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Skin Breathing in Vertebrates

It can supplement or replace breathing through lungs or gills. Special adaptations of the skin and the circulatory system help to regulate the cutaneous exchange of oxygen and carbon dioxide

by Martin E. Feder and Warren W. Burggren

Perhaps because people breathe almost exclusively with their lungs, respiration is often thought of as taking place only in specialized organs: if not in the lungs, then in the gills of fishes and crustaceans, the tracheae of insects or the book lungs of spiders. Yet whenever a relatively thin membrane separates the respiratory medium (the air or water an animal breathes) from living cells or flowing blood, oxygen can enter the cells and the blood and carbon dioxide can leave them. The recent findings we shall discuss here suggest that the skin serves as an effective and highly regulated organ of gas exchange in many vertebrates.

Cutaneous gas exchange has long intrigued physiologists. Pioneering studies were made by August Krogh at the turn of the century in Denmark. Krogh obstructed the airflow to the lungs of frogs and observed that the skin could supply enough oxygen to the blood during the winter, when frogs are normally quiescent; during other seasons, however, lungs proved to be necessary. Krogh's research on blood circulation through capillaries earned him the 1920 Nobel prize in physiology or medicine.

Numerous experimental studies in the 1960's and 1970's examined the partitioning of gas exchange among an animal's respiratory organs: the skin, lungs and gills, if present. For example, by placing plastic masks over the faces of salamanders, Victor H. Hutchison and his students at the University of Rhode Island were able to determine what proportion of the animal's total oxygen is taken in through the skin and what proportion of the total carbon dioxide is eliminated through it. The results of these and many other such experiments provide a surprisingly long list of vertebrate skin breathers.

Probably the best-known of these skin breathers are the amphibians.

Among amphibians it is not unusual for at least 30 percent of the total oxygen uptake and as much as 100 percent of the carbon dioxide elimination to take place across the skin. Frog larvae, for example, exchange approximately 60 percent of their respiratory gases through their skin even though they also have both gills and lungs.

Amphibians that spend almost all their time on land rather than in water face potentially life-threatening difficulties because the same characteristics that make skin an effective membrane for gas exchange also facilitate water loss. Nevertheless, cutaneous gas exchange has been found in every species of terrestrial amphibian examined for this capacity. In fact, the skin is the sole respiratory organ in adult salamanders of the family Plethodontidae. Scores of these species inhabit terrestrial environments as diverse as the ground litter of New England woods and the canopy of tropical rain forests. Although some tropical plethodontids may attain a body mass of 150 grams and a body length of 24 centimeters, they accomplish all respiratory gas exchange between tissue and environment by way of their skin.
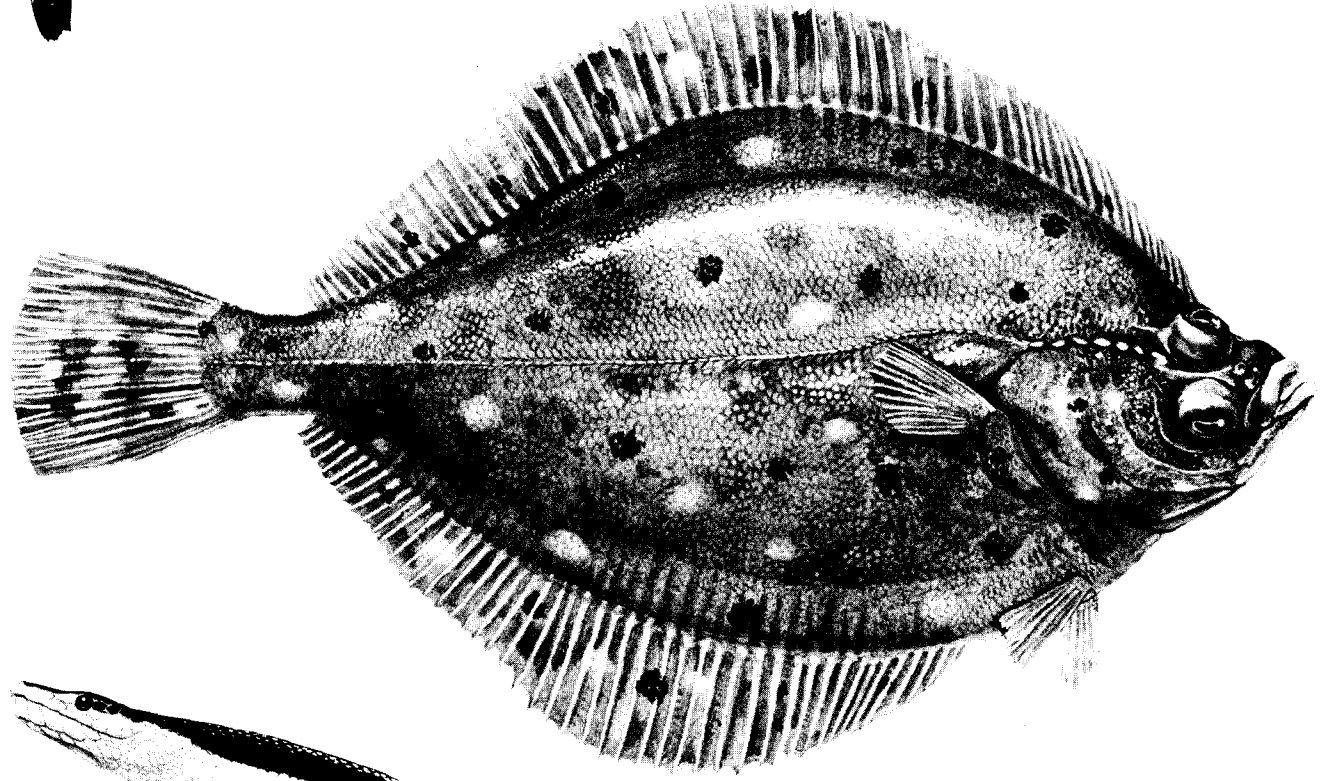
Skin breathing has been looked for in other vertebrates, from fishes to mammals. It has been demonstrated experimentally, for example, that amphibious (air breathing) fishes rely on their skin for as much as half of their gas exchange, particularly if they venture onto land: gills typically collapse
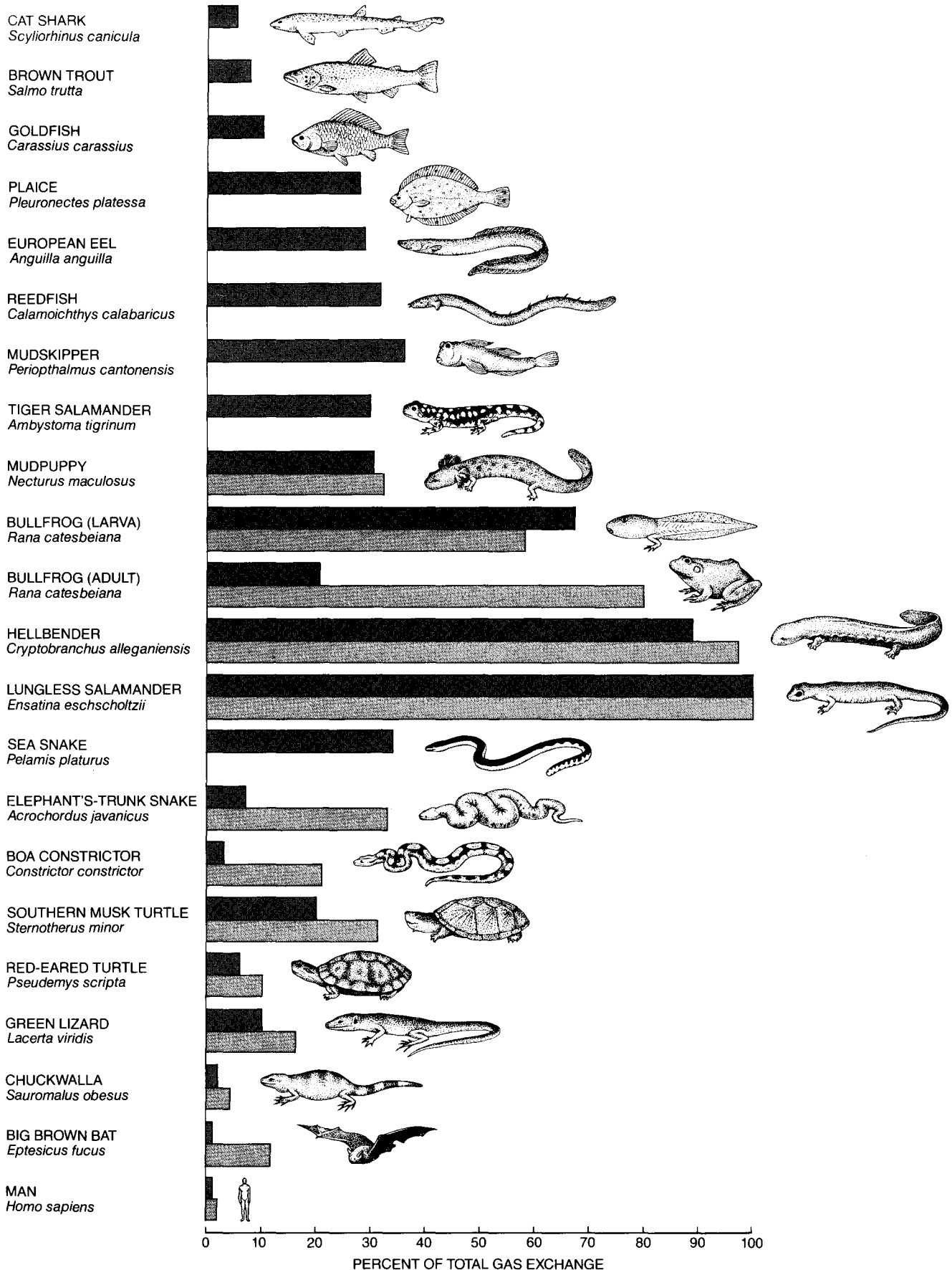
in the air and become useless. The adequacy of the skin as an air-breathing organ seems to have escaped the attention of many biologists who assume that lungs were a prerequisite for the evolution of terrestrial animals.

