

## THE WATER-TOWER ANALOGY OF THE CARDIOVASCULAR SYSTEM

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**T**he cardiovascular system is a complex arrangement of hydraulic, yet living, components. The complexity of this system may make it difficult for students to see the “forest” instead of the “trees.” To better explain the dynamics of cardiovascular function and control, an analogy has been drawn to the operation of a city water supply. In cities that use a water tower, fresh water is pumped up into the tower from a river or other source. The tower serves as a pressure reservoir for providing water to homes through a largely parallel arrangement of distribution pipes. Local homeowners control their own water usage through faucets, whereas the city maintains water pressure by monitoring the level in the tower. Key analogous points with the cardiovascular system are the heart as the city pump, the aorta as the water tower, arteries as parallel distribution pipes, and arterioles as faucets. Baroreceptor reflex control is discussed as well as such features as the capacitance role of veins, the skeletal muscle pump, and the competition between locally mediated vasodilation and sympathetically mediated vasoconstriction. Subjective student and peer evaluations have indicated that this analogy is effective in improving student comprehension of the cardiovascular system.

*ADV PHYSIOL EDUC 24: 43-50, 2000.*

**Key words:** physiology teaching; blood flow; blood pressure; systems control

The cardiovascular system is wondrous in its function and complexity. It distributes an appropriate level of blood flow to a vast diversity of tissue beds under a variety of conditions. This flow distribution is controlled by a complex system involving sensors and their afferent neural pathways, control centers, neural and humoral efferent pathways, and effector organ sites. When students are confronted with the details of this information, it is sometimes difficult for them to grasp the overall picture of how the system operates.

This article presents an analogy for the cardiovascular system involving a city water supply that provides a relatively simple and cohesive illustration of the system's components and operation. There are many

variations in how municipalities accomplish water distribution, and this article is not intended to provide an authoritative explanation of the civil engineering involved. The reader is referred to professional literature in that field for further information (6). Additional sources are also available for more detailed descriptions of the cardiovascular system and its control (2, 7).

Analogies are effective teaching tools because they provide the student with a familiar frame of reference (domain) that is similar to the new concept being taught (4). Thus a transfer of understanding from the familiar to the new can be obtained. Research has shown that basic-level science information is best learned from literal expression of the material but that

inferential understanding is enhanced by the use of analogies (5). The cardiovascular system lends itself to analogies. One recent report in *Advances in Physiology Education* described numerous analogies including vehicular traffic patterns to explain network flow, a rubber band to explain arterial compliance, and a gentle stream versus white-water rapids to explain laminar versus turbulent flow (1). In the last example, the author pointed out that the stream analogy was not technically correct. It must be remembered that analogies have the potential to create more confusion than they resolve if inappropriately applied (12). I use analogies extensively in my own teaching and previously published an analogy for the teaching of blood-glucose control (10).

I developed the water-tower analogy several years ago, inspired in part by the Vander et al. (11) model of arterial pressure, and have refined it in use with many physiology classes for exercise science and allied health students at both the undergraduate and graduate level. In actual classroom use, I present the basics of cardiovascular-system physiology, and then I describe the city

water supply and its control. While describing the city water supply, I do not make any reference to the cardiovascular system. The intent at this point is to present the students with the familiar—the water supply—and to let them make their own inferences. Once I complete the description of the water supply, I go back through it and ask the students to identify the analogies between it and the cardiovascular system, beginning with the pump, as presented in **THE CARDIOVASCULAR SYSTEM AS A CITY WATER SUPPLY**.

### A CITY WATER SUPPLY

The water tower is a familiar sight on the landscapes of many towns and small cities. This is both the focal point of water distribution for such towns and also a symbol in many communities of simpler times. We recognize the tower as the source of water in our homes but may not have thought much about how it got there to begin with or how it is distributed.

