Snakes, Blood Circulation and Gravity

body shape
heart position
pooling
brain perfusion

When a snake climbs or rears up, its cardiovascular system must resist strong pressure gradients. These effects of gravity explain why the circulatory system of a tree snake differs from that of a sea snake

length of lung & why
corr w/ habitat

by Harvey B. Lillywhite

Gravity is a pervasive force in the world, and both animals and plants have adapted to it in a variety of ways. Trees, for example, can grow to extraordinary heights (as much as 364 feet) and still circulate vital fluids to their upper branches. At the other extreme, consider animals that live at the bottom of the sea. How do they function at depths of more than 19,000 feet, where the weight of the water column exceeds 8,800 pounds per square inch? It is not surprising that these and other adaptations to gravity have inspired the curiosity of scientists for centuries.

In terrestrial environments gravity places special demands on the cardiovascular system of animals, and its effects can be particularly pronounced in larger species that adopt vertical orientations. Because the design of an animal's cardiovascular system reflects its lifestyle and the extent to which it is affected by gravity, certain animals have proved to be valuable models for studies of circulatory regulation. The giraffe is one such animal. Because its head is so far above its heart, unusually large pressures are needed to send blood to its brain. Of all the vertebrates, however, snakes perhaps excel in the extent and variability of adaptations involving gravity and the cardiovascular system.

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Snakes are remarkably well-adapted animals. During their evolutionary history, which exceeds 100 million years, they have successfully diversified to fill a great variety of ecological niches. Today there are approximately 16 families and 2,700 species of snakes in the world. They exhibit a broad range of body sizes, occupy many different environments and display wide variation in behavior. Some snakes are totally aquatic, others are terrestrial and a large number live in trees.

Such diversity is possible in part because snakes have wonderfully effective cardiovascular systems that enable them to circulate blood against the force of gravity. A corn snake, for example, may crawl straight up the trunk of a tree in search of eggs in an unprotected nest; a tree boa may hang with its head down while pursuing prey in a tree. Both animals are exhibiting behaviors that would not be possible without a cardiovascular system adapted to maintain adequate blood circulation when the body deviates from a horizontal orientation.

In order to understand why gravity places such demands on the circulatory systems of animals, it helps to think of blood vessels as cylindrical tubes. If a sealed cylinder filled with water is turned to stand on one end, the weight of the water in it creates a vertical pressure gradient, which is lowest at the top of the tube and greatest at the bottom; at the center of the column it remains essentially unchanged. If instead of a rigid cylinder a thin balloon is filled with water and held vertically, it will bulge at the bottom and perhaps be broken by the pressure of the water inside. The pressure thus created is called gravitational pressure. It increases with depth and is present in any continuous fluid column regardless of whether the fluid is in motion or not. If the fluid is set in motion by a pump, as in the circulatory system, overall pressure is increased: the pressure created by the pump, or heart, is added to that imposed by gravity.

Gravitational pressure can severely affect larger animals that are not physiologically adapted to withstand its force. Increased pressure in the lowermost vessels of an animal's circulatory system tends to cause blood pooling: it distends the walls of the vessels and may cause plasma to leak from the capillaries. As blood pools in the lower body, central blood pressure falls and circulation to critical organs, such as the brain, eventually fails. If all but the smaller snakes were highly susceptible to blood pooling, they would be restricted to aquatic or horizontal habits. But this clearly is not the case.

A little more than 10 years ago I became curious about the ability of snakes to maintain adequate blood circulation while they are in a vertical position. Why, I wondered, did a long snake not faint while climbing a tree? I had the chance to address this question while I was a visiting lecturer at Monash University in Australia. There I collaborated with Roger S. Seymour, who is now at the University of Adelaide. Together we began a comparative analysis of the effects of gravity on the blood pressures of snakes. We studied sea snakes, which when surrounded by water are virtually immune to the effects of gravity; terrestrial nonclimbing snakes, which live on the ground and are usually horizontal, and arboreal snakes, which often assume a vertical posture as they climb up and down trees.

