal.
- C. pH same as normal.

Hemoglobin is a protein. It does its job because it has a fairly high **binding affinity** for oxygen – in other words, oxygen sticks to it. It can grab O₂ molecules when the blood gets oxygenated in the lungs, and carry the O₂ throughout the body in the blood. In order for that O₂ to be useful to you, the hemoglobin has to let go of it at the right time. The O₂ binding affinity of hemoglobin is normally just right – the hemoglobin becomes completely saturated with oxygen in the lungs, but then loses a significant percentage of its oxygen as the blood flows through the tissues that need oxygen. The binding affinity of hemoglobin changes with pH in a way that helps it to deliver more oxygen to the tissues.

17. In order to ensure that oxygen is delivered where it's needed, should the binding affinity of hemoglobin for oxygen increase or decrease as pH decreases?

- A. Binding affinity should increase as pH decreases.
- B. Binding affinity should decrease as pH decreases.

There are several different kinds of hemoglobin and related O₂ carriers in mammals. When a woman is pregnant, there are two different blood circulation systems involved: the mother's blood and the blood of the fetus. These two blood systems are separate, but they come in close contact in the placenta. In the placenta, oxygen is transferred from the mother's blood to that of the fetus. The fetus makes fetal hemoglobin, which is slightly different from adult hemoglobin; it has a higher affinity for O₂ than does adult hemoglobin.

18. If the fetal blood and maternal blood are in equilibrium in the placenta, will the blood of the fetus be more or less saturated with oxygen than the blood of the mother?

- A. More saturated.
- B. Less saturated.

19. Will the level of O₂ available to the tissues of a fetus be higher or lower than the level available to the mother?

- A. More oxygen will be available to the fetal tissues (higher P_{O₂}).
- B. Less oxygen will be available to the fetal tissues (lower P_{O₂}).

20. Suppose a person was born with a mutation that caused him to make only fetal hemoglobin throughout his life. Would the level of O₂ saturation of his hemoglobin tend to be higher or lower than that of a normal person?

- A. Higher.
- B. Lower.

21. Would the level of O₂ normally available to his tissues (P_{O₂}) tend to be higher or lower?

- A. Higher.
- B. Lower.

There is also another version of the oxygen carrier, called myoglobin. While hemoglobin circulates in the blood, myoglobin stays in the muscles to ensure that oxygen is transferred from the blood into the muscles.

- 22. Does myoglobin have a higher or lower oxygen affinity than hemoglobin?** (You may have to guess – but if you guess sensibly, you'll be right.)
- A. Higher.
 - B. Lower.
- 23. Suppose you're breathing normally and sitting there staring at a cup of water that's open on the table in front of you. Which will have a higher P_{O_2} – the water in the cup or the freshly oxygenated blood in your arteries?** (Assume that the water is in equilibrium with the air.)
- A. The water.
 - B. Your blood.
- 24. In the above example, which will have a higher concentration of O_2 as measured in ml O_2 per 100 ml liquid?**
- A. The water.
 - B. Your blood.

HYPERVENTILATION AND PH

People sometimes have panic attacks and hyperventilate. Hyperventilation can be defined simply as breathing a lot more than you need to.

- 25. How would hyperventilation affect the P_{CO_2} of a person's blood?**
- A. Hyperventilation would increase the amount of CO_2 in the blood.
 - B. Hyperventilation would decrease the amount of CO_2 in the blood.
 - C. Hyperventilation would not affect the CO_2 concentration in the blood.
- 26. How would hyperventilation affect the pH of a person's blood?**
- A. Hyperventilation would increase blood pH (more alkaline).
 - B. Hyperventilation would decrease blood pH (more acidic).
 - C. Hyperventilation would not affect blood pH.
- 27. How would hyperventilation affect the oxygen concentration in the freshly oxygenated blood leaving the alveolar capillaries?**
- A. Hyperventilation would significantly increase blood oxygen concentration.
 - B. Hyperventilation would decrease blood oxygen concentration.
 - C. Hyperventilation would not affect blood oxygen concentration very much, because the arterial blood is close to being saturated with oxygen anyway.

COMPARING GAS EXCHANGE IN PLANTS & ANIMALS

Plants must also do gas exchange, mainly to take in CO_2 . With plants, as with animals, the rate of gas exchange must be proportional to the metabolic rate. In both cases, as gas exchange

increases, so does water loss. One key difference is the lower partial pressure of CO_2 compared to O_2 in the atmosphere.

- 28. Suppose a plant is doing a certain amount of photosynthesis, and it needs to take in 100 ml of CO_2 (assume standard temperature & pressure). The plant can only absorb CO_2 from the air that actually enters the airspace in the leaf. What is the approximate minimum amount of air the plant would have to take in to meet its needs?**
- A. 100 ml.
 - B. 300 ml
 - C. 0.03 ml
 - D. 300,000 ml, or 300 liters.
- 29. Suppose an animal is doing a certain amount of respiration, and it needs to take in 100 ml of O_2 (assume standard temperature & pressure). The animal can only absorb O_2 from the air that actually enters the lungs. What is the approximate minimum amount of air the animal would have to process to meet its needs?**
- A. 100 ml.
 - B. 21 ml
 - C. 0.21 ml
 - D. 476 ml
 - E. 476,000 ml