Commoner types of fishes also rely on cutaneous gas exchange. Sharks, trout, cod and goldfish—to name a few—acquire between 5 and 30 percent of their total oxygen by way of the skin. Apparently neither the structure of the integument nor the shape of the body determines the extent to which a particular fish breathes through its skin. Both the flat, scaleless plaice and the elongated, heavily scaled reedfish derive about a third of their required oxygen cutaneously.

Reptiles have been shown to take advantage of cutaneous gas exchange as well. In spite of their thick shells, some freshwater turtles rely heavily or even totally on cutaneous gas exchange, particularly while passing the winter in ice-covered ponds. Snakes inhabiting both fresh and salt water typically exploit their skin as a respiratory organ. These reptiles often dive for long periods and supplement oxygen stores in the lungs and blood with oxygen acquired by way of the skin. Roger S. Seymour of the University of Adelaide in Australia has even suggested that some sea snakes use their skin to eliminate nitrogen during prolonged deep dives, thereby preventing decompression sickness (the formation of nitrogen bubbles in blood) as they surface. Many reptiles that live in arid environ-

THREE SKIN-BREATHING VERTEBRATES are depicted on the opposite page: a lungless salamander, a plaice and a sea snake. The salamander *Ensatina eschscholtzii* lives in the forests of California and Oregon; it is about five centimeters long when fully developed. The skin is the sole respiratory organ in adults of this species. The plaice *Pleuronectes platessa*, a commercially valuable flatfish of the North Atlantic, takes in 27 percent of its oxygen through the skin. The fish can grow to a weight of five kilograms and a length of 90 centimeters. The sea snake *Pelamis platurus* absorbs more than a third of its oxygen and excretes more than three-fourths of its metabolic carbon dioxide cutaneously. The snake reaches a length of about a meter; it ranges the tropical Pacific Ocean, between America and Africa.

CAT SHARK
Scyliorhinus canicula

BROWN TROUT
Salmo trutta

GOLDFISH
Carassius carassius

PLAICE
Pleuronectes platessa

EUROPEAN EEL
Anguilla anguilla

REEDFISH
Calamoichthys calabaricus

MUDSKIPPER
Periopthalmus cantonensis

TIGER SALAMANDER
Ambystoma tigrinum

MUDPUPPY
Necturus maculosus

BULLFROG (LARVA)
Rana catesbeiana

BULLFROG (ADULT)
Rana catesbeiana

HELLBENDER
Cryptobranchus alleganiensis

LUNGLESS SALAMANDER
Ensatina eschscholtzii

SEA SNAKE
Pelamis platurus

ELEPHANT'S-TRUNK SNAKE
Acrochordus javanicus

BOA CONSTRICTOR
Constrictor constrictor

SOUTHERN MUSK TURTLE
Sternotherus minor

RED-EARED TURTLE
Pseudemys scripta

GREEN LIZARD
Lacerta viridis

CHUCKWALLA
Sauromalus obesus

BIG BROWN BAT
Eptesicus fucus

MAN
Homo sapiens

0 10 20 30 40 50 60 70 80 90 100

PERCENT OF TOTAL GAS EXCHANGE

CUTANEOUS GAS EXCHANGE is widespread among verte-brates. Although it is most prominent in amphibians, this mode of respiration is also important in many other animal groups. Cutane-ous excretion of carbon dioxide (*gray bars*) typically accounts for a larger fraction of total gas exchange than cutaneous oxygen uptake does (*colored bars*) in those cases where both gases were measured.

