

The Challenges of Diving to Depth

The deepest sea divers have unique ways of budgeting their oxygen supply and responding to pressure

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People flatter themselves by placing humankind at the top of the evolutionary tree. The implication, of course, is that people represent the "paragon of animals," the perfect marriage of noble reason and angelic form, to paraphrase William Shakespeare. Ironically, what people do with this much-lauded ingenuity is fashion devices that allow them to mimic the animals. One of humankind's greatest achievements, after all, is the invention of flying machines.

Some animal tricks still elude people. Take, for example, deep-sea diving. At present, the world record-holder for a descent assisted with weights and pulleys has reached a depth of 133 meters, a feat that required the diver to hold his breath for longer than two minutes. Most marine mammals can exceed that depth within their first few months of life. And the premier divers in the animal kingdom—elephant seals and sperm whales—occasionally dive to depths greater than a kilometer.

The restraints on people relate to their very basic need for oxygen and their difficulty in dealing with dramatic changes in pressure. Without the means to extract oxygen from the water, a diver must take in all of the oxygen he or she will use for the duration of the dive before becoming submerged. Further complicating matters is the way the human body reacts to the increasingly high pressures encountered during the descent. The pressure at depth becomes enormous, enough to collapse the diver's lungs and force all remaining oxygen out of them.

But of all the dangers, the greatest are apparent when the diver ascends toward the surface. On the way up, the decrease in pressure poses a range of perils, including decompression sickness, commonly known as "the bends," and "shallow-water blackout," a probable result of a sharp drop in the concentration of oxygen in the arteries, ultimately reducing the amount of oxygen that gets to the brain. This in turn causes the diver to lose consciousness just before reaching the surface. Indeed, most human diving accidents occur on the way up, not down.

Curiously, marine mammals and birds do not seem to experience these problems, although one would expect them to. The respiratory systems of diving mammals are basically the same as ours. These animals are dependent on their lungs for respiration just as people are. In spite of these similarities, the deep-sea divers among them can remain submerged for long periods, up to two hours, and there is no indication that they suffer from the bends on ascent.