As illustrated in Fig. 1, it is typical for the town to draw water from a river and pump it up into the

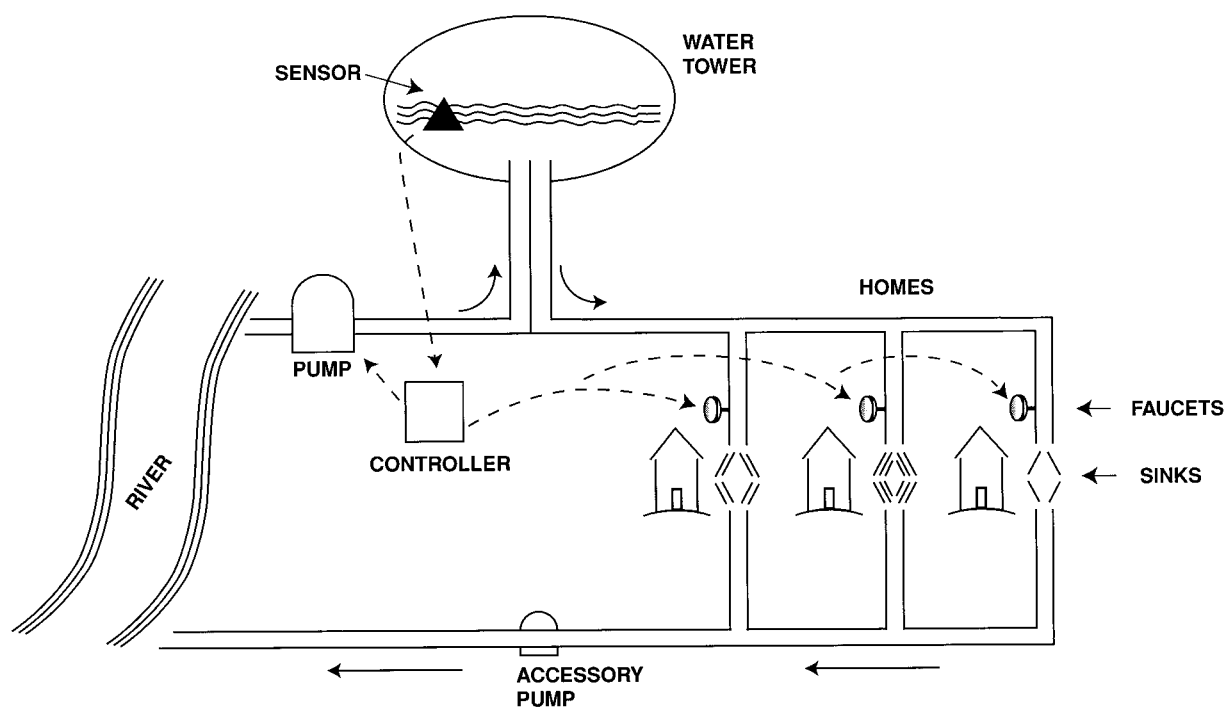


FIG. 1.

An illustration of a city water supply. Dashed lines indicate distribution of information.

tower. The tower then serves as the pressure head for driving water through pipes connecting the tower to the various homes and businesses. Why use a tower at all? Couldn't the pump be directly attached to the pipes? The tower serves to prevent large fluctuations in pressure that would occur if the pump were directly attached to the distribution pipes. Whereas the flow rate from the pump into the tower needs to match the flow rate out of the tower to the homes over time, the large capacity of the tower means that these two flow rates do not have to match exactly at all times. Fluctuations in water demand from the homes cause the water level in the tower to vary. These fluctuations in demand would cause large variations in the pressure within the pipes if the pipes were directly attached to the pump. Direct attachment to the pump would require more energy to produce the same flow rate and would also result in greater wear and tear on the pump. (Municipalities that do not use towers manage pressure fluctuations through the use of a variable-speed pump with more complex controls.)

The city's pump operates intermittently. It pumps water up into the tower at a rate that is normally much greater than the flow rate out of the tower to the homes. Once the tower is filled, the pump is turned off. The water level in the tower falls for a time, as much as a few hours, and then the pump is turned on again.