Sea snakes (close relatives of cobras and coral snakes) occupy tropical re-

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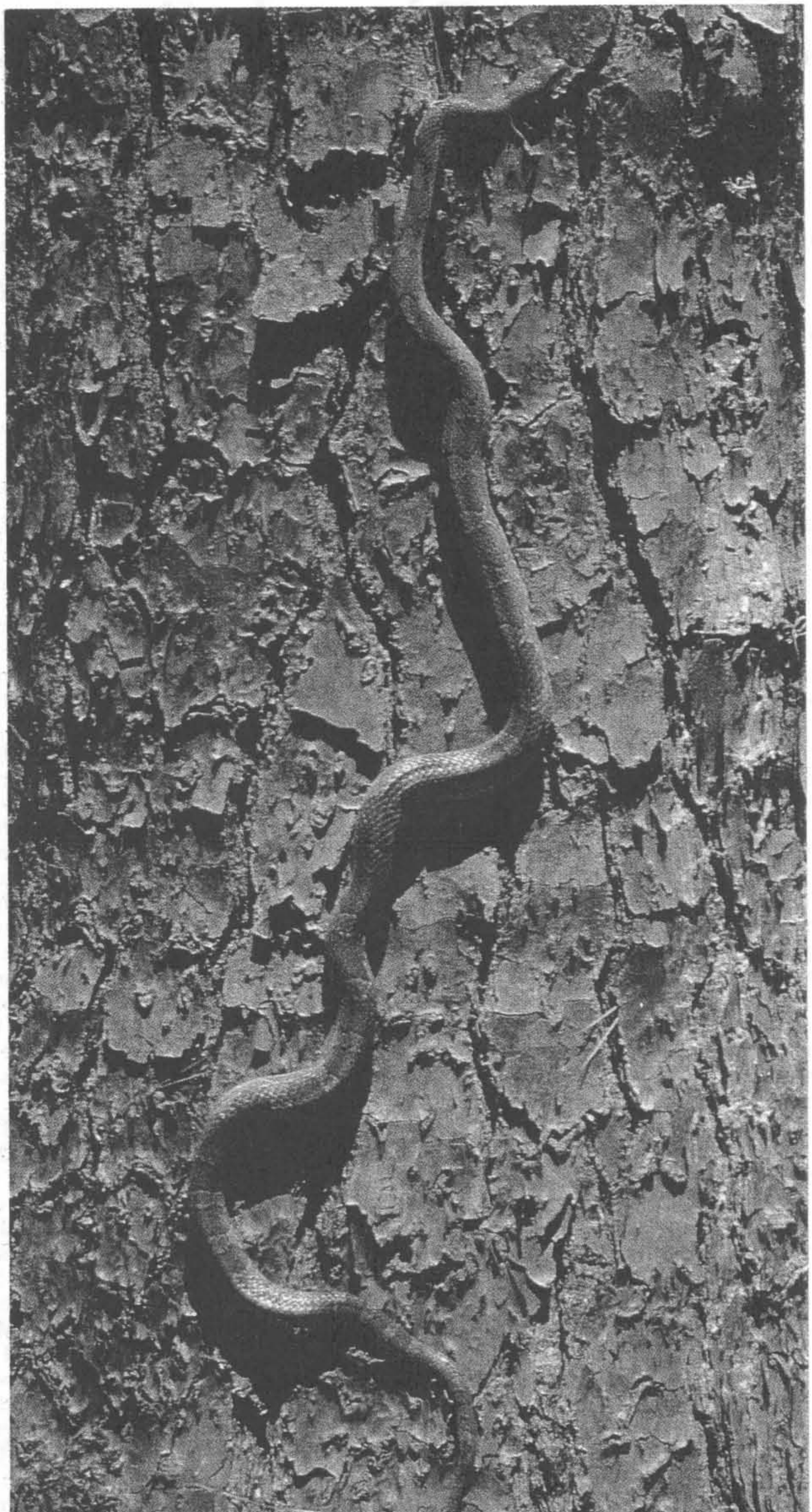
gions of the Pacific Ocean and are particularly abundant in coral reefs surrounding Australia, where they can be captured with a hand-held net. In the ocean they are supported by salt water, whose density is nearly equal to that of blood. Buoyed by the weight of the water, snakes can adjust their lung volume so as to be effectively weightless, much like objects floating in outer space. In theory blood circulation in these aquatic snakes is affected very little by gravity. The reason is that vertical pressure gradients within the blood vessels are counteracted by similar gradients in the pressure of the surrounding water; hence there is no tendency for gravity to expand the vessel wall, and the distribution of blood remains about the same regardless of orientation.

Sea snakes are descended from terrestrial ancestors. We therefore wondered whether they retain a physiological capacity to withstand gravitational pressure when they are removed from the supportive medium in which they normally live. Captured snakes were brought into the laboratory, chilled with chipped ice and anesthetized briefly. One or more catheters—small, flexible tubes filled with saline—were then inserted into their blood vessels to measure changes in pressure. Before mobility was restored the snakes were put in long plastic tubes attached to a central pivot.

By rotating the tubes from a horizontal position to various angles with the head tilted up, we were able to measure the effects of gravity on an animal's cardiovascular system. Using an electronic pressure transducer connected to a catheter inserted into the snake's dorsal aorta, we recorded blood pressures at the midpoint of the snake's body. Recalling the analogy to a closed tube, we expected that a snake not adapted to gravity would lose pressure at its midpoint and be unable to compensate for the fall of pressure at the head. We monitored the heart rate of each snake to see if the heart would compensate for failing blood pressure by beating faster.

