Bulk Flow

In single cells and tiny animals such as the tardigrade, or water bear, diffusion is enough to move oxygen, nutrients, and wastes where they need to go (Figure 34-7). But diffusion works only over very short distances. Larger animals depend on bulk flow to move materials longer distances. Examples of bulk flow include the movements by which the digestive system pushes food into the stomach and through the intestines, the movement of blood through the circulation, the movement of air in and out of the lungs, the passage of water over the gills of a fish, and the movement of urine through the urethra.

In each case, some force pushes a fluid or substance from one place to another. In the digestive system, muscular movements of the esophagus, stomach, and intestines squeeze the food along. In the circulation, the heart pressurizes the blood, forcing it into lower-pressure capillaries and veins. In respiration, muscles in the wall of the chest and the diaphragm muscle together pump air in and out of the lungs.

How Do Animals Use Countercurrent Systems?

Bulk flow and diffusion often work together to move materials. The heart pumps blood in bulk to the lungs. From the lungs, oxygen diffuses into the blood. The circulation then carries the oxygen in bulk to the tissues of the body, where the oxygen then diffuses into individual cells.

Bulk flow and diffusion can work together in interesting arrangements called countercurrent systems, systems in which fluids or gases run past each other and exchange heat or materials. Essentially, countercurrent systems enable animals to establish steep gradients of temperature or concentration.

Animals use countercurrent systems in dozens of ways. Whales use countercurrent systems to keep their fins from radiating too much heat into cold Arctic water. Gazelles living on the hot plains of Africa use countercurrent systems to keep their heads from getting too hot. Fish use countercurrent systems to maximize the absorption of oxygen in the gills and a similar system to keep their swim bladders pumped up with pressurized gases.

The structures of countercurrent systems are intricate and can involve any tissues in the body. Inside the noses of many vertebrates, including humans, are elaborately folded turbinate bones, which increase the surface area of the inside of the nose. Since the mucous membranes inside the nose are moist, evaporation from this large surface area tends to cool the inside of the nose.

Dogs depend on their cool noses to cool themselves off on a hot day. A dog inhales air through its wet nose, which cools the air before it enters the lungs. In the lungs, the cool air absorbs heat from the lungs and is then exhaled out through the mouth. As a result, the dog continually inhales cool air and exhales warm air. Because so much water evaporates inside the nose, it is important for dogs to drink lots of water on a hot day.

Desert animals, which conserve water by letting their body temperature rise on hot days, use their cool noses even more efficiently than dogs. The brain, unlike the other organs of the body, functions poorly at high temperatures. Many of us have experienced the delirium that sometimes accompanies a high fever, for example. In the desert, keeping the whole body cool would require more water than is usually available. The solution is to allow the body to heat up while keeping the head cool.

Many gazelles and antelopes keep a large volume of cool blood from the nose in an expanded blood vessel called a sinus. As hot blood from the heart enters the head, it separates into a network of hundreds of small arteries, which pass through the sinus filled with cool blood from the nose. In the oryx, such an arrangement keeps the brain nearly 3°C cooler than the central arteries of the body (Figure 34-8A).

Dolphins and whales use countercurrent systems to keep the cold blood in their flippers from chilling the rest of the body (Figure 34-8B). The body of a whale that swims in the freezing waters of the Arctic Ocean is well insulated against the cold. But its flukes and flippers, which are thin and flat, become extremely cold.

To prevent blood that has cooled in the flukes from chilling the body, the veins that carry the cold blood back to the body run adjacent to and surround the arteries that carry warm blood from the heart to the flippers. As a result, the warm arterial blood leaving the body heats the cold venous blood before it enters the body. Likewise, the cold venous blood leaving the fins cools the arterial blood before it enters the flippers.

This system, specifically called a countercurrent heat exchanger, occurs also in the legs of wading birds and in the testes of mammals. In most mammals, sperm develop best when the testes are cooler than the rest of the body. A countercurrent heat exchanger, along with other adaptations, keeps the testes cool but prevents them from radiating too much heat and cooling off the body.

The end result of a countercurrent system is a steep gradient—often in temperature. But the same system can be used to create pressure gradients or concentration gradients. In Chapter 39, we'll see how such gradients in the kidneys control the balance of water and salts in the blood and urine.

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Figure 34-7 Look Ma, no circulation! Tardigrades, such as this one, as well as rotifers and other microscopic animals, rely on diffusion alone to move nutrients and wastes. They need no circulatory system. (Diane R. Nelson)
Figure 34-8 Countercurrent heat exchange. A. The desert oryx uses countercurrent heat exchange to keep its head cool. B. Whales and other marine mammals use countercurrent heat exchange to minimize heat loss from the flippers, whose large surface area is wonderful for swimming but a hazard in Arctic waters. As warm, arterial blood from the heart flows out into the flippers, it passes in close proximity to the returning venous blood, which is cold. The arterial blood becomes cooler and cooler as it enters the flippers, while the venous blood, warmed by the arterial blood, becomes warmer and warmer. In this way body heat stays in the interior and the flippers remain cool.

Fish use a countercurrent system to extract oxygen from water flowing past their gills. The gills of fish consist of a huge surface folded into flat panels, or lamellae. Water enters a fish's mouth and flows out of the body by way of the gills (Figure 34-9). Blood vessels inside of the lamellae are arranged so that the blood flows in the opposite direction to that of the water. The water that first meets the blood in these vessels is rich in oxygen. But the blood coming the other way has already picked up oxygen from water it has already passed. So the blood is carrying a heavy load of oxygen already. Because the fresh water had even more oxygen, however, the blood picks up just a bit more. The water then moves past blood that is ever poorer in oxygen. At every point along its path, the water carries more oxygen than the blood and oxygen will diffuse into the blood.