The pipes that deliver water to individual homes each come off a main water line. This is a branching, or "parallel," arrangement of the distribution pipes (Fig. 1), as opposed to a series connection. A series connection would mean that water would pass through one home before going to the next, and then the next and so on. Of course, no one would be willing to accept water from the sinks and toilets of the home next door, much less after having passed through the entire neighborhood. A parallel arrangement makes it possible for each water customer to receive the same supply of fresh water as every other customer.

The water pipes within an individual home branch out, again in a parallel manner, to the various sinks, showers, etc. within the home. At each end point, there is a faucet or valve used to control the amount of flow. The faucet can be opened wide to allow a

high flow rate to pass into the sink or shower or closed down to whatever level the local user desires at any given time.

The used water collects in the drain and passes through a separate set of pipes for waste-water return. This waste water flows under very low pressure ("gravity" flow) through the return pipes to be deposited back into the river from whence it came (hopefully *downstream* of the intake site!). The energy needed for this return comes from the original pumping of water up into the tower—it flows downhill from that point on. However, for a small percentage of low-lying neighborhoods, accessory pumping stations may be used along the return pathway, to assist in moving the water back to the river.

### CONTROL OF A CITY WATER SUPPLY

The various homes and businesses served by this system use water at different rates during the day. Sometimes, several users may have a great demand for water all at once, opening their faucets wide, and the flow rate out of the water tower will increase. If the pump doesn't increase its output, the water level in the tower will fall precipitously, and the pressure head to the various users will no longer be adequate to maintain effective flow. Obviously, the pump needs to increase its pumping rate, but how does it know to do this? There is a sensor within the tower that detects the water level, which is synonymous with the water pressure, and that transmits this information to the control center of the pumping station. It is not even necessary for a human worker to become consciously aware of changes in the water tower's level to effect change. Rather, there is circuitry to automatically respond to the information from the sensors, adjusting the pump rate to compensate for the drop in water level. This type of control is known as a negative-feedback loop and can, of course, compensate for temporary decreases in water demand as well as the increased demand described here.

Competition can occur between the desires of individual homeowners and the needs of the community at large. For example, in times of drought, there may not be enough water available from the river to maintain a sufficiently high level in the tower. In this case, increased pump action will not be sufficient, and the

control center for the pumping station will request that homeowners restrict their water usage, telling them, in effect, to tighten their faucets.

### THE CARDIOVASCULAR SYSTEM AS A CITY WATER SUPPLY

The cardiovascular system operates in much the same way as does the city water supply (Fig. 2). The heart is, of course, analogous to the city's pump. The city's pump pumps water into a tower. Is this tower analogous to any feature of the cardiovascular system? Yes, the tower is the body's aorta. The aorta serves as a pressure reservoir for the body, just as the tower does for the city. The aorta also serves to smooth out pressure fluctuations in the system, although in the case of the body, these are created primarily by the pump itself. The heart is an intermittent pump, providing forward flow only during a portion of each cardiac cycle. During the left ventricle's systolic ejection into the aorta, some of the blood moves forward towards the arteries while some acts to expand the aorta (i.e., filling the water tower). During ventricular

diastole, the aorta recoils, propelling the blood that was stored by its expansion forward into the arteries. Thus the aorta converts the intermittent flow of the heart into a continuous blood flow to the periphery. Analogously, the city pump pumps water into the tower for a time, and then the water drains from the tower before the pump is turned on again. The heart and aorta perform this function approximately once per second, whereas the city pump and water tower operate on a much longer time frame; but the principle is the same.