128

ments, where dehydration is a constant danger, have countered this problem by evolving thick scales, a shell or leathery skin. A few species, such as the chuckwalla lizard (*Sauromalus obesus*) of the southwestern deserts of the U.S., do exhibit some cutaneous gas exchange regardless of their thick, protective skin.

Although cutaneous respiration is often significant and even crucial in lower vertebrates, the skin is seldom an important avenue for gas exchange among higher vertebrates such as birds and mammals. Even if the furred or feathered integument of such creatures were as permeable as the skin of frogs, the higher vertebrates would need lungs to sustain their much greater metabolic rate. Lungs offer a larger and thinner surface for gas exchange than the skin can provide. Yet there are exceptions to this generalization. Clyde F. Herreid II and his colleagues at Duke University found that in bats as much as 12 percent of total carbon dioxide elimination may take place across the thin, well-vascularized wing membranes.

Young mammals and birds are often born or hatched with thin skin, richly supplied with blood and lacking fur or feathers. Cutaneous respiration may therefore be more important in the developing forms of such higher vertebrates than it is in the adults. There is probably significant cutaneous gas exchange in the mammalian embryo and fetus; gas exchange through the shell and the shell membrane is the major avenue of respiration available for the eggs of birds and indeed of all egg-laying vertebrates [see "How Bird Eggs Breathe," by Herman Rahn, Amos Ar and Charles V. Paganelli; SCIENTIFIC AMERICAN, February, 1979].

What about cutaneous gas exchange in people? Human skin certainly does not serve as a respiratory organ for the general benefit of the body tissues. Yet the skin, like any living tissue, consumes oxygen and generates carbon dioxide. All the respiratory gases consumed or produced by skin cells, as well as an undetermined additional quantity of carbon dioxide from capillary blood flowing through the skin, are exchanged directly between skin and air. In fact, the permeability of the skin is exploited medically when drugs are administered by applying patches to the skin.

In spite of their number, studies of cutaneous gas exchange generally have discounted the prevalence of skin breathing among vertebrates by stressing its limitations. For example, investigators have tended to contrast the skin to the elegantly structured lungs
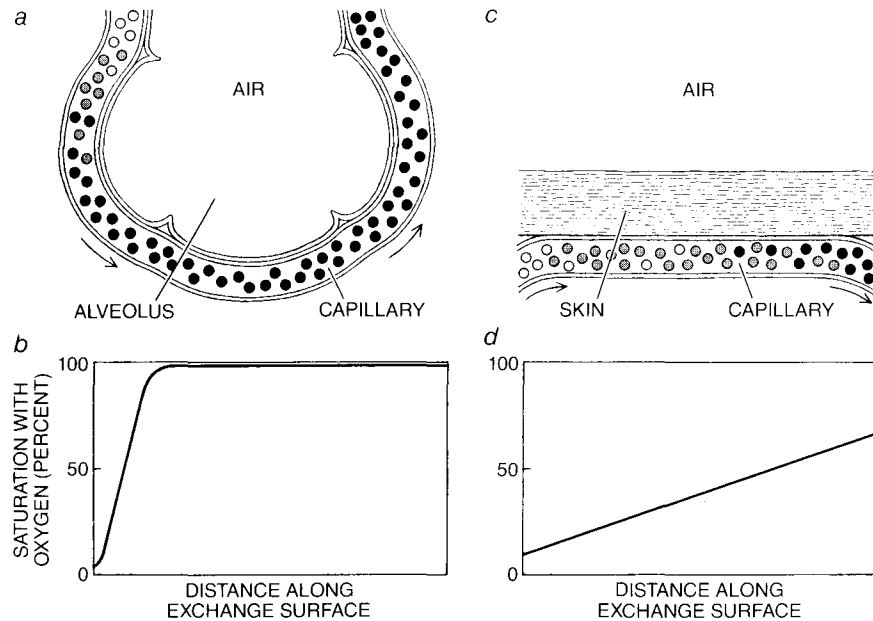
CUTANEOUS OXYGEN UPTAKE is limited by the thickness of the skin's diffusion barrier: the distance between the respiratory medium (air or water) and the blood. Oxygen can diffuse quickly through the thin alveolar membrane of the mammalian lung (*a*); blood-cell hemoglobin is rapidly oxygenated (*dark red*) and blood in adjacent capillaries is completely saturated with oxygen (*b*). Because diffusion of oxygen through the thicker skin (*c*) is much slower, the blood in capillaries under the skin is never fully saturated with oxygen (*d*).

and gills. They have emphasized the circumstances under which cutaneous gas exchange would be precluded and pointed to the thick skin or scales and the limited cutaneous surface area of most vertebrates as characteristics likely to hinder cutaneous gas exchange. The thrust of most of these contentions rests on the physical principles governing gas exchange.

Oxygen and carbon dioxide pass through the membrane of a gas exchanger by means of a physical process called diffusion. Diffusion is defined as the equilibrating flow of matter, through the random movement of molecules in a fluid or gas, from a region of high concentration to one of low concentration. Because the gas-exchange membranes of lungs and gills are typically very thin (less than a thousandth of a millimeter in the human lung), equilibration with the respiratory medium is achieved extremely rapidly. A more important limitation to gas exchange in lungs and gills is the speed with which the blood carries oxygen away from the exchange surface or delivers carbon dioxide to it. Rapid diffusion makes it possible for animals with lungs or gills to regulate gas exchange by simply increasing or decreasing blood flow through the respiratory organ.

In contrast, increasing the flow of blood to the skin has been thought to have little effect on total gas exchange in vertebrates. Johannes Piiper, Peter

Scheid, Randall Gatz and Eugene Crawford of the Max Planck Institute for Experimental Medicine in Göttingen have shown that cutaneous gas exchange is diffusion-limited. That is, the diffusion of respiratory gases through the relatively thick skin of vertebrates is so slow that it is not able to transfer oxygen and carbon dioxide as rapidly as the gases are transported from or to the skin by the blood and the respiratory medium.

Other studies demonstrated another problem encountered by cutaneous gas exchange. Equilibration between the gas concentrations in the blood flowing through capillaries inside the skin and in the respiratory medium outside the skin is governed by Fick's law of diffusion: the rate of gas exchange is proportional to the difference between the partial pressure of the gas in the respiratory medium and its partial pressure in the blood. (Partial pressure, the pressure of a gas in a solution or a gas mixture, reflects both the concentration of the gas and its solubility.) A gas will therefore diffuse through the skin only if its local partial pressure on one side of the skin is greater than its partial pressure on the other side; the greater the difference is, the faster it will diffuse.

