MATH AND SCIENCE @ WORK

AP* BIOLOGY Educator Edition

PREVENTING DECOMPRESSION SICKNESS ON SPACEWALKS

Instructional Objectives

Students will

- recall the concepts, data analyses, and conclusions of AP Lab 12: Dissolved Oxygen and Aquatic Primary Productivity;
- correlate gas solubility and function of vertebrate respiratory systems;
- analyze the effect of pressure on gas solubility from experimental data; and
- predict the physiological consequence with varying nitrogen and oxygen concentrations.

Degree of Difficulty

For the average AP Biology student, the problem may be at a moderate to advanced difficulty level. AP Biology Lab 12 allowed students to investigate and evaluate the physical and biological factors that affect the solubility of dissolved oxygen and subsequent effects on aquatic ecosystems of Earth. This activity requires students to apply principles learned in Lab 12 to evaluate nitrogen solubility in the human body. It may be challenging for students who have not taken, or are not concurrently enrolled in, an Anatomy/Physiology or Environmental Science course.

Class Time Required

This problem requires 90 minutes.

- Introduction: 25 minutes
  - Read and discuss the background section with the class before students work on the problem.
  - If this activity is used before students have learned about human physiology systems, an introduction of the respiratory system should also be discussed.
- Student Work Time: 45 minutes
- Post Discussion: 20 minutes

Grade Level
10–12

Key Topic
Gas solubility in living systems; synthesis and application of Lab 12

Degree of Difficulty
Moderate to advanced

Teacher Prep Time
15 minutes

Class Time Required
90 minutes

AP Biology Framework Alignment
Essential Knowledge:
2.A.3, 2.C.1, 2.C.2, 2.D.3, 2.E.1, 2.E.2. 2.E.3, 4.A.6, 4.B.1

NSES Science Standards
- Unifying Concepts and Processes
- Science as Inquiry
- Life Science
- Science in Personal and Social Perspectives
- History and Nature of Science

Background

This problem is part of a series of problems that apply Math and Science @ Work in NASA's research facilities.

Neutral buoyancy is the term used to describe an object that has an equal tendency to float as it does to sink. In water, items can be made neutrally buoyant using a combination of weights and flotation devices. In such a state, even a heavy object can be easily manipulated.

Because of the similarities to microgravity (weightlessness), NASA uses neutral buoyancy to help astronauts train for spacewalks. NASA's training facility is the Neutral Buoyancy Laboratory (NBL) located inside the NASA Sonny Carter Training Facility in Houston, Texas. The NBL is a pool large enough to hold full-sized mockups of the International Space Station (ISS), and flight payloads (like the Hubble telescope). The dimensions of the pool are 62 m (202 ft) long, 31 m (102 ft) wide, and 12 m (40 ft) deep, allowing two different training activities to be performed at either end of the pool simultaneously. For astronauts, the facility provides important pre-flight training in becoming familiar with planned crew activities and with the dynamics of body motion under weightless conditions.

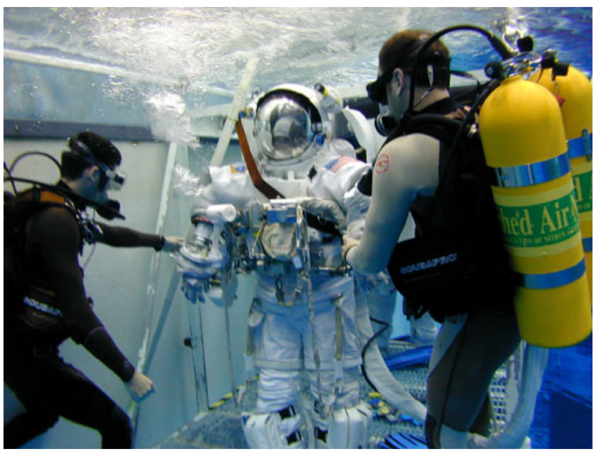

Figure 1: Astronaut Barbara Morgan participating in an underwater simulation of extravehicular activity (EVA) with diver assistance at the NBL