Pressures within the aorta fluctuate from 120 to 80 mmHg during a normal cardiac cycle, whereas pressures within the left ventricle fluctuate from 120 to ~0 mmHg. If the heart were directly attached to a stiff set of pipes, instead of to a compliant aorta, blood flow to the tissues would be intermittent, and arterial pressure would fluctuate wildly. Moreover, it would require much more energy from the cardiac muscle to drive blood flow under such circumstances. When arteriosclerosis hardens arteries, blood pressure is

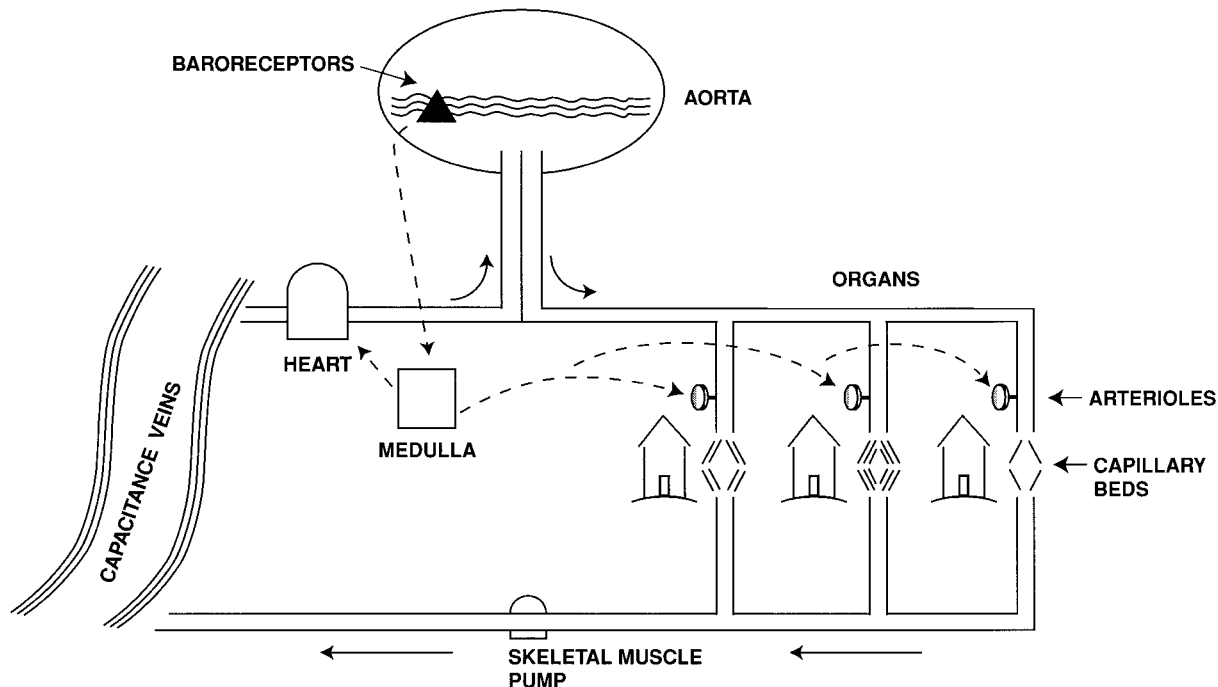


FIG. 2.

An illustration of the cardiovascular system patterned after a city water supply. Dashed lines indicate distribution of neural signals.

higher and the heart must work harder to produce the same amount of blood flow.

Distribution pipes from a city's water tower branch in a parallel arrangement to provide fresh water to each user. Arteries also have a parallel arrangement, so that each capillary bed receives blood with the same oxygen content as well as the same composition of other constituents, such as glucose, amino acids, electrolytes, etc. This is a crucial feature of the cardiovascular system of large multicellular organisms: to reduce the distance between cells and a fresh supply of blood. Conversely, insects and many other invertebrates have an open circulatory system in which blood leaves the heart (dorsal vessel) and simply bathes one tissue space after another in series (3). Such an arrangement is only effective in small organisms or those with low metabolic activity. A high metabolism may be attained in the case of insects due to a separate system for the distribution of respiratory gases.