As studies by Donald C. Jackson and his colleagues at Brown University have shown, this relation may have fateful consequences for skin-breathing vertebrates. If the respiratory me-

...in surrounding a skin-breathing animal has a greater partial pressure of carbon dioxide than the animal's blood, the animal will actually gain carbon dioxide from the environment instead of losing it. Similarly, if high temperature or activity increases carbon dioxide production, many skin-breathing amphibians cannot immediately excrete the excess; they must first wait for the internal carbon dioxide partial pressure to rise above the external partial pressure. Fick's law governs the diffusion of oxygen as well. Our own studies have shown that amphibians may actually lose oxygen when their blood contains more oxygen than the water surrounding them.

Human beings can excrete excess carbon dioxide by simultaneously increasing blood flow to the lungs and raising the respiration rate while maintaining a constant partial pressure of carbon dioxide in the blood. The internal gas partial pressures of skin-breathing animals, on the other hand, seem to be poorly controlled and subject to the ever changing balance between external gas concentrations and internal demands for gas exchange.

The fact remains that in spite of the daunting limitations imposed by the diffusion process, vertebrates do rely on cutaneous gas exchange to a significant degree. We recognized that this paradox could be resolved by considering the different mechanisms vertebrates have at their disposal to regulate cutaneous gas exchange. Some of these mechanisms seem obvious, although they had seldom been recognized as potentially important in this respect. Other suggested regulatory processes are subtler. The various regulatory mechanisms can be divided into two categories: mechanisms that are permanent morphological adaptations or responses to long-term changes (days, weeks or months) in the environment or in the animal's physiology, and mechanisms that are called on from minute to minute as an organism's immediate respiratory

needs or the environment varies. Together these mechanisms support a remarkably effective capability for controlling cutaneous gas exchange.

One obvious way to regulate skin breathing depends on the fact that cutaneous gas exchange is limited in part by the total skin surface area. Consequently a change in surface area can increase or decrease the amount of gas exchanged through the skin. In spite of a rigid internal skeleton and a relatively fixed form, many vertebrates exhibit seasonal changes in surface area that augment cutaneous gas exchange precisely in this way.

For example, some male amphibians engage in elaborate and strenuous courtship rituals that may include repeated body movements lasting for hours. Associated with this behavior is a greatly increased requirement for oxygen uptake and carbon dioxide elimination. Apparently in response to the increased respiratory burden, parts of the skin in these amphibians gradually become enlarged or develop outgrowths during the courtship season. Such surfaces act as accessory gas-exchange organs.

Changes in the skin structure to this end appear in the male hairy frog, *Astylosternus robustus*. Tiny dermal papillae that superficially resemble hair appear on its hindquarters. The enlarged tail fin and the dorsal crest developed by males of many species of newts during the courtship season also could contribute to the total amount of gas diffusing through the skin. The male skin enlargements typically regress when the breeding season ends. Moreover, such structures do not occur at all in the relatively quiescent females of these species.

In addition to these seasonal changes in cutaneous surface area amphibians have evolved a number of permanent morphological characteristics that promote skin breathing. Many amphibians have what seem to be disproportionately elongated bodies or tails. It has been argued that such

shapes arose to equip these organisms with enough skin for adequate cutaneous gas exchange.

Other species of amphibians permanently bear numerous skin folds that also increase the surface area for cutaneous gas exchange. The most spectacular of these is the Lake Titicaca frog, *Telmatobius culeus*, which inhabits the lake for which it is named in the Andes between Peru and Bolivia. As Victor Hutchison and his colleagues at the University of Oklahoma discovered, the Lake Titicaca frog is so well adapted for skin respiration that it does not need to ventilate its lungs at all. One major explanation for this ability is the pendulous folds of skin that protrude from its hind limbs and trunk. Other species in the genus *Telmatobius* and in other genera of frogs have similar skin folds. In some types of amphibians such as the hellbender, *Cryptobranchus alleganiensis*, a large aquatic salamander, the skin folds are minute but numerous and are richly invested with capillaries.

A second adaptation enhancing the capability for cutaneous gas exchange is a reduction in the thickness of the skin to lessen its resistance to the diffusion of respiratory gases. In addition to being devoid of such physical barriers as hair, feathers or scales, amphibian skin is typically only between 10 and 50 micrometers (millionths of a meter) thick. Actually the significant morphological factor governing diffusion in this connection is not the total thickness of the skin but rather the thickness of the "diffusion barrier," the distance between the respiratory medium outside the skin and the blood flowing through the cutaneous capillaries. Hence any morphological change that reduces the distance between the bloodstream and the respiratory medium helps to increase gas exchange.

We demonstrated through a simple experiment that such changes are indeed possible within a fraction of an amphibian's lifetime. Frog larvae were reared in two enclosures, one containing well-aerated water and the other
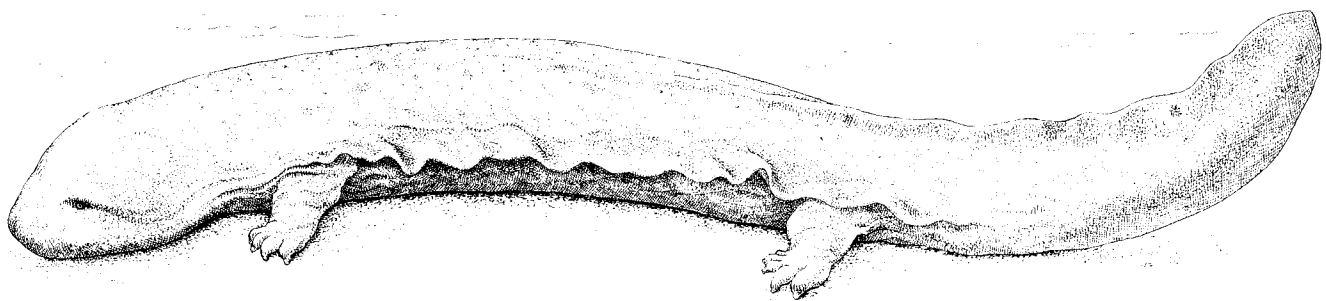
HELLBENDER (*Cryptobranchus allegiensis*) is a large aquatic salamander found in swift-flowing streams of the eastern and central U.S. It reaches a length of about 70 centimeters. Although the hellbender has lungs, it breathes primarily through its very wrinkly skin.
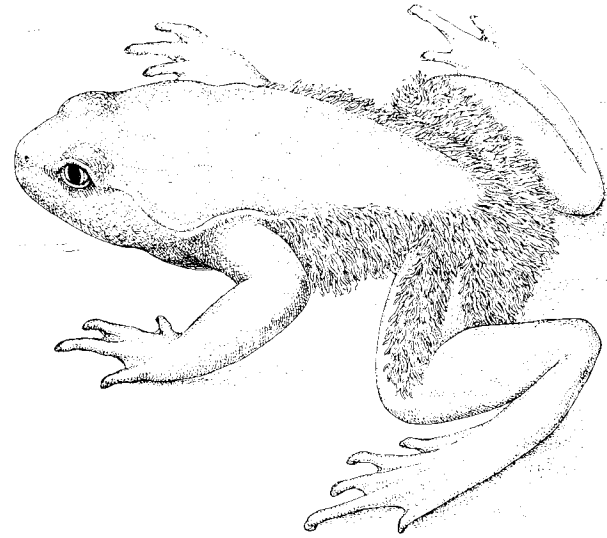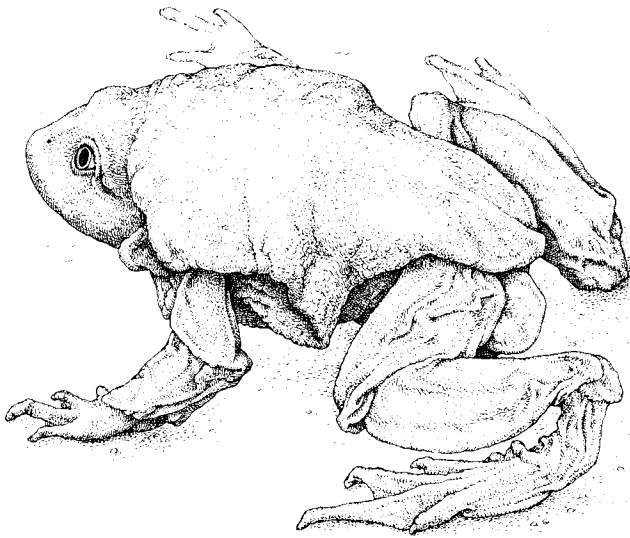
INCREASED SKIN SURFACE AREA is a prominent morpho-
logical adaptation in two skin-breathing frog species. Pendulous
folds of skin have evolved on the Lake Titicaca frog *Telmatobius
culeus* (*left*). These loose folds provide so much skin area for gas
exchange that the Titicaca frog does not need to breathe through
its lungs at all. The male hairy frog, *Astylosternus robustus* (*right*),
sprouts dermal papillae on its hindquarters as an accessory gas-ex-
change organ to meet the respiratory demands of the mating season.