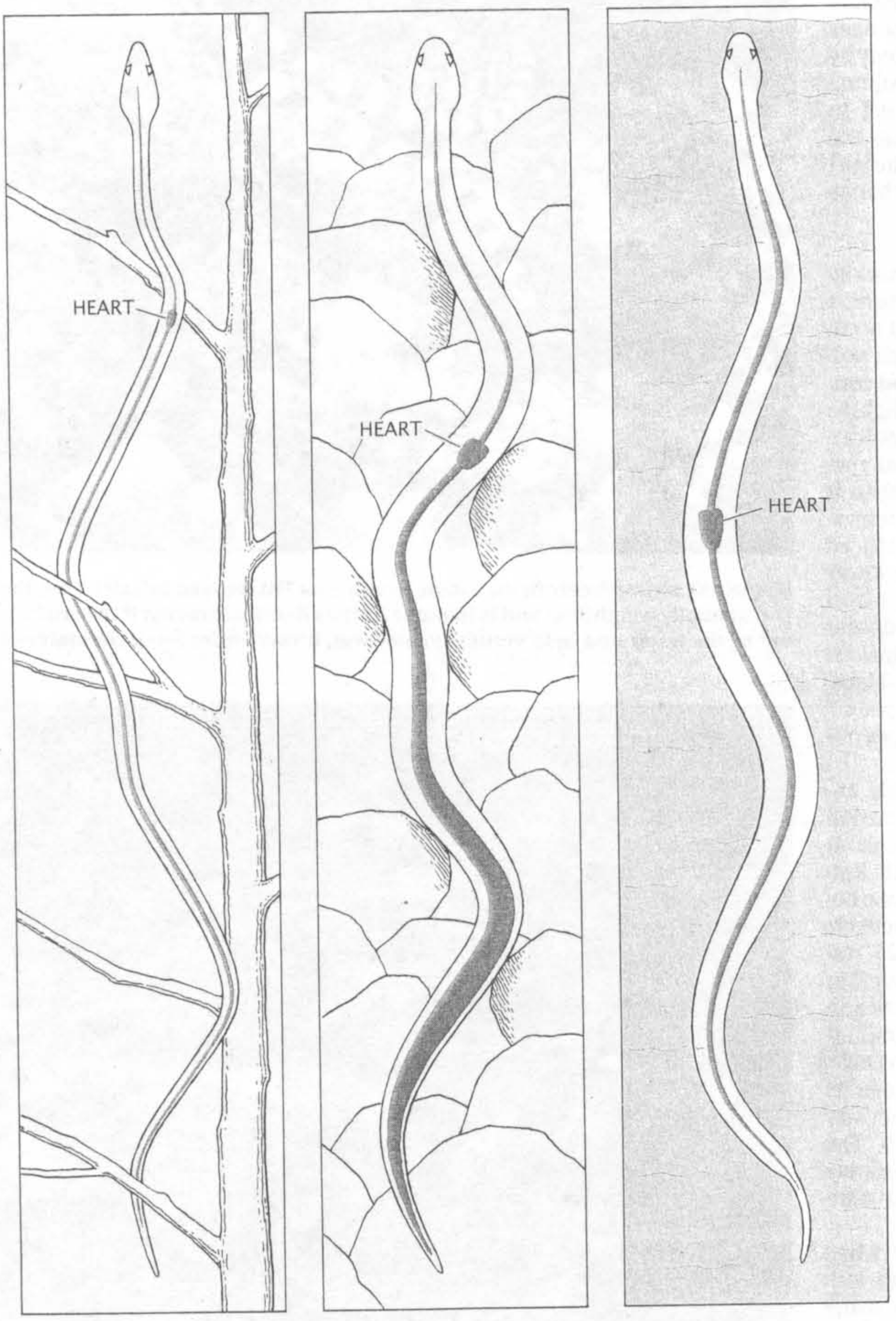
The results were interesting. As the angle of tilt increased, pressure at the snake's midpoint decreased, a sign that blood was pooling at the snake's lower end. The heart beat faster but could not compensate for the drop in pressure, which at the level of the brain fell to zero or even became negative. Presumably the anterior blood vessels had collapsed and could no longer accommodate adequate blood flow while in that orientation.

When the same experiment was re-



CORN SNAKE *Elaphe guttata* of North America has the long, narrow body typical of many arboreal and semiarboreal snakes. Without a skinny body and a circulatory system specifically adapted to cope with pressure changes due to gravity, a snake of this length could not maintain adequate blood circulation while in a vertical posture.

peated with terrestrial snakes, the results were quite different. I experimented with the tiger snake *Notechis scutatus*, considered by many taxonomists to be a member of the same family (the Elapidae) in which sea snakes are classified. Tiger snakes are endemic to Australia, where they inhabit a broad range of habitats including floodplains and rain forest. When these snakes were tilted head up, blood pressure actually increased at the body's midpoint. As a result cranial pressure decreased only slightly and there were no signs of circulatory failure. Clearly terrestrial snakes have evolved a variety of physiological mechanisms by which they are able to regulate blood pressure.



EFFECTS OF VERTICAL ORIENTATION on the circulatory system (*red*) of a generalized climbing snake, a nonclimbing terrestrial snake and a sea snake are compared. Because the heart of a climbing snake (*left*) is close to the head, the brain remains well supplied with blood; the pooling of blood in the tail is insignificant because of the animal's narrow body and tight skin. In the terrestrial snake (*middle*), which normally does not climb but is shown here on a vertical rock face, the heart is nearer the body's midpoint. Blood pooling is pronounced because the vessels are distensible and expand in response to increased pressure in the lower body. Thus the blood is not circulated as effectively as it is in the tree snake. In the sea snake (*right*) the heart is about at the body's midpoint; pooling does not occur because the tendency for blood pressure to distend the vessels is opposed by external water pressure.

Since these initial experiments were carried out we have found that the ability to regulate blood pressure, although it is present in all terrestrial snakes, varies in relation to the snake's habitat. Arboreal snakes have a greater ability to regulate pressure in an upright position than nonclimbing species, for example. These differences also correspond to the levels of blood pressure that are maintained by the various species.

Seymour and I measured resting blood-pressure values for a diverse number of species and discovered we could consistently relate a snake's blood pressure to its behavior and habitat. In the five or six arboreal species we tested, arterial pressure in a horizontal position ranged from 50 to 90 millimeters of mercury, whereas in the five or six aquatic species we tested, blood pressure was much lower, ranging from 15 to 39 millimeters of mercury. Semiaquatic species, such as sea snakes that lay their eggs on land, and such nonclimbing terrestrial species as the rattlesnake had intermediate levels of arterial pressure.