Figure 2: Hyperbaric chamber located at the NBL used to treat diving-related decompression illness

Astronauts wear pressurized Extravehicular Mobility Unit (EMU) suits, weighing approximately 280 lbs (127 kg), while training in the NBL. They are assisted by at least four professional SCUBA divers wearing regulation SCUBA gear. For every hour the astronaut plans to spend on a spacewalk, the team will spend seven hours training in the water. On a training day at the NBL, astronauts normally spend up to six consecutive hours in the pool. For safety reasons, the SCUBA divers are limited to five hours of dive time per day and this time is broken into at least two different dives. A fully staffed and equipped medical team is on site to provide emergency medical treatment and to monitor the health of astronauts and divers participating in NBL operations.

One medical condition that can occur while training in the NBL is decompression sickness (DCS). DCS is the result of inadequate decompression following exposure to increased pressure. During a dive, body tissues absorb nitrogen in proportion to the surrounding pressure. As long as the diver remains at pressure, the dissolved nitrogen in tissues and blood presents no problem. If the pressure is reduced too quickly, however, the nitrogen comes out of solution and forms bubbles in the tissues and bloodstream. For divers, DCS is a condition that could occur at the end of a dive when ascending to the surface. To avoid DCS, divers do not ascend too quickly and are required to take decompression stops after long and/or deep dives. A hyperbaric chamber is available at the NBL for the immediate treatment of a diving-related DCS.

Astronauts must also take precautions to avoid DCS that could occur when going on spacewalks. The pressurized spacesuits astronauts wear on spacewalks is significantly lower than the ambient pressure of the International Space Station (ISS). For this reason, astronauts go through a denitrogenation process prior to all spacewalks.

AP Biology Framework Alignment

Big Idea 2: Biological systems utilize free energy and molecular building blocks to grow, to reproduce, and to maintain dynamic homeostasis.

- **Enduring understanding 2.A:** Growth, reproduction and maintenance of the organization of living systems require free energy and matter.
  - **2.A.3:** Organisms must exchange matter with the environment to grow, reproduce and maintain homeostasis.
- **Enduring understanding 2.C:** Organisms use feedback mechanisms to regulate growth and reproduction, and to maintain dynamic homeostasis.
  - **2.C.1:** Organisms use feedback mechanisms to maintain their internal environments and respond to external environmental changes.
  - **2.C.2:** Organisms respond to changes in their external environments.
- **Enduring understanding 2.D:** Growth and dynamic homeostasis of a biological system are influenced by changes in the system's environment.
  - **2.D.3:** Biological systems are affected by disruptions to their dynamic homeostasis.
- **Enduring understanding 2.E:** Many biological processes involved in growth, reproduction and dynamic homeostasis include temporal regulation and coordination.
  - **2.E.1:** Timing and coordination of specific events are necessary for the normal development of an organism, and these events are regulated by a variety of mechanisms.
  - **2.E.2:** Timing and coordination of physiological events are regulated by multiple mechanisms.
  - **2.E.3:** Timing and coordination of behavior are regulated by various mechanisms and are important in natural selection.

Big Idea 4: Biological systems interact, and these systems and their interactions possess complex properties.

- **Enduring understanding 4.A:** Interactions within biological systems lead to complex properties.
  - **4.A.6:** Interactions among living systems and with their environment result in the movement of matter and energy.
- **Enduring understanding 4.B:** Competition and cooperation are important aspects of biological systems.
  - **4.B.1:** Interactions between molecules affect their structure and function.

NSES Science Standards

Unifying Concepts and Processes

- Change, constancy and measurement
- Form and function

Science as Inquiry

- Abilities necessary to do scientific inquiry

Life Science
- The cell

Science in Personal and Social Perspectives
- Environmental health
- Science and technology in local, national, and global challenges

History and Nature of Science
- Science as a human endeavor

Problem and Solution Key (One Approach)

AP Biology Lab 12 allows students to investigate and evaluate the physical and biological factors that affect the solubility of dissolved oxygen and subsequent effects on aquatic ecosystems of Earth. The concentration of dissolved oxygen in an aquatic environment is an important indicator of the environment's water quality. Some organisms, such as salmon, require high concentrations of dissolved oxygen. Other organisms, like catfish, can survive in environments with lower concentrations of dissolved oxygen.