containing water with approximately
half the oxygen concentration of the
aerated water. After four weeks the
diffusion barrier in larvae reared in the
well-aerated water was 40 microme-
ters, a typical value. In contrast, the
diffusion barrier averaged only 20 mi-
crometers in animals reared in the oxy-
gen-poor water. Furthermore, the cu-
taneous capillary network of the ox-
ygen-deprived larvae was finer and
denser. It appears these larvae under-
went an acclimatory change that aug-
mented their capacity for cutaneous
gas exchange.

Even vertebrates with a relatively
thick skin can carry on significant cuta-
neous gas exchange as long as evolu-
tion has led to advantageous place-
ment of the cutaneous capillaries. In
the scaly skin of some lizards, for ex-
ample, the cutaneous capillaries eith-
er underlie the skin between the scales
or run under the scale's hinges, where
the scale is thinnest. In some snakes
the cutaneous capillaries penetrate the
scale itself. The dermal scales of fishes
are generally covered by a layer of liv-
ing tissue, an arrangement that places
cutaneous capillaries above the diffu-
sion-resistant scale and very close to
the respiratory medium.

Adaptations such as skin folds, der-
mal papillae and generally thin
skin, as well as the specialized circula-
tion that may serve these structures,
obviously develop slowly over days or
weeks, if not time measured on an evo-
lutionary scale. How can a vertebrate
regulate cutaneous gas exchange in-
stantaneously if its oxygen require-

ment suddenly increases (as it does
during activity), or if it suddenly en-
counters a region of water that has a
high carbon dioxide concentration?

In most of the vertebrates we have
examined not all skin capillaries are
constantly perfused with blood. Skin
that is distant from underlying capil-
laries or that is underlain by nonper-
fused capillaries does not contribute to
overall gas exchange; the functional
surface area of the skin at any given
time consists only of those skin re-
gions that overlie perfused cutaneous
capillaries.

The initiation of blood flow through
capillaries (what is called capillary
recruitment) can occur in seconds.
(Blushing is a classic, if nonrespirato-
ry, example of this in humans.) Capil-
lary recruitment in the skin of amphib-
ians was documented many years ago
by Piotr Poczopko and his colleagues
in Poland. They found that in frogs
breathing gas with an elevated carbon
dioxide concentration, and in frogs
prevented from using their lungs, the
number of perfused skin capillaries in-
creased by nearly a third.

Further experimental confirmation
that capillary recruitment is linked to
cutaneous gas exchange has emerged
recently from our own studies of bull-
frogs. Working at the University of
Massachusetts at Amherst, we ob-
served that when frogs submerged in
water were exposed to air, the number
of perfused skin capillaries rapidly fell
by 60 percent; simultaneously carbon
dioxide elimination by way of the skin
fell by 44 percent. When the frogs were
returned to water, capillaries were re-

cruited and cutaneous carbon dioxide
elimination resumed immediately.

More recent experiments conducted
by Gary Malvin and Michael P. Hlas-
tala of the University of Washington
School of Medicine have also demon-
strated that frogs control capillary
blood flow in their skin. These investi-
gations revealed that frogs can reduce
gas loss through the skin by from 15 to
30 percent when they are exposed to
an atmosphere devoid of oxygen, pre-
sumably by decreasing the amount of
blood-perfused skin.

Just as important as morphological
adaptations and capillary blood
flow are physiological processes or
behavioral responses that affect the
partial pressures of the respiratory
gases in the blood within the skin or in
the respiratory medium outside the
skin. The most important of these are
processes that regulate the flow of
either the respiratory medium or the
blood along the diffusion barrier.