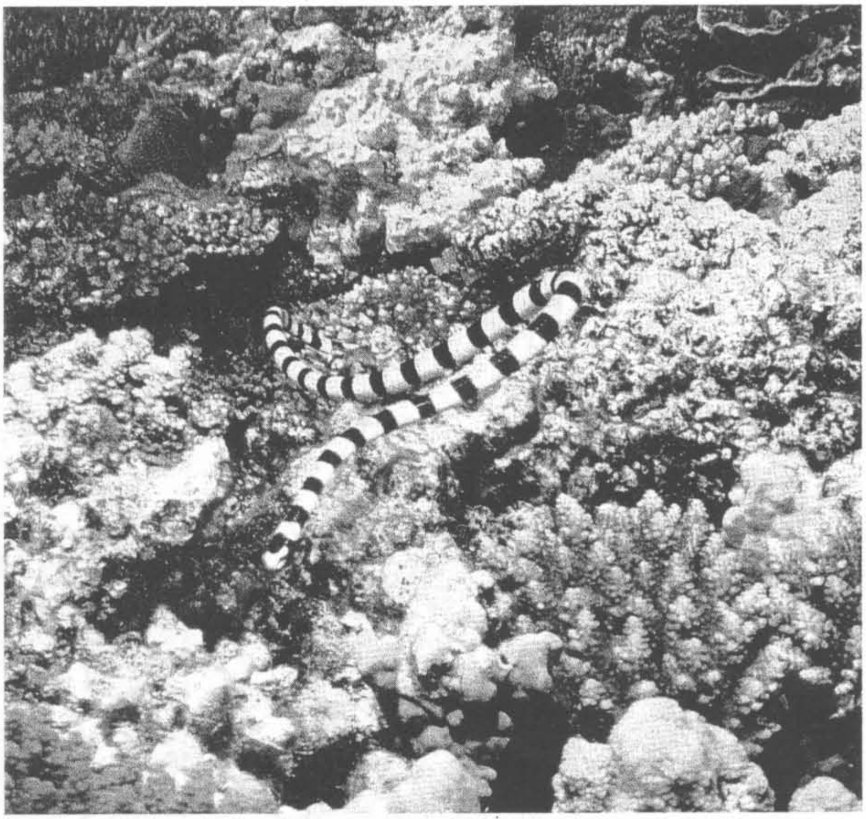
It is reasonable to speculate that the high blood pressures of arboreal snakes are largely a secondary consequence of better muscle tone in the vessels of these species. By constricting the blood vessels, vascular muscles increase the vessels' resistance to blood flow and thereby elevate the pressure. Whatever their cause, higher blood pressures minimize the possibility that gravity will impair blood flow to the brain when the snake is in a head-up position. For example, if the passive pressure drop brought on by the orientation shift is 39 millimeters of mercury at the head of a meter-long sea snake, when the snake is out of water, its cranial vessels may collapse, whereas those of an arboreal snake will still have a pressure of from 20 to 60 millimeters of mercury. (It should be noted that in this example only the passive change of gravitational pressure caused by tilting is subtracted from the normal, resting blood pressures described above. The example does not consider other factors affecting pressure, such as the pumping action of the heart.)

After establishing that a snake's blood pressure varies with its ecology, I wanted to test the susceptibility of different species to blood pooling, which I could do by measuring changes in the volume of a snake's tail during tilting. Working at the University of Kansas, I placed the tail of a snake in a small tube and sealed the tube so that it was airtight. I then placed the entire snake inside a larger plastic tube attached to a pivot apparatus similar to the one used at Monash. The small tube was connected to a plethysmograph, a device that records changes in volume as they are revealed by air-pressure changes. As the volume of a snake's tail increases (owing to blood pooling), air pressure in the tube increases and is read by the plethysmograph as a percentage change in volume.

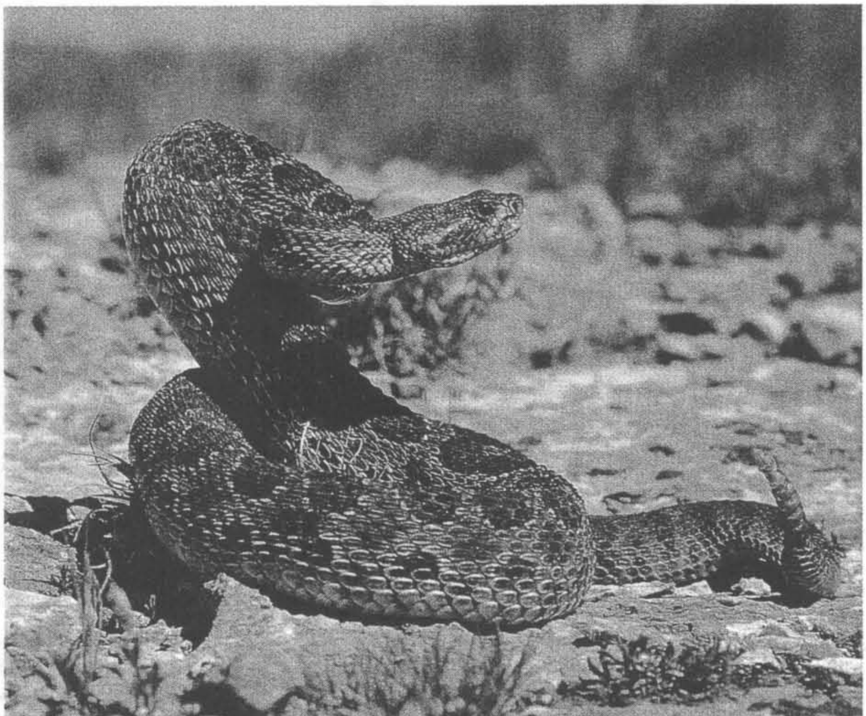
In snakes that have poor physiological control over blood pressure, a head-up position led to fluid accumulation and an increase in tail volume; in those with relatively good control, tail volume changed only slightly. Data from these experiments indicated that blood pooling in arboreal species is at least 30 percent less than it is in aquatic and nonclimbing terrestrial species. Sea snakes experienced extensive blood pooling in the lower body. The pooling explains why blood pressure drops at the body's midpoint during head-up tilting in these snakes. Pooling reduces the amount of blood returning to the heart, thereby reducing cardiac output and causing central blood pressure to fall.