The distribution pipes for the city water supply eventually branch down to the level of individual homes (organs) and discrete sinks and showers (capillary beds) within the home. A faucet can be opened or closed to control the local flow at that end point. The faucets are analogous to the body's arterioles. Arterioles are microscopic arteries that have a large muscular coat relative to their lumen diameter. They are able to constrict or dilate to a remarkable degree, thus varying the local resistance to blood flow and thereby affecting the flow rate to their daughter capillaries. Arterioles are thus referred to as the resistance vessels of the body. Arteriolar dilation is largely under local control. Byproducts of local tissue metabolism, such as  $H^+$ ,  $K^+$ , inorganic phosphate, and adenosine, accumulate in the interstitial spaces and cause the smooth muscle of the arterioles to relax. This muscular relaxation produces vasodilation that results in an increased blood flow to the area undergoing the metabolism. As discussed below, this local control can come into conflict with central control.

Once the water within the sink (capillary bed) has served its purpose, it passes into drainage pipes (venules and veins) for return to the river. Venous blood flow is driven by a relatively small pressure gradient between the capillaries and the right side of

the heart. This pressure gradient derives from the energy originally imparted to the blood by the left ventricle. However, passage through veins can become sluggish, as in the case of venous return from lower extremities. A means of enhancing venous return from these areas is the skeletal muscle pump. If an individual walks about, or simply taps one's toes, the contractions of the skeletal muscles within the legs will compress the veins passing through them. Because the veins have one-way valves oriented towards the heart, this compression will move the blood upward towards the right side of the heart. In this way, skeletal muscles can contribute a small amount of energy for venous return, adding this to that produced by the left ventricle. The skeletal muscle pump is analogous to pumping stations that cities place in low-lying communities for the return of waste water.

The city's water returns to the river, which is the source of the water for the city's pump. Analogously, the large veins of the body serve as a volume reservoir (the capacitance vessels). Approximately two-thirds of the total blood volume are located within the systemic veins at any moment as opposed to only ~10% within the systemic arteries (2). The heart extracts blood from this venous reservoir and creates a pressure gradient by pumping it into the aorta, just as the city's pump creates a pressure gradient by pumping water out of the river and into a tower. Of course, the analogy between the river and the veins is not complete; for the veins are part of a closed system of vessels, with all of the returning blood becoming the arterial blood in the next circuit. Whereas, the river is an open system from which the city merely extracts and returns a small portion of the available water.

## CONTROL OF THE CARDIOVASCULAR SYSTEM

Just as control of the city water supply centers on maintaining a set water level, i.e., pressure, in the tower, control of the cardiovascular system centers on maintaining the blood pressure in the aorta at a level close to 120/80 mmHg. Just as the city water pressure is a function of the amount of water in the tower, arterial blood pressure is largely a function of the volume of blood within the aorta (as well as its compliance). As discussed previously, ventricular sys-



tole ejects blood into the aorta at a greater rate than what is leaving the aorta to the periphery, with the difference expanding the aorta. This extra volume in the aorta during systole means that its pressure rises. During ventricular diastole, the aortic valve is closed and blood drains out of the aorta into the periphery, and aortic pressure falls. Thus the pressure changes are largely due to volume within the aorta at any given moment.

If peripheral resistance decreases, due to large amounts of local vasodilation at the arteriolar level, the run off from the aorta will increase and arterial pressure will drop (several homes have opened their faucets wide). Whereas there are many compensating factors, the principal one is the baroreceptor reflex. Baroreceptors are located in the arch of the aorta, and they respond to stretch of the aorta. They are not “baro” (pressure) receptors per se, but stretch receptors. However, as with the water-level indicator in the city’s tower, this measure of blood volume in the aortic pressure reservoir is tantamount to a pressure gauge.

The baroreceptors are connected neurally to the cardiovascular control center in the medulla (the control center of the pumping station). If aortic pressure falls, these baroreceptors will detect less stretch and fire fewer nerve impulses. Automatic, i.e., reflex, neural connections within the cardiovascular control center will respond by increasing sympathetic drive and decreasing parasympathetic drive, with a resultant increase in heart action. The greater heart action (coupled with peripheral vasoconstriction, as described in greater detail below) results in an increased blood pressure, and the signals from the baroreceptors return to normal. Exactly as in systems engineering of water pressure, this control mechanism of the cardiovascular system is referred to as a negative-feedback loop. In the case of the city water supply, the water pressure in the tower is controlled by feedback from the water-level indicator via the control center to the pump, whereas blood pressure in the cardiovascular system is controlled by feedback from the baroreceptors via the medulla to the heart.