A. Aquatic and terrestrial vertebrates both depend on gas exchange mechanisms for the absorption of dissolved oxygen and release of carbon dioxide.

I. Compare and contrast the respiratory systems of a fish and a mammal.

The respiratory systems of fish and mammals both utilize maximized surface area and concentration gradients for the diffusion of carbon dioxide and oxygen across capillary membranes. However, fish use their mouths to generate continuous water flow over their gills, which are located externally. Mammals use their mouths and nasal passages to inhale air and to fill their lungs, which are located internally.

II. Explain how each is adapted to make efficient use of oxygen in its environment.

Fish gills contain numerous lamellae on their gill filaments to increase surface area for gas exchange. They also use a countercurrent flow of water to blood to create maximum diffusion gradients. Mammal lungs contain numerous branched bronchi which become smaller as they make their way out to the lung tissue and are then referred to as bronchioles. The bronchioles are subdivided further and eventually terminate into small collections of air sacs, or alveoli, surrounded by capillaries. This branching maximizes the surface area for gas exchange. Ventilation of mammalian lungs is assisted by the diaphragm—a muscular partition that divides the thoracic cavity from the abdominal cavity.

III. Discuss two factors that would affect dissolved oxygen availability in aquatic environments.

List of factors: Temperature, salinity, wind, turbulence, high elevation (change in atmospheric pressure), nitrogen from fertilizers/agricultural runoff, large numbers of photosynthetic plants (algal blooms), etc.

As temperature increases, oxygen solubility decreases; as salinity increases, oxygen solubility decreases; as atmospheric oxygen becomes mixed into a stream at turbulent, shallow riffles, dissolved oxygen levels increase; as atmospheric pressure decreases due to elevation changes, oxygen content decreases; as aquatic plants photosynthesize, they give off large amounts of dissolved oxygen during daylight hours—however, respiration from aquatic vegetation, microorganisms, and algae consume oxygen at all hours of the day and *night. Therefore, a stream experiencing an algal bloom due to high levels of available nitrogen exhibits large daily fluctuations in dissolved oxygen as extreme oxygen production during the day contrasts with the bacterial decomposition of algal detritus at night.*

At the Neutral Buoyancy Laboratory (NBL), astronauts breathe a special mixture of 46% oxygen and 54% nitrogen, known as “nitrox”. The increased oxygen level allows the crewmembers and divers to stay under water for long periods of time with a reduced risk of developing decompression sickness (DCS). DCS is most commonly associated with deep sea divers who ascend too quickly from a dive, or do not carry out the required decompression stops after a long and/or deep dive.

B. Data collected from a deep sea dive is shown in Table 1.

Table 1: Data from a Deep Sea Dive (Breathing 21% O_2, 78% N_2, 1% Trace Gases)

Depth (meters)	Amount of Dissolved N_2 in Lean Tissue (ml $_{STPD}$)	Atmospheric Pressure (kPa)	N_2 Partial Pressure (kPa)
0	510	101	79.8
10	1021	202	159.6
20	1532	303	239.4
30	2043	404	319.2

I. Using the data in Table 1, identify and discuss the factor(s) that affect nitrogen solubility in human tissues.

In the dissolved oxygen lab, experimental data with dissolved oxygen showed that gases are more soluble at lower temperatures. The experimental data collected from the deep sea dive shows an increase of dissolved nitrogen in the lean tissue of the diver’s body at deeper depths since the diver is breathing a higher partial pressure of nitrogen the deeper he/she dives. The data does not provide information on temperature; however, we do know that human body temperature remains fairly consistent, and thus, would not be a factor in altering the nitrogen solubility.