I extended these results with another series of experiments carried out at the University of California at San Diego in collaboration with Kim P. Gallagher. We injected semiarboreal rat snakes with radioactively labeled microspheres—beads 25 microns (thousandths of a millimeter) in diameter—that lodge in capillaries in numbers proportional to the amount of blood flow those capillaries receive. Radioactivity in different tissues is then compared with the radioactivity of blood drawn from an artery. The comparisons enabled us to determine the volume of blood that was circulating to various organs.

We found, for example, that when a rat snake is oriented head up at a 45-degree angle, blood flow to many of the organs and muscles in the lower half of its body is reduced, whereas blood flow to critical anterior organs such as the lung, heart and brain is essentially unchanged. The selective reduction in blood flow results from vasoconstriction: the contraction of smooth-muscle fibers in the walls of the blood vessels. By selectively narrowing certain blood vessels (predom-



SEA SNAKE swims freely in the Pacific Ocean near Fiji. Buoyed by salt water, the snake is essentially weightless and is immune to the effects of gravity. If the snake is taken out of the water and held vertically, however, it may suffer from circulatory failure.



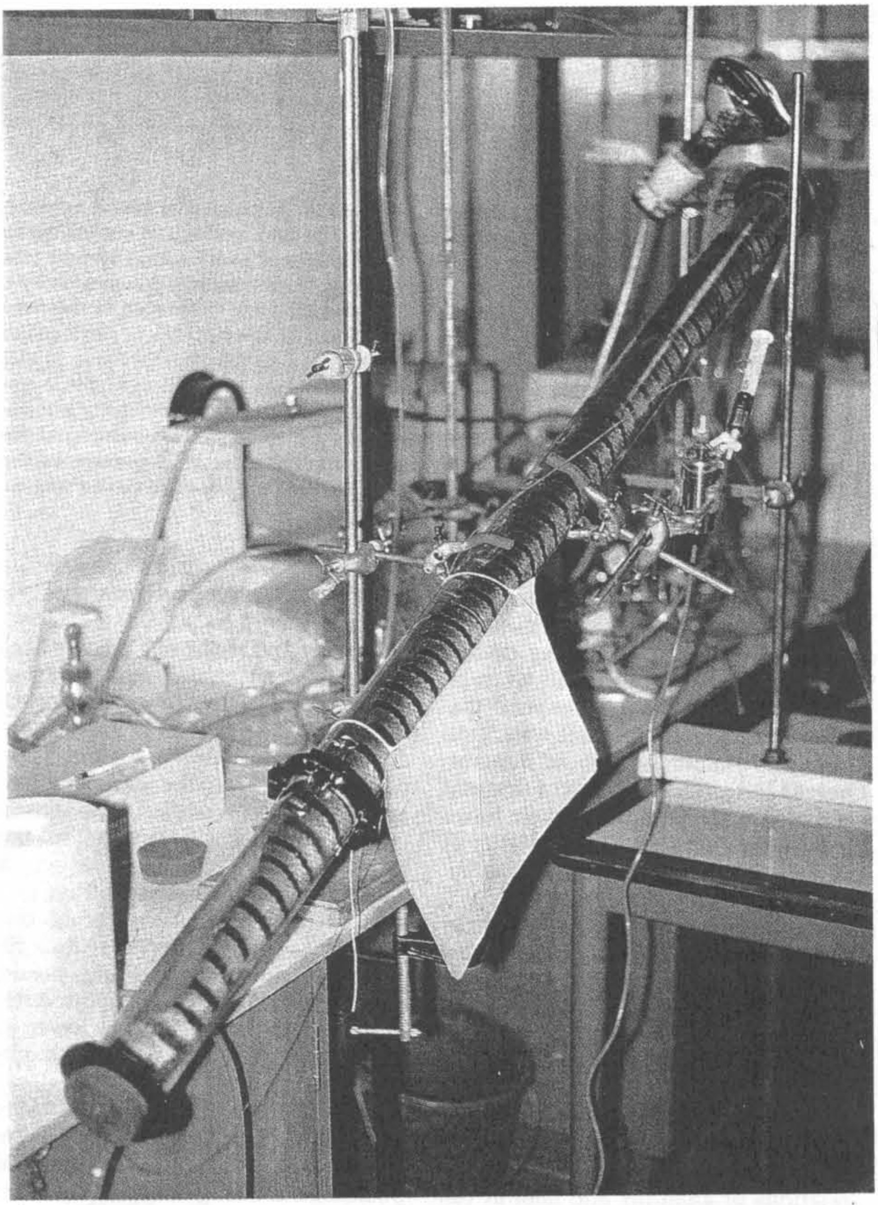
RATTLESNAKE *Crotalus viridis,* like many terrestrial snakes, occasionally adopts a more vertical position, say as it prepares to strike. Its circulatory system is able to adjust, at least temporarily, to the resulting changes in gravitational pressure.