If the body is experiencing a significant decrease of blood volume, due to dehydration or hemorrhage for example, the response of the cardiovascular control

center will be much greater than as described above. The lack of signals from the baroreceptors will result in substantial increases in sympathetic drive. In addition to innervating the heart, sympathetic drive also innervates blood vessels throughout the periphery. The sympathetic nerve fibers release norepinephrine onto the smooth muscle of arterioles that respond by contracting. This increases peripheral resistance to blood flow throughout the body, reduces aortic outflow, and helps to restore aortic blood pressure. Locally active vasodilatory metabolites will act in competition with this sympathetically mediated vasoconstriction. During exercise, the large production of metabolites by the active skeletal muscle will win out, producing local vasodilation and increased muscle blood flow. However, the metabolism of less-active tissues will not produce such a large vasodilatory effect, and the sympathetic vasoconstrictor effect will win out, resulting in a decreased blood flow to those regions—in effect, shunting blood from less active to more active regions. A somewhat analogous situation with the city water supply occurs when there is a break in a water main, and interconnecting pipes allow for a shunting of water from one region to another to maintain flow. In the case of dehydration or hemorrhage, the sympathetic drive will be large enough to constrict almost all vascular beds, thus maintaining blood pressure and blood flow to the heart and brain at the expense of less vital regions. This is analogous to water rationing by the city in times of drought. Local control—homeowners opening their faucets to water lawns, wash cars, etc.—is in conflict with the city’s overall need, and the city responds by requesting homeowners to “tighten their faucets,” i.e., to vasoconstrict their arterioles.

## DISCUSSION

A city water supply has been described to provide an analogy of the cardiovascular system. Whereas no formalized evaluation of its effectiveness has been performed, for example, by comparing test scores against a control group, it has been my experience that students’ comprehension of the material is enhanced by the analogy. As stated earlier, the city water supply is presented in class without direct reference to the cardiovascular system, and then the analogous features between the two systems are reviewed as an in-class exercise. All students immedi-

ately identify the city pump as the heart, but only the better students initially are able to identify the water tower as the aorta. However, once this is verbalized by some students in the class, the others rapidly catch on to the entire system. Two means of subjective evaluation of this analogy have been performed. Anonymous student comments as part of systematic course evaluation have consistently endorsed the analogy as being helpful. In addition, an external review by a professor from another institution was performed. The reviewer endorsed the analogy and asked to use it in his own lectures.

Whereas there are many analogous features between these two systems, there are some aspects that differ. One example described above is that the city's water is drawn from a river, which is a separate and open system, whereas the cardiovascular system uses its own veins as the source of blood volume in a closed system. Another example is that the branching network of distribution pipes in a city water supply is actually more complex than described above. Whereas a parallel arrangement is a principal feature of both systems, the city water supply has looped connections between the distribution pipes to ensure pressure to all areas even when some sections are shut down for repairs. The cardiovascular system has similar loops (e.g., the circle of Willis in support of cerebral blood flow), but such connections are not a basic feature of its arterial branching.

A key feature of both systems that was not presented in the analogy is the means employed for filtration of the respective fluids. Cities use a variety of filtration and purification methods, sometimes at both the intake site of water from the river and at the site for returning waste water back to the river. This is generally done in series with the water-distribution system such that all of the water passes through the filtration site before being used and/or before being returned to the river. The cardiovascular system performs this task in a different manner. A portion of the blood on each circuit through the system [ $\sim 20\%$  of cardiac output at rest (2)] passes through the kidneys in one of the parallel distribution channels. The kidneys produce a filtrate of plasma, discarding undesirable constituents via the urine and returning desirable constituents to the blood. Because this is done in parallel to other organs, the remaining 80% of the

blood supply is not filtered on any given circuit. However, mixing of the venous blood and repeated circuits ensure adequate filtration of the entire supply. The pulmonary circulation is in series to the systemic circulation, so its function of restoring the  $O_2$  and  $CO_2$  concentrations of systemic arterial blood is nearly 100% effective on each circuit (an insignificant amount of systemic venous blood from cardiac tissue and from systemic vessels that feed the bronchial tree bypasses this circuit).