II. Explain what will happen to the nitrogen in a diver’s body as he ends the dive and returns to the surface.

When a diver returns to the surface, the pressure is decreasing. During this time, the tissues cannot retain the excess nitrogen at new lower pressure and the nitrogen becomes insoluble and returns to the gaseous state. If a diver returns too quickly, this could result in gas bubbles that could become lodged in red blood cells and tissues, causing extreme pain. In addition, diminished blood flow to the brain could result in headaches, or much worse.

Currently, astronauts wear pressurized spacesuits in order to work in space environments. The pressure of these suits (29.65 kPa) is significantly lower than the ambient pressure of the International Space Station (101.3 kPa). Therefore, astronauts must go through a denitrogenation process prior to all spacewalks. The denitrogenation process, called an “oxygen prebreathe”, will decrease nitrogen partial pressure in lean tissue and blood before depressurization to avoid subsequent DCS.

C. DCS is a condition that both astronauts and SCUBA divers must take precautions to avoid.

Table 2: Prebreathe Conditions for the ISS “Campout” Decompression Protocol

Prebreathe Protocol Steps	Ambient Pressure (kPa)	Start Time (min)	End Time (min)	Breathing Gas (% of O_2)
1. O_2 mask is put on to start denitrogenation	101.3	0	30	100
2. Decompression from 101.3 to 70.3 kPa	70.3	30	60	100
3. 8 hrs and 40 min living at 70.3 kPa, mostly sleeping in the ISS airlock	70.3	60	580	26.5
4. Recompression from 70.3 to 101.3 kPa	101.3	580	590	100
5. Stay at 101.3 kPa for hygiene break and to collect breakfast	101.3	590	620	100
6. Decompression from 101.3 to 70.3 kPa	70.3	620	650	100
7. Eat breakfast in the airlock, don the spacesuit	70.3	650	710	26.5
8. 50 min of in-suit prebreathe with 100% O_2	70.3	710	760	100

I. Determine when the symptoms of DCS would most likely occur for an astronaut who is scheduled for a spacewalk.

For astronauts, DCS would be the result of transitioning from the higher pressure of the ISS to the lower pressure of the spacesuit. The astronauts would start feeling the symptoms of DCS while on the spacewalk. They would not be able to perform the functions necessary, and the mission of the spacewalk and the astronauts’ health would be compromised.

II. Define contributing factors leading to the onset of DCS and evaluate the potential health effects of DCS.

Contributing factors to DCS include fatigue, dehydration, and hypothermia. Health effects including fatigue, mild to severe pain in the joints, rashes or itchy patches, dizziness, nausea, disorientation, numbness, mild to severe paralysis, loss of vision or hearing, unconsciousness, and even death.

III. Review the data in Table 2 and discuss how the eight steps in the “prebreathe” protocol serve as countermeasures for the astronauts against DCS.

***Instructor Note:** The solution below provides an in-depth and detailed explanation of the procedural steps and physiological effects of the NASA “prebreathe” protocol, detailed in Table 2. It is called the “campout” prebreathe protocol since two astronauts literally campout in the ISS airlock at 70.3 kPa while breathing 26.5% oxygen. They must* *be in the airlock because the ISS atmosphere must remain at 101.3 kPa and 21% oxygen. This is provided mainly for the teacher who wishes to share with the students the advanced physiology topics involved. AP Biology students will not be able to provide answers with this level of detail.*

All eight steps of this prebreathe protocol serve to remove nitrogen molecules through passive diffusion, from the tissues and out the lungs before the final depressurization to the suit pressure of 29.65 kPa.

All of us are in equilibrium with the nitrogen gas partial pressure in our atmosphere. Our tissues have a nitrogen partial pressure of about 80 kPa; this is the starting point for the denitrogenation protocol. By breathing either 100% oxygen or air enriched with oxygen, the lungs and then arterial blood are provided with a nitrogen partial pressure, less than that in the tissues. So nitrogen molecules diffuse from tissue regions with high nitrogen partial pressure into the venous blood, and then are removed at the lungs with every exhaled breath.

