The concentration of glucose is tightly regulated in the blood by a complicated set of physiological variables. To provide students with a means to more readily understand these complex mechanisms, the control of the water level in a beaver pond is presented as an analogy. A beaver must maintain a constant water level in the pond for the proper functioning of the lodge, just as blood glucose is maintained for, among other reasons, brain function. The beaver controls the water level by changing outflow over the dam and inflow from stream beds. Water flow over the dam is analogous to glucose leaving the blood for tissues, which is controlled by insulin. Inflow of water from streams is analogous to glucose absorption from the gastrointestinal tract and glucose release from the liver, the latter being controlled by glucagon and other counterregulatory hormones. The analogy is extended by considering the effects of exercise in normal and diabetic individuals on blood glucose levels.

Key words: physiology teaching; exercise; diabetes mellitus

Glucose is an important constituent of the plasma portion of blood, being regulated within the range of 70 to 110 mg/dl. The physiological mechanisms that accomplish this regulation are well known, but their complexity often makes them difficult for students to understand beyond the level of memorization.

The beaver is a useful animal for many reasons. It constructs dams that provide flood control, and the resulting ponds create habitats for many other species. Moreover, the beaver is a paragon of productivity, pointed out as an example to otherwise profligate children. Now, it is revealed, the beaver is also a physiology educator.

A beaver’s efforts at controlling the water level within its pond provide a good analogy of the control of blood glucose. I developed this teaching tool for use in exercise physiology courses and Diabetes Educator classes. First, let me examine the beaver’s activities in their normal context (5), and then I will illustrate glucose control through them.

THE BEAVER POND

A beaver, or more typically a pair of mated beavers, will locate an area through which one or more small streams pass to serve as its home. It will block off the streams by cutting down trees and using trunks, branches, and mud to build a dam (Fig. 1A). The waters behind the dam will rise until a pond is formed that reaches the top of the dam. Once spillover equals the rate of inflow from the streams, a relatively stable pond level is achieved. The beaver establishes the level of the pond in relation to its lodge, which is built along the periphery of the pond. A beaver lodge is the animal’s dwelling and serves to protect its family from predators. A critical point concerning beaver lodges is that, whereas the floor of the lodge is above water, the entrance is located underwater. The beaver maintains the water level in the pond with precision: it must be
high enough to keep the entrance of the lodge underwater, thus preventing predators from entering, but it must be lower than the floor of the lodge, or else the beaver’s family will be flooded out of its home.

The beaver maintains this water level with daily physical labor. The pond’s surface level is unlikely to rise too high, because runoff over the dam will automatically increase if the inflow from the streams increases, as in the case of heavy rains. However, if necessary, the beaver could adjust the dam to increase spillover. The principal concern for the beaver is that the water level might fall too low. A falling water level could be due to an excessive outflow through a breach in the dam or to inadequate inflow from the streams. The beaver regularly inspects the dam to find and repair breaches (in fact, it will repair the breaches instinctively, even before the pond surface falls to dangerous levels). If water flow into the pond is diminished, the beaver may clear debris from the stream beds upstream of the pond to increase the inflow. Through these actions, the water level is held relatively constant.

**A BEAVER’S-EYE VIEW OF BLOOD GLUCOSE CONTROL**

The level of glucose in the bloodstream, specifically the plasma concentration, is tightly controlled by a number of physiological mechanisms. I will present only a general review of glucose regulation, and the reader is referred to other sources for more detailed information (3, 4, 6).

Glucose is held within a narrow range, primarily to serve the needs of the central nervous system, which relies on glucose as virtually its sole energy source. If glucose levels fall too low, a condition referred to as hypoglycemia, neurological consequences such as lightheadedness, confusion, and coma can result.
Analogously, if the level of water in the beaver pond falls too low, the lodge will be placed in jeopardy. The opposite situation, hyperglycemia, also is associated with deleterious sequelae, as seen in uncontrolled diabetes mellitus.

The level of glucose in the bloodstream is analogous to the water in the beaver’s pond (Fig. 1) and is determined by the balance of glucose entry into the bloodstream from the gastrointestinal tract and the liver and by glucose removal from the bloodstream to the various tissues of the body (and to the urine in diabetes mellitus). Glucose entry from the gastrointestinal tract and liver is analogous to water entering the beaver pond from two streams. Glucose removal to the tissues is analogous to water over the dam.

**BLOOD GLUCOSE CONTROL DURING EXERCISE**

Let me examine how the human body maintains blood glucose at a constant level when this homeostasis is threatened by a perturbation such as exercise. Exercising skeletal muscle will take up glucose at an increased rate. If unopposed, this would result in an unacceptable drop in the blood glucose level. The beaver sees this as a break in the dam. Water is pouring out faster than usual. To protect the water level in the pond, the beaver can dredge upstream channels to increase inflow and can build up the dam to reduce outflow. During exercise, the human body increases the production of glucagon and other counterregulatory hormones such as growth hormone and epinephrine, which stimulate the liver to increase gluconeogenesis and glycogenolysis (Fig. 2A). These result in an increased release of glucose from the liver into the bloodstream. However, hepatic glucose production cannot keep pace with the removal of glucose from the bloodstream by active skeletal muscle and is thus insufficient to prevent the level from falling. It is also necessary to decrease the outflow, i.e., glucose removal by tissues, or water over the dam. During exercise, insulin production is decreased. This action reduces glucose uptake by most tissues, thereby preventing a drop in the glucose level. The beaver responds by building up the dam. Of course, the beaver cannot build up the entire dam all at once. Some areas will continue to have a higher spillover while the beaver is reducing the loss from another section of the dam. The decrease in insulin production affects active skeletal muscle and relatively inactive tissues differently. During exercise, the decreased insulin production reduces glucose removal by inactive tissues (the beaver is building up the dam in this area) but not by active skeletal muscle.