Ventilation, the flow of the respira-
tory medium into or past a gas-ex-
change organ, is clearly critical in
lungs and internal gills. If ventilation
stops, gas exchange in these internal
organs declines precipitously because
oxygen is quickly depleted (its partial
pressure falls) and carbon dioxide is
rapidly accumulated (its partial pres-
sure increases) in the respiratory medi-
um enclosed within the body. Ventila-
tion in the context of cutaneous gas
exchange, on the other hand, has of-
ten been considered unnecessary; after
all, the skin of a vertebrate in air or
in a large body of water is in constant
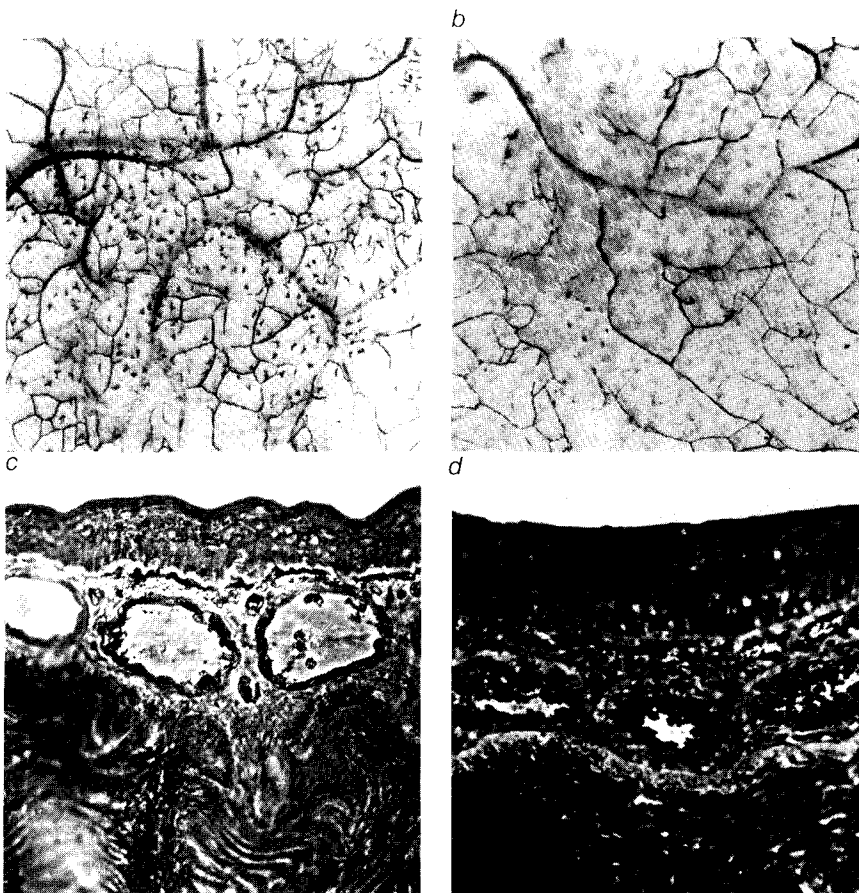
MICROSCOPIC MORPHOLOGICAL RESPONSES that facilitate skin breathing under adverse conditions are shown in two pairs of photomicrographs. The capillary network in the skin of frog larvae becomes finer and denser when the larvae live in oxygen-poor water (*a*) than it does when they live in oxygen-rich water (*b*). The distance between capillaries and the surface of the skin in frog larvae can also vary depending on the oxygen content of the water: the capillaries of larvae reared in oxygen-poor water are closer to the skin surface (*c*) than the capillaries of larvae raised in water having a high oxygen concentration (*d*).

contact with an "infinite pool" of respiratory medium containing abundant stores of oxygen and only small amounts of carbon dioxide.

Yet the Lake Titicaca frog waves its large skin folds and the hellbender rocks its body. Moreover, both animals increase the frequency of these movements when the concentration of oxygen in the water decreases. Are these behaviors unrelated to respiration or might they serve to augment cutaneous gas exchange by ventilating the skin?

As we examined these peculiar behaviors we reflected on the physical considerations that influence the exchange of heat. Heat exchange is often severely limited in still air or water and is facilitated when the medium (or the heat emitter) is moving. If, for example, one sinks into a tub of hot water and remains still, one feels pain as heat enters the skin. As the heat leaves the layer of water surrounding the skin, the fluid forms a relatively cool boundary layer. Any rapid movement of the skin or the water will dissipate the

boundary layer, allowing hot water again to come in contact with the skin and again to cause pain until the boundary layer is reestablished. Even in an infinite pool (or finite tub) of hot water, stagnation of the medium next to the skin can limit heat transfer.

We envision a similar relation for the exchange of respiratory gases, particularly in water. If both the animal and the water are stationary, oxygen diffusing out of water adjacent to the skin and into the bloodstream would create a diffusion boundary layer of low oxygen partial pressure. Because the rate of diffusion is proportional to the difference in oxygen partial pressures on each side of the diffusion barrier, cutaneous gas exchange would decrease. Movement of either the animal, the water or both could dissipate the boundary layer and thereby increase the diffusion of oxygen across the skin. We calculated that the diffusion boundary layer should offer a significant resistance to gas exchange at water flow velocities of four centimeters per second or less. Much lower

velocities would suffice to dissipate the diffusion boundary layer in air.

To test our hypothesis we immobilized bullfrogs in wire-mesh envelopes to ensure that spontaneous body movements would not dissipate the boundary layer and that their cutaneous surface area would be constant and maximal. We then placed each animal, sandwiched in its envelope, in a leakproof chamber. The chamber was filled with water so that only the frog's nostrils were above the surface. We could measure the decline in oxygen concentration in the air and the water compartments and so calculate the respective pulmonary and cutaneous oxygen consumption. By actuating a stirrer at the bottom of the chamber we could ventilate the skin with the surrounding water.

The results support our hypothesis. When we stopped ventilating the skin, the cutaneous oxygen consumption (determined by measuring the oxygen concentration in the water) declined by about a third. This result is clearly in conflict with the notion that ventilation is unimportant in cutaneous gas exchange.

As we have stressed, the extent of cutaneous gas exchange is determined by many variables other than ventilation, including the skin's functional surface area and the oxygen partial pressure on the inside of the diffusion barrier. Might the decrease in cutaneous oxygen consumption associated with the stopping of ventilation in fact be due to one of these other factors?

Our previous experiments had impressed on us the importance of functional surface area and capillary recruitment. We therefore repeated the ventilation experiments with frogs in which we could observe the relative numbers of perfused and nonperfused capillaries. The amount of oxygen taken in through the skin could have been lessened by a reduction in the number of perfused capillaries in the frog's skin. We found the opposite to be the case: whenever stirring was stopped, the frogs recruited additional skin capillaries. Because capillary recruitment should increase cutaneous gas exchange, the decline in cutaneous oxygen consumption, observed whenever ventilation stopped, cannot be due to changes in functional surface area.

In a third experiment we measured the partial pressure of oxygen in blood carried by arteries leading to the skin. If the partial pressure of oxygen increased every time stirring stopped, this could explain the observed drop in the rate of oxygen diffusing from the water into the blood. Stirring had no

on the blood's oxygen partial pressure, however. The results suggest that the formation of a diffusion boundary layer was indeed responsible for the decrease in cutaneous oxygen uptake, and that skin ventilation could serve to regulate gas exchange by dissipating the layer.

The partial pressures of oxygen and carbon dioxide in blood within cutaneous capillaries vary according to whether or not the blood is oxygenated. This provides another possible regulatory device. By controlling whether the blood flowing to the skin is primarily oxygenated or deoxygenated, an organism could presumably regulate the amount of oxygen and carbon dioxide diffusing through the skin.

Cutaneous gas exchange would be most effective if only deoxygenated blood flowed to the skin, in the same way that only deoxygenated blood flows to the lungs in mammals. The partial pressure differentials across the skin of both oxygen and carbon dioxide would be largest in this circumstance. The skin of most vertebrates, however, is no different from any other living tissue: it receives blood only from the major systemic arteries, which typically deliver oxygenated blood. Because the difference between the oxygen partial pressure of oxygenated blood and that of the respiratory medium is often rather small, oxygen uptake from the environment is normally limited by the very blood the skin cells need to live. Even under this seemingly major constraint the skin may nonetheless be important in carbon dioxide elimination because carbon dioxide levels in arterial blood may still be considerably greater than they are in the environment. This explains in part why carbon dioxide elimination typically exceeds oxygen consumption in cutaneous gas exchange among vertebrates.