For astronauts, this continues until the tissue partial pressure of nitrogen has been reduced far enough that few bubbles form in the tissues when they make a final depressurization to the suit pressure of 29.65 kPa.

NASA Prebreathe Protocol

***Step 1** of the prebreathe protocol reduces the initial nitrogen partial pressure in the tissues by transporting nitrogen molecules from the venous blood in the tissues to the lungs prior to the first depressurization of the ISS airlock. Nitrogen bubbles can form in the tissues even with this small depressurization from 101.3 kPa down to 70.32 kPa.*

***Step 2** allows for thirty additional minutes of 100% oxygen prebreathe during the time of the first depressurization, removing additional nitrogen while the crew is still on breathing masks. It is not ideal to keep astronauts on breathing masks for many more hours, which leads to step 3.*

***Step 3** allows for a continued, but slower, denitrogenation rate while the crew mainly sleeps in the ISS airlock at 70.32 kPa. The nitrogen partial pressure (while breathing 26.5% oxygen and 73.5% nitrogen) is lower than in the tissues, so nitrogen molecules continue to diffuse from the tissues and are carried by the venous blood to the lungs.*

***Step 4 and 5** are required so that the crew can return to the ISS pressure of 101.3 kPa to have a hygiene break and to gather some breakfast. The transition is made while breathing 100% oxygen from a mask so their tissues are not renitrogenated by breathing the ISS atmosphere. By breathing 100% oxygen, they continue the denitrogenation process all through the thirty-minute hygiene break.*

***Step 6** returns the astronauts back to the ISS airlock, again while breathing 100% oxygen by mask. Once they return to 70.3 kPa and enrich the airlock atmosphere to 26.5% oxygen, they remove the masks.*

***Step 7** provides time to eat breakfast and don their spacesuits, still while transferring nitrogen molecules from their tissues into the airlock atmosphere.*

***Step 8** replaces 26.5% oxygen and 73.5% nitrogen with 100% oxygen once the astronauts attach their helmets to their suits. The final fifty minutes of prebreathe allow for even more nitrogen molecules to leave the tissues and enter the spacesuits. The remaining partial pressure of nitrogen in the tissue (about 48 kPa) is now low enough so that a significant number of bubbles do not form when the astronauts (protected inside their suits pressurized to 29.65 kPa) step from the airlock into the vacuum of space.*

Scoring Guide

Suggested 10 points total to be given.

There is 1 additional point possible to earn; however, students should not receive more than 10 total points for the questions or more than the allotted points per question.

Question		Distribution of points
A	*4 points*	1 point for explaining that oxygen and carbon dioxide are exchanged as a result of diffusion across concentration gradients 1 point for any of the following: lamellae and alveoli increase the surface area, continuous flow of water increases efficiency, or ventilation assisted by diaphragm 1 point each for identifying two factors that affect dissolved oxygen in aquatic systems **1 additional point earned if student elaborates on what specific effects these factors have on the dissolved oxygen concentration*
B	*2 points*	1 point for identifying a factor 1 point for describing the situation correctly for a diver
C	*4 points*	1 point for identifying in step 1 that the astronaut is given 100% oxygen to reduce the levels of dissolved nitrogen in his tissues/blood 1 point for identifying in step 2 that the decrease from 101.3 kPa to 70.32 kPa could lead to symptoms of DCS in the astronaut if 100% oxygen was not given before and during the decrease in pressure 1 point for identifying in step 3 that the 24-hour living period at 70.32 kPa is for further tissue/ blood denitrogenation and/or could serve as an observation period for negative health effects 1 point for identifying in step 4 that the 100% oxygen given is in preparation for exiting the airlock to step into the vacuum of space with a suit pressurized only to 29.65 kPa

Contributors

This problem was developed by the Human Research Program Education and Outreach (HRPEO) team with the help of NASA subject matter experts and high school AP Biology instructors.

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