inantly in the lower body in this case), the vasoconstriction increases pressure at the snake's midpoint and promotes blood flow to tissues where the vessels are less constricted. A similar phenomenon occurs in humans and other tall mammals when they suddenly stand up after being in a horizontal position.

I have focused on physiological changes that take place when snakes assume a head-up position. It must be remembered, of course, that some snakes also assume head-down positions, particularly when they descend vertically or hang from the branch of a tree. How is blood flow to the tail maintained and excessive cranial pressure avoided when a snake is oriented with its head down?

The cardiovascular adjustments are essentially reversed. The snake's heart rate slows and the smooth muscle surrounding the blood vessels in various tissues relaxes, partially offsetting the gravitational increase of pressure near the head. Because venous volume in the head is small compared with that at the posterior end of the body, and because the head is encased in a hard cranium, pooling is insignificant.

Snakes have adapted in other ways to their varied habitats. Certain anatomical features, such as the position of the heart, are also consistent with their various lifestyles. Snakes (having lost their limbs) lack a pectoral, or shoulder, girdle and therefore do not have the same limitations on heart position that most four-legged animals do. In mammals, for example, bones associated with the pectoral girdle restrict the heart to the chest cavity. But in snakes the ends of the ribs are free and the cylindrical body cavity is unobstructed by bony structures for its entire length. Consequently the heart in aquatic snakes can be close to the middle of the body, a position that minimizes the work involved in moving blood to both ends of the body; in nonclimbing terrestrial species the heart is generally about a fourth of the body's length from the head; in arboreal species the average distance from the head is as little as 15 percent of the overall body length. The reduction in the distance from the heart to the head helps to ensure that the brain is adequately perfused with blood regardless of the body's orientation.



TILT APPARATUS consists of a plastic tube in which a snake can be rotated to various positions. Here a sea snake is shown head up at a 45-degree angle. A pressure transducer connected to a catheter inserted in the snake's dorsal aorta measures blood pressure at the snake's midpoint; when the snake is inclined, the pressure decreases, an indication that blood is accumulating in the sea snake's lower half.

John Donald, a postdoctoral fellow in my laboratory, recently demonstrated that the blood vessels posterior to the heart in rat snakes and other arboreal species are richly invested with nerves, whereas the blood vessels anterior to the heart have considerably fewer nerves. Nerves of various types may be present in both sets of vessels, but their precise functions are not known. The pattern of association of nerves and blood vessels suggests, however, that the nerves play an important role in regulating the tone of the muscular walls of the vessels, particularly the posterior vessels most susceptible to blood pooling.

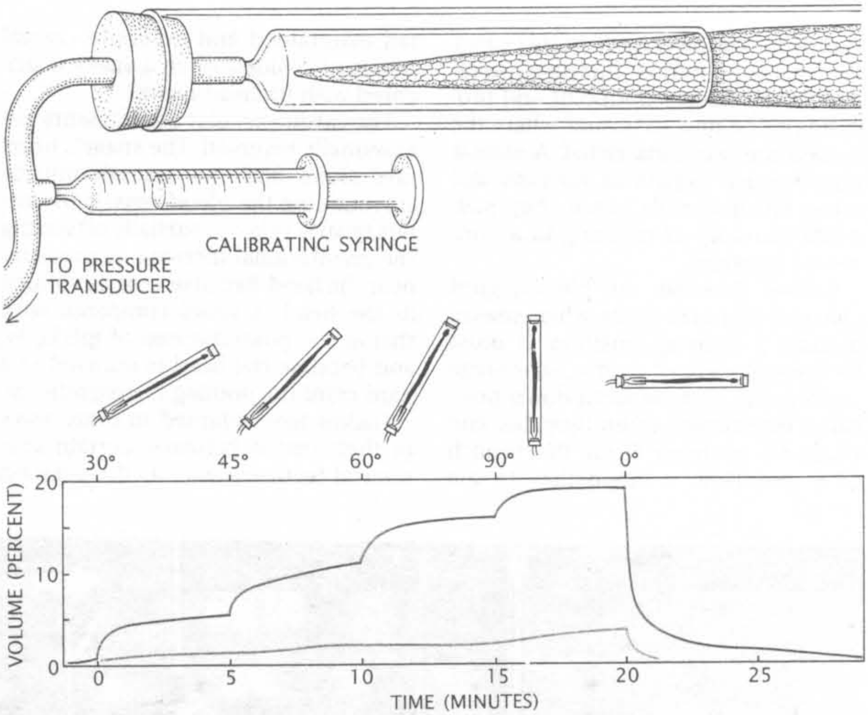
The nerves that control vasoconstriction in most animals are connected by reflex loops to special sensory receptors called baroreceptors. The exact location of baroreceptors in snakes has not yet been identified, but they are thought to be both in and near the heart, as they are in most of the vertebrates in which they have been identified. Baroreceptors innervate the walls of blood vessels, where they are stimulated when pressure within the vessels increases and the vascular wall begins to stretch. Nerve impulses from the baroreceptors modulate heart rate and cause the smooth muscle in the vessel walls to contract by way of a reflex arc involving the brain. The combined actions of the heart and smooth muscle serve to return arterial pressure to its regulated level, a type of control called negative feedback.

