Staying Warm in Frigid Waters: Heat Exchange

Teacher Background

We can't promise exactly how many whales students will see close-up during LFA 2, but we hope to record at least a few as our crew travels to Palmer. None of the researchers we'll meet this year have whales as primary research targets, but as the "top" of the Antarctic food chain they're obviously of great interest. This Activity allows students to model some key features of whale physiology in a very direct way. (See sidebar, below, for more real-world occurrences of biological counter-current heat flow.)

Whales are warm-blooded mammals who spend their entire lives in the open sea. Their transition from land-dwelling creatures to the oceans over 50 million years presented whales with great physical problems to solve. Like all mammals, their core body temperature needs to be between 35 and 38° C. But their skin is often close to the temperatures of the waters in which they swim, anywhere from -2 up to 30° C. So the degree of thermal protection they need can vary 5-fold. Going from rest to maximum activity produces another 10-fold change in metabolic heat production. A whale resting in the cold Southern Ocean may need 25 to 50 times the heat conservation of a whale swimming at high speed in tropical waters! Students will probably cite blubber as what keeps whales warm, but ironically, during times of great exertion, it also prevents them from cooling off. Metabolic heat produced from eating as much as they do-and moving enormous muscles-has to be dissipated somehow. Why don't they overheat and die? How is the whale's metabolic system uniquely adapted to the task of preventing frostbite and overheating?

Sidebar

Biological Occurrences of Counter-Current Flow

Counter-current flow is widely found in fish and animals. Counter-flowing blood conserves body heat for whales, seals, cranes, herons, manatees, sloths, anteaters and armadillos. Other animals don't have counter-current arrangements even though they live in cold climates. These include ducks, geese, sea gulls, foxes and huskies.

Camels have scroll-like passages called turbinates in their nose which turn back upon each other creating counter-current airflow to conserve both energy and water.

The bumblebee produces lots of heat with its flight muscle. Counter-current blood flow is used to regulate heat transfer during warm weather and during vigorous wing activity. Kidneys concentrate urine by counter-flowing body fluids in the loop of Henle.

Fish gills are another fine example of counter-current efficiency. Animals which breathe air inhale 200 cubic centimeters of oxygen with each quart, but a quart of sea water has only 5 cubic centimeters of oxygen. A fish can take up 80% of that oxygen by arranging capillaries in the gill plate to allow blood to flow counter to the flow of water across them. Go to a fish monger and obtain gillrakes from fish being cleaned. You'll be able to see the folded double loop.

Objective

- Students will demonstrate the principle of counter-current heat exchange and illustrate their experimental data in chart form.

Materials

- 1/2 inch plastic tubes one meter long
- 1/4 inch copper tubes a meter and a half long
- short sections of flexible tubing to fit on ends of copper
- 4 funnels
- 4 foam cups
- 4 thermometers
- towels
- lab stands or pegboard walls
- safety goggles
- Student Worksheet, "Staying Warm in Frigid Waters"

Engage

Complete the following demonstration: pour 1 cup of hot water through a 1 meter long tube, collecting it at other end of tube. Ask students if they think the water changed in any way as it traveled through the tube. Write all guesses on the board. Direct discussion to the possible cooling of the hot water. Ask how they might measure any changes in temperature.

Have students brainstorm a human system that moves a liquid through tubes throughout the body. (circulatory system) What functions does the circulatory system have? (takes food and oxygen to cells, removes waste from cells, regulates body heat) What must humans do to protect themselves from the cold? How is this different from Antarctic marine mammals?

Explore / Explain

Explain that students will explore counter-current heat exchange.

Procedure

1. Distribute and review the Student Worksheet. Organize lab teams and answer procedural questions. Post a class data table on the chalkboard.
2. When teams have completed Part A, compare and discuss data. Continue with Part B; then compare and discuss data.

Expand / Adapt / Connect

Although rudimentary, there's artery-to-vein heat transfer in humans. This is the mechanism by which we blush or our skin flushes after exercise. The human arm has three veins nestled around deep arteries with isolated veins occurring just under the skin. Arterial blood flows outward toward the hand and venous blood returns to the body core producing counter directional flow quite similar to the model created in the classroom.

Explain

Whales and seals swim in sub-zero Antarctic water with uninsulated fins and flippers continually submerged. How do they maintain their warm body temperature?

Whales and seals bypass the static insulation of blubber and produce active temperature regulation by having two alternative venous blood return systems. One pathway conserves metabolic heat at times when their environment is too cold. The other pathway allows them to dissipate heat even when they are well insulated with blubber. The cooling pathway is what we might typically expect to find with deep arteries taking warm blood to the extremity, and veins returning along the under-surface of the skin in such a way that blood cools. The heat conservation pathway is an ingenious counter current heat-exchange system consisting of deep parallel arteries and veins which allows warm outgoing arterial blood to pass its heat over to blood returning in the venous system.

The heating and cooling needs of whales change rapidly. Muscles can flatten veins and shunt blood into one system or the other. Heat is produced throughout the muscle bulk of the whale when it exercises. With movement, arterial pressure is increased. The enlarged artery pushes on the encircling veins and restricts blood flow in them. The counter-current exchanger is cut off and the blood must return through veins near the skin. Thus, heat is lost at the surface of fins and flippers. Fins and flippers are efficient cooling surfaces because they have many blood tubes and very little insulation, allowing blood to cool quickly as heat is lost in the sea.

If whale blood systems have such complexity in order to provide sufficient cooling, what is the purpose of all that blubber? It appears that blubber is needed as a food storehouse while whales make their yearly, several month excursion to warmer water. It is calculated that half of a whale's blubber could provide energy for metabolism for four to six months, which is very close to the interval spent not eating.

Expand / Adapt / Connect

Search the internet for "marine mammals". Download articles that further explain the heat exchange concept in Antarctic marine biology.