Some vertebrates are indeed able to direct a fraction of their deoxygenated blood into the systemic arteries and thereby augment cutaneous gas exchange. Amphibians and reptiles, for example, have an incompletely divided heart that allows deoxygenated blood to flow to the skin without first traversing the lungs. Comparative anatomists have traditionally regarded this arrangement as a primitive and inefficient one. Kjell Johansen of the University of Aarhus in Denmark, Fred White of the Scripps Institution of Oceanography and others have suggested that the opposite is true. They argue that the heart structure of amphibians and reptiles is actually an important adaptation that allows these vertebrates to distribute blood where
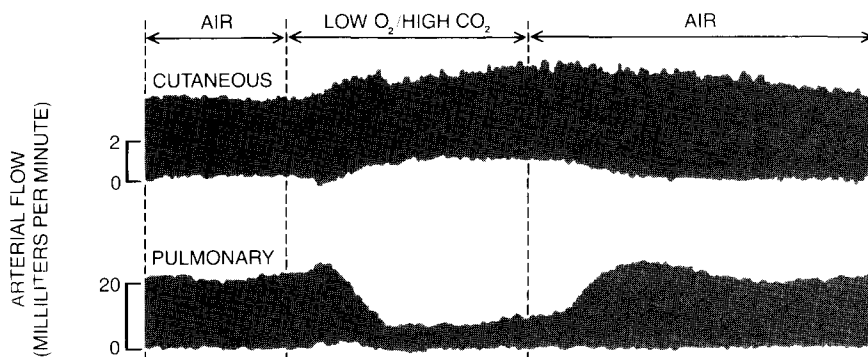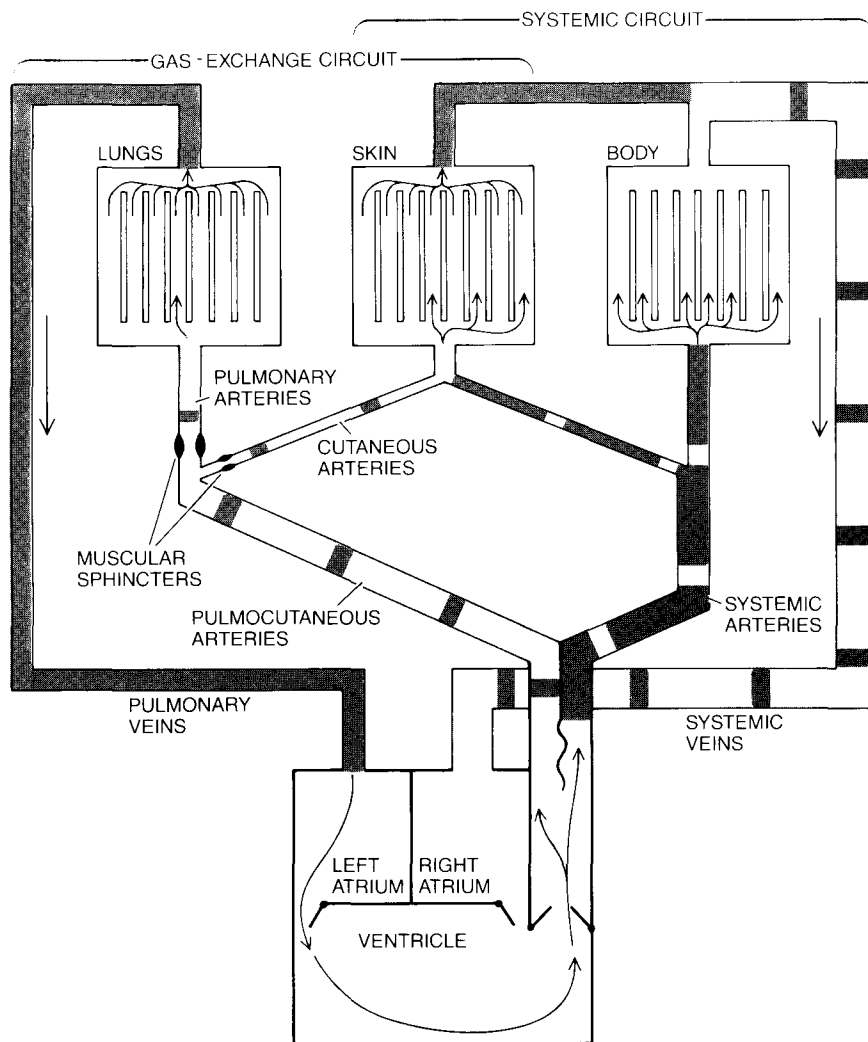
it would best promote gas exchange.

Amphibians, moreover, are unique in having cutaneous arteries, which direct transfer of deoxygenated blood to the skin. Blood can leave the single ventricle of an amphibian heart by either of two routes. One way is through the systemic arteries, which carry oxygenated blood directly to the brain, muscles, viscera and ultimately to the skin. The second route is through the pulmocutaneous arteries, which supply deoxygenated blood to the lungs by way of the pulmonary arteries and

to the skin by way of the cutaneous arteries.