Whereas the analogy as presented is used to describe the systemic circulation, many of its aspects could be applied to the pulmonary circulation. A significant difference in the two systems that would need to be addressed is regional differences in blood flow. In the systemic circulation, shunting occurs during exercise from areas of low metabolism to areas of high metabolism. This is accomplished by a combination of sympathetically mediated vasoconstriction and metabolically mediated vasodilation. In the pulmonary circulation, shunting occurs at all times in response to regional variations in ventilation. Areas of the lungs that receive little ventilation are hypoxically vasoconstricted to allow appropriate matching of ventilation/perfusion for optimum gas exchange. The pulmonary circulation also experiences regional differences in flow as a result of gravitational effects on intravascular pressures (2).

A key feature in the use of analogies is to keep them simple. The analogy must entail a concept that is familiar to the student to be effective (4). Overly complicated analogies are not effective teaching tools (12). A possible extension of the analogy would be to construct a working model of the city water system to illustrate the components. Simple working models of the cardiovascular system have been recently described (8, 9) that could be adapted to this purpose.

In conclusion, an analogy of the cardiovascular system using a city water supply has been presented. Whereas there are some differences in the design and operation of a city water supply and the cardiovascular system, the many similarities between the relatively familiar city system and the complex cardiovascular system make this a very good analogy for teaching purposes. This analogy has been used by the author for several years in university exercise-physiology classes and in cardiovascular physiology lec-

tures to allied health students. Subjective student and peer evaluations have indicated that the analogy is an effective means of enhancing comprehension of this complex physiological system.

Many thanks to William A. Drewry, Old Dominion Univ., for constructive comments on the civil engineering aspects of the manuscript. Oversimplifications and any remaining errors are those of the author alone.

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Received 6 December 1999; accepted in final form 7 July 2000

## REFERENCES

1. **Belloni FL.** Teaching the principles of hemodynamics. *Am J Physiol Adv Physiol Educ* 22: S187-S202, 1999.
2. **Berne RM and Levy MN.** *Cardiovascular Physiology* (7th ed.), St. Louis, MO: Mosby-Year Book, 1996.
3. **Chapman RF.** *The Insects: Structure and Function* (4th ed.), Cambridge, UK: Cambridge Univ. Press, 1998, p. 94-105.
4. **Dagher ZR.** Review of studies on the effectiveness of instructional analogies in science education. *Sci Educ* 79: 295-312, 1995.
5. **Donnelly CM and McDaniel MA.** Use of analogy in learning scientific concepts. *J Exp Psych* 19: 975-987, 1993.
6. **McGhee TJ.** *Water Supply and Sewerage* (6th ed.), New York: McGraw-Hill, 1991, p. 131-157.
7. **Mitchell JH.** Neural control of the circulation during exercise. *Med Sci Sports Exerc* 22: 141-154, 1990.
8. **Rodenbaugh DW, Collins HL, Chen CY, and DiCarlo SE.** Construction of a model demonstrating cardiovascular principles. *Am J Physiol Adv Physiol Educ* 22: S67-S83, 1999.
9. **Smith AM.** A model circulatory system for use in undergraduate physiology laboratories. *Am J Physiol Adv Physiol Educ* 22: S92-S99, 1999.
10. **Swain DP.** The beaver pond analogy of blood glucose control. *Am J Physiol Adv Physiol Educ* 21: S69-S73, 1999.
11. **Vander AJ, Sherman JH, and Luciano DS.** *Human Physiology: The Mechanisms of Body Function* (3rd ed.), New York: McGraw-Hill, 1980, p. 285, 300-303.
12. **Venville GJ and Treagust DF.** Analogies in biology education: a contentious issue. *Am Biol Teacher* 59: 282-287, 1997.