The probable location of the baroreceptors in or near the heart suggests yet another advantage of the anterior heart in arboreal snakes. The effects of gravitational pressure are greatest at the ends of a snake; therefore the closer baroreceptors are to the head, the more effective they will be in controlling gravitational disturbance and preserving brain function.

Two minor disadvantages to having a heart that is unusually close to the head must be mentioned. One is that when an arboreal snake is head down, it may have trouble maintaining blood flow to the tail (although blood flow to the tail is much less critical than blood flow to the brain). The other is that whenever a snake is head up, blood from the tail must travel almost the entire length of the venous column—against the force of gravity—to return blood to the heart. How are such feats accomplished?

Unlike the veins of mammals, those of snakes do not appear to have internal valves to prevent backward flow. Instead the uphill movement of blood is assisted in three ways: by baroreceptor-mediated contractions of vascular smooth muscle, by the 2 movement of skeletal muscle, which compresses the snake's veins, and by 3 tight skin. Arboreal snakes that have been climbing for a while often pause momentarily to wiggle their bodies, causing undulating waves of muscle contraction that advance from the lower torso toward the head. The advancing contractions compress the veins, forcing blood forward and increasing central venous pressure near the heart. The behavior improves venous blood flow to the heart so that it can maintain arterial blood pressure.

Similar behavior can be induced in the laboratory. When I experimentally removed from 30 to 50 percent of the blood volume from rat snakes, lowering their arterial pressure to an average of 36 percent below normal, the animals responded by wiggling. The wiggling response in turn increased their cranial pressure to roughly normal levels. Because wiggling behavior cannot be similarly induced in aquatic species, it appears to have evolved specifically to assist blood circulation in snakes that occupy arboreal habitats. Other body movements also improve circulation, but they do not usually elevate blood pressure as effectively as the stereotyped wiggling.



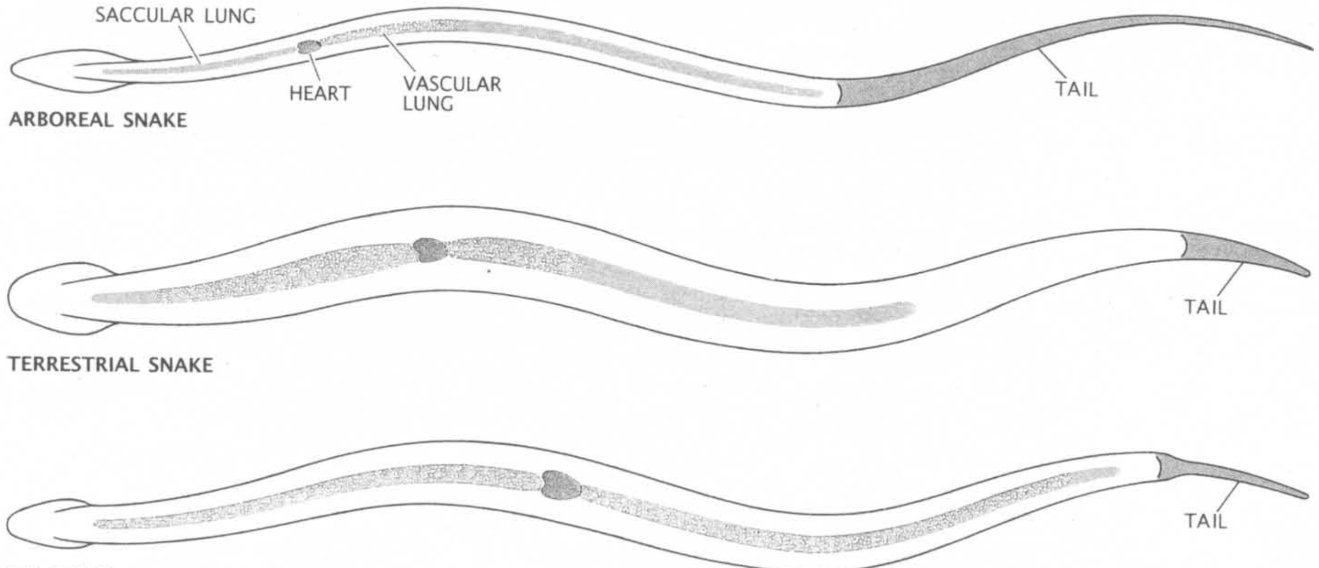
PLETHYSMOGRAPH measures the increase in body volume caused by blood pooling. The tail of a snake is inserted into a small tube, which is then sealed and connected to a transducer that records pressure changes. The plunger of a calibrating syringe lets the experimenter change the pressure by increasing or decreasing the volume by a measured amount. The pressure changes within the tube are calibrated in this way and the results are recorded on a graph as is shown at the bottom. A rattlesnake (*C. viridis*), which is not adapted to climbing, shows a significant increase in tail volume owing to blood pooling as its tilt angle increases (*red*). In contrast, a gopher snake (*Pituophis melanoleucus*), which climbs frequently, experiences a minimal increase in tail volume (*blue*). When the snakes are returned to a horizontal position, the tail volume decreases abruptly, indicating that at least 75 percent of the fluid had pooled in the blood vessels and had not filtered out into the tissue spaces.