Graham Shelton and his colleagues at the University of East Anglia in England have shown that amphibians can channel deoxygenated blood into the pulmocutaneous arteries and thence selectively to either the lungs or the skin for gas exchange. The basis for such ability may lie in the structure of the heart and in the muscular sphincters that surround the pulmonary and cutaneous arteries after they diverge from the common pulmocutaneous
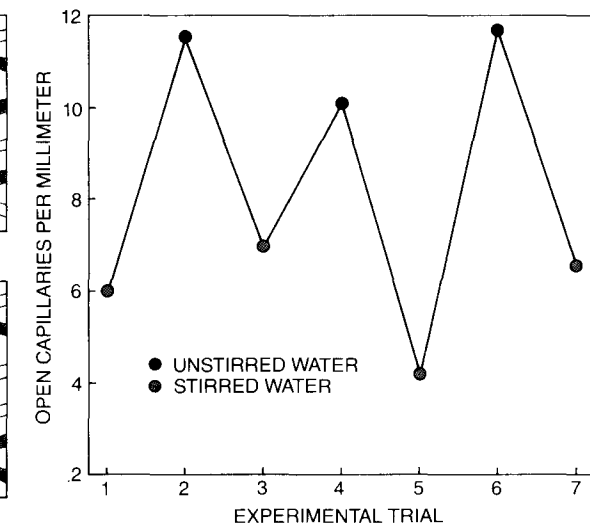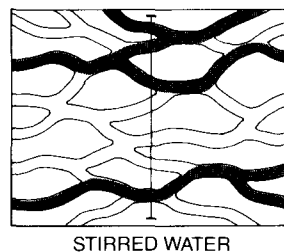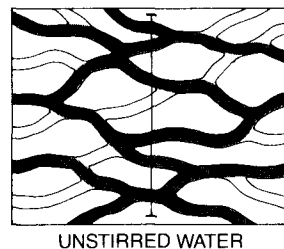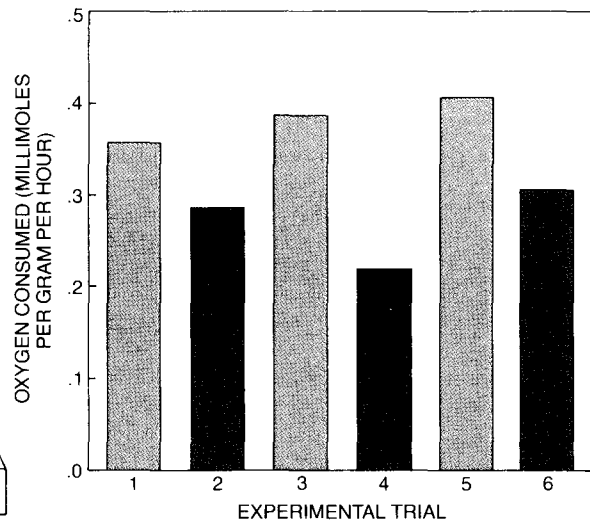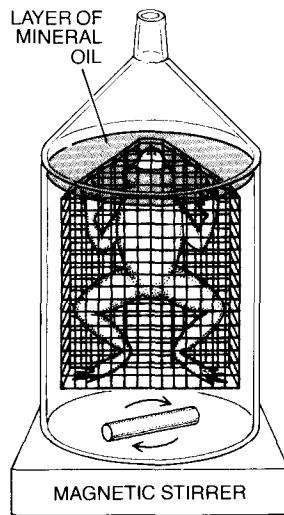
SKIN VENTILATION affects cutaneous gas exchange. A frog, immobilized in a wire-mesh envelope, was immersed in a water-filled chamber so that only its nostrils were above the surface (*top left*). The skin could be ventilated by actuating a magnetic stirrer at the bottom of the chamber. Cutaneous oxygen uptake could be monitored by measuring the decrease in concentration of oxygen in the chamber. (A surface layer of mineral oil prevented aeration of the water.) Cutaneous oxygen exchange (*top right*) was greater when the water was stirred (*gray bars*) than when the water was left still (*colored bars*). The reduction in oxygen consumption when the water was still was shown not to result from a decrease in capillary blood flow. A frog's leg was led through the side of the container so that the capillaries in the web of the foot could be seen under a microscope. The number of blood-filled capillaries that intersected a line in the microscope's eyepiece was counted while the water was stirred and while it was left still (*bottom left*). In the absence of stirring, and thus of skin ventilation, the number of blood-perfused capillaries actually increased (*bottom right*).

139

GAS-EXCHANGE CIRCUIT

LUNGS   SKIN   BODY

PULMONARY
ARTERIES

CUTANEOUS
ARTERIES

MUSCULAR
SPHINCTERS

PULMOCUTANEOUS
ARTERIES

SYSTEMIC
ARTERIES

PULMONARY
VEINS

SYSTEMIC
VEINS

LEFT
ATRIUM   RIGHT
ATRIUM

VENTRICLE

AIR   LOW O₂/HIGH CO₂   AIR

CUTANEOUS

PULMONARY

ARTERIAL FLOW
(MILLILITERS PER MINUTE)

AMPHIBIAN CIRCULATORY SYSTEM, diagrammed here, allows deoxygenated blood (*blue*) to reach the skin and thereby promotes the diffusion of oxygen through the skin and into the blood. Most of the deoxygenated blood delivered to the skin comes from the heart by way of the cutaneous arteries (*top*); a small quantity is mixed into oxygenated blood (*red*) in the ventricle of the heart and is transported by the systemic arteries to the skin. (Some oxygenated blood also finds its way into the pulmocutaneous arteries.) In spite of the fact that a single ventricle pumps both oxygenated and deoxygenated blood into the arteries, a segregation of blood is maintained: primarily oxygenated blood is routed to the systemic circuit and primarily deoxygenated blood is routed to the gas-exchange circuit. Part of the primarily deoxygenated blood in the pulmocutaneous arteries can then be shunted to either the lungs or the skin, depending on which organ is better suited for respiration at the time. Electromagnetic cuffs measuring the blood flow within the cutaneous and pulmonary arteries recorded (*bottom*) the decrease in pulmonary arterial flow and the increase in cutaneous arterial flow when the lungs were flushed with gas rich in carbon dioxide and poor in oxygen. Muscular sphincters around the arteries may act as valves and so regulate the flow.

artery. The sphincters may act as valves that shunt blood flow one way or the other. In any case the exact distribution depends on the level of oxygen and carbon dioxide prevailing at these two respiratory organs.

Working with Nigel West of the University of Saskatchewan, we measured the distribution of pulmocutaneous blood between the skin and the lungs by implanting electromagnetic flow transducers around the pulmonary and cutaneous arteries of anesthetized toads. When we simulated the oxygen and carbon dioxide partial pressures typically found in the lungs of toads holding their breath, the toads diverted blood from the lungs to the skin. This response facilitates cutaneous gas exchange.

Such a reaction must also be relied on by frogs whenever pulmonary breathing is hindered, as it is when a frog is underwater. Recently Robert Boutilier, Mogens Glass and Norbert Heisler of the Max Planck Institute in Göttingen conducted a series of experiments similar to ours on intact, unanesthetized bullfrogs. They injected microscopic radioactive spheres into the bullfrogs' circulatory systems. The spheres, which were slightly larger than red blood cells, lodged in capillaries through which blood flowed. The distribution of blood flow between the lungs, skin and other body tissues could then be calculated from the radioactive emissions of the various body tissues exposed by dissection.

When frogs dived in oxygenated water after breathing gas mixtures low in oxygen, pulmocutaneous blood was preferentially distributed to the skin rather than to the lungs. Conversely, when frogs with air-filled lungs were submerged in water containing little oxygen, pulmocutaneous blood was distributed from the skin to the lungs. Clearly amphibians can regulate cutaneous blood flow both to optimize cutaneous gas exchange and to coordinate the respiratory activity of the skin with that of the lungs.

Although skin breathing may account for only a small component of total gas exchange in certain animals, in others it can play a major if not vital role. The sheer diversity of species that resort at least in part to cutaneous gas exchange should be sufficient to convince one that skin breathing is commonplace rather than exceptional in vertebrates. Through closer investigation cutaneous gas exchange has emerged as a well-regulated, energetically inexpensive process that can respond to immediate, prolonged and evolutionary changes in an animal's respiratory requirements.

142