The reason why active skeletal muscle is able to increase glucose uptake in the face of reduced insulin production is not clear. It is commonly suggested that skeletal muscle becomes more sensitive to insulin during exercise, but the answer may simply be related to the increased blood flow to skeletal muscle: there is an increased insulin delivery (blood flow × concentration) during exercise and, due to the opening of more capillaries, a decreased diffusion distance for both insulin and glucose to the muscle cell membranes. Regardless of the mechanism for increasing glucose uptake by skeletal muscle, the overall effect on the blood glucose level is clear. The increased removal of glucose from the bloodstream by skeletal muscle during exercise is balanced by increasing the glucose entry from the liver and by decreasing the glucose removal by inactive tissues. During extended bouts of endurance exercise, glucose can also be added to the bloodstream by consuming simple carbohydrates, which are rapidly absorbed from the gastrointestinal tract (1), i.e., the beaver can dredge out the second stream to increase inflow from that site.

**THE EXERCISING DIABETIC**

Diabetes mellitus is a condition in which a lack of insulin (type I) or an insensitivity to insulin (type II) prevents glucose from entering tissues, resulting in high blood glucose levels. Diagnostic criteria for diabetes mellitus are fasting plasma glucose concentrations \( \geq 126 \text{ mg/dl} \) or casual, i.e., nonfasting, levels \( \geq 200 \text{ mg/dl} \) (2). In the untreated state, plasma glucose concentrations can substantially exceed these levels. Type I diabetes mellitus is controlled by exogenous insulin. Type II can be controlled through exercise and dietary modification or by pharmacological therapy with oral hypoglycemic agents or exogenous insulin. Exercise presents a special challenge for the maintenance of blood glucose levels for individuals with diabetes mellitus.

Consider an untreated type I diabetic, i.e., one who has not had a recent insulin injection (Fig. 2B). During exercise, the mechanisms for increasing the production of glucagon and other counterregulatory hor-
FIG. 2.
Control of blood glucose during exercise in a nondiabetic (A), a type I diabetic who has not had a recent insulin injection (B), and a type I diabetic who has had a recent insulin injection (C). In A and B, X indicates restricted exit of glucose to the tissues due to lack of insulin. Dashed lines in B and C represent changes in blood glucose level during exercise.
mones are still intact, and release of glucose into the bloodstream from the liver is increased as in a nondiabetic. However, because no insulin is available to facilitate the transport of glucose out of the bloodstream, the concentration of blood glucose increases during exercise, worsening the hyperglycemia. This situation is analogous to the beaver building its dam too high and then compounding the problem by dredging out the upstream channels to increase water entry into the pond. The pond level will rise and flood the lodge.

A type I diabetic who has had a recent insulin injection responds quite differently (Fig. 2C). Glucagon release still increases liver glucose production, but now the availability of insulin allows glucose to be removed by the skeletal muscle as well as by other tissues. In the nondiabetic, the onset of exercise results in a decrease in insulin production, which limits glucose removal by active tissues. Because the type I diabetic obtains insulin exogenously, no physiological mechanism exists to decrease the insulin availability when exercise commences. Thus the inactive tissues continue to remove glucose along with the skeletal muscle, and blood glucose levels fall. This results in hypoglycemia, which is a common complication of exercise in type I diabetics and is potentially life threatening. This scenario is analogous to the beaver responding to a break in the dam only by dredging the upstream channels. If it fails to build up the dam as well, the increased inflow will not be enough to match the increased outflow, and water level in the pond will fall, placing the lodge entrance within reach of predators. The exercising type I diabetic can avoid hypoglycemia by either reducing the preexercise insulin dosage (building up the dam) or by consuming a preexercise complex carbohydrate snack (opening up the second channel).

Type II diabetics are less prone to severe changes in blood glucose during exercise than are type I diabetics, because all regulatory mechanisms are intact, although not fully functional in the type II diabetics. However, persons with poorly controlled type II diabetes who have resorted to insulin injections for therapy are more likely to respond like type I diabetics.

DISCUSSION

A beaver’s control of the water level in its pond has been presented to illustrate the physiological control mechanisms for blood glucose. As with any analogy, it must be remembered that the two situations being compared are similar in some ways, but not all. For example, whereas beavers do in fact engage in the type of pond building and water-level control activities described here, they frequently live along large, existing rivers and lakes where water level is set by external factors (5). Whereas one might be tempted to draw comparisons between this behavior and a diabetic on an insulin pump, it would strain the analogy beyond useful purposes.

I have used the pond analogy for several years in university exercise physiology courses and in lectures to health professionals seeking certification as diabetes educators. Very favorable responses from students have indicated that this analogy is a useful tool in increasing students’ understanding of this complex physiological system.

Special thanks go to the industrious beaver for inspiring this insight.

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Received 18 August 1998; accepted in final form 2 February 1999.

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