Body type also appears to be an important factor in counteracting gravitational pressure. Snakes specialized for arboreal living tend to have slender bodies with firm muscle tone and tightly adhering skin. The small body circumference and tight tissues resist stretching caused by blood pooling. The *g* suit worn by fighter pilots during high-speed maneuvers functions the same way. Similarly, tall mammals such as humans, horses and giraffes have tight skin and connective tissue around their lower legs, which counteract the tendency of vessels to dilate, whereas short mammals such as rabbits do not.

Aquatic and nonclimbing terrestrial snakes, whose cardiovascular systems are affected minimally, if at all, by gravitational pressure, have more flaccid bodies with looser skin. The nonclimbing terrestrial snake *Python regius*, for example, has a ratio of body circumference to body length that is three times as great as its arboreal relative *Corallus enhydris*. Similar correlations of anatomy and habitat can be found among species in other families. In the Colubridae, which contains many of the commoner North American snakes such as the garter and king snakes, arboreal snakes may be as much as 10 times slenderer than their terrestrial relatives.

The size and shape of a snake's lung also reflect its habitat and behavior. Many tissues of the body are susceptible to edema as a result of gravitational pressure, but few are more likely than the lungs to be seriously impaired by fluid retention. The reason is that fluid, which collects in the lungs, increases the distance across which blood and air must diffuse and thereby reduces the transfer of respiratory gases. In order to reduce filtration of fluid into the lung tissue, blood pressure in all tetrapod vertebrates, including snakes, is lower in the lungs than it is in the body's other tissues.

The evolution of most snake lungs into a single long membranous chamber poses no problem in a horizontal position, but a long lung presents special problems for arboreal species. Gas exchange takes place through radial pockets (analogous to the saclike alveoli of mammals) in the spongy, mem-



LUNG ANATOMY varies according to a snake's habitat. The lung of arboreal snakes (*top*) is vascular (that is, rich in blood vessels) for a short region (*dark blue*) behind the animal's heart (*red*). At both ends the lung differentiates into a long saccular region (*light blue*), which lacks the blood vessels involved in gas exchange. In terrestrial snakes (*middle*) the lung has a somewhat longer vascular region near the heart. In sea snakes (*bottom*) the lung consists almost entirely of vascular tissue.

branous walls of the lung. The region where gas exchange takes place is richly endowed with blood vessels and is referred to as the vascular lung. The remainder of the lung, which extends for varying distances depending on the species, may be entirely devoid of blood vessels involved in gas exchange and is called the saccular lung.

In a snake oriented vertically, gravity increases pressure both in arteries and in veins, which form a continuous fluid column extending the length of the vascular lung. These pressures are transmitted to capillaries, placing the lung at risk of severe edema. Because the risk of edema increases in direct proportion to the length of lung vasculature, reducing the length of the pulmonary vessels would seem to be the best solution to gravitational pressure. Examination of lung anatomy in various snakes confirms that the length of the vascular part varies according to habitat.

In aquatic snakes the vascular tissue extends almost the entire length of the body cavity (although in some species a short saccular tip may be present). In arboreal species the vascular tissue is much shorter and may occupy less than 10 percent of body length, usually extending a short distance posterior to the heart. The result of the short vascular lung is that the pulmonary blood vessels of arboreal snakes are not subject to significant gravitational pressures even when the snakes are oriented vertically. The vascular lungs of nonclimbing terrestrial and semiaquatic species are generally intermediate in size.

To demonstrate the effects of gravity on the lung of an aquatic snake, I measured pulmonary blood pressure in the olive sea snake, *Aipysurus laevis*. Snakes were anesthetized and their pulmonary vessels catheterized. When the anesthesia had worn off, each snake was placed in a dry rotating plastic tube. As predicted, blood pressures increased in the lower sections of the lung as the tilt angle of the tube increased. Subsequent microscopic examination of lung tissue from these snakes revealed evidence of severe edema as well as ruptured capillaries in the lower lung. The greater the tilt angle—and therefore the length of the vertical blood column—the greater the damage. When snakes were tilted in salt water, no such effect was demonstrated. In its normal aquatic environment the snake avoids edema, even when it swims vertically, because water pressure collapses portions of the lung and reduces the length of the blood column exposed to lung gas. (Parts of the lung collapse because lung gas compresses as the gravitational pressure of the surrounding seawater increases.)

These physiological experiments show that snakes, because of their elongated form and diverse habits, are valuable models for studying cardiovascular design and regulation. The adoption of arboreal habits in particular has necessitated several important anatomical and physiological changes. The heart has moved to a more anterior location and the vascular lung has been shortened; blood pressure is more tightly regulated; blood vessels show specialized patterns of association with nerves; there is a reduction in the expansibility and diameter of the body wall, and specialized behaviors enhance the flow of venous blood toward the heart. Judged by their cardiovascular systems, snakes are highly specialized and adapted animals. Perhaps understanding their mechanisms of cardiovascular regulation will someday help physiologists to understand how gravity affects human beings, particularly in the context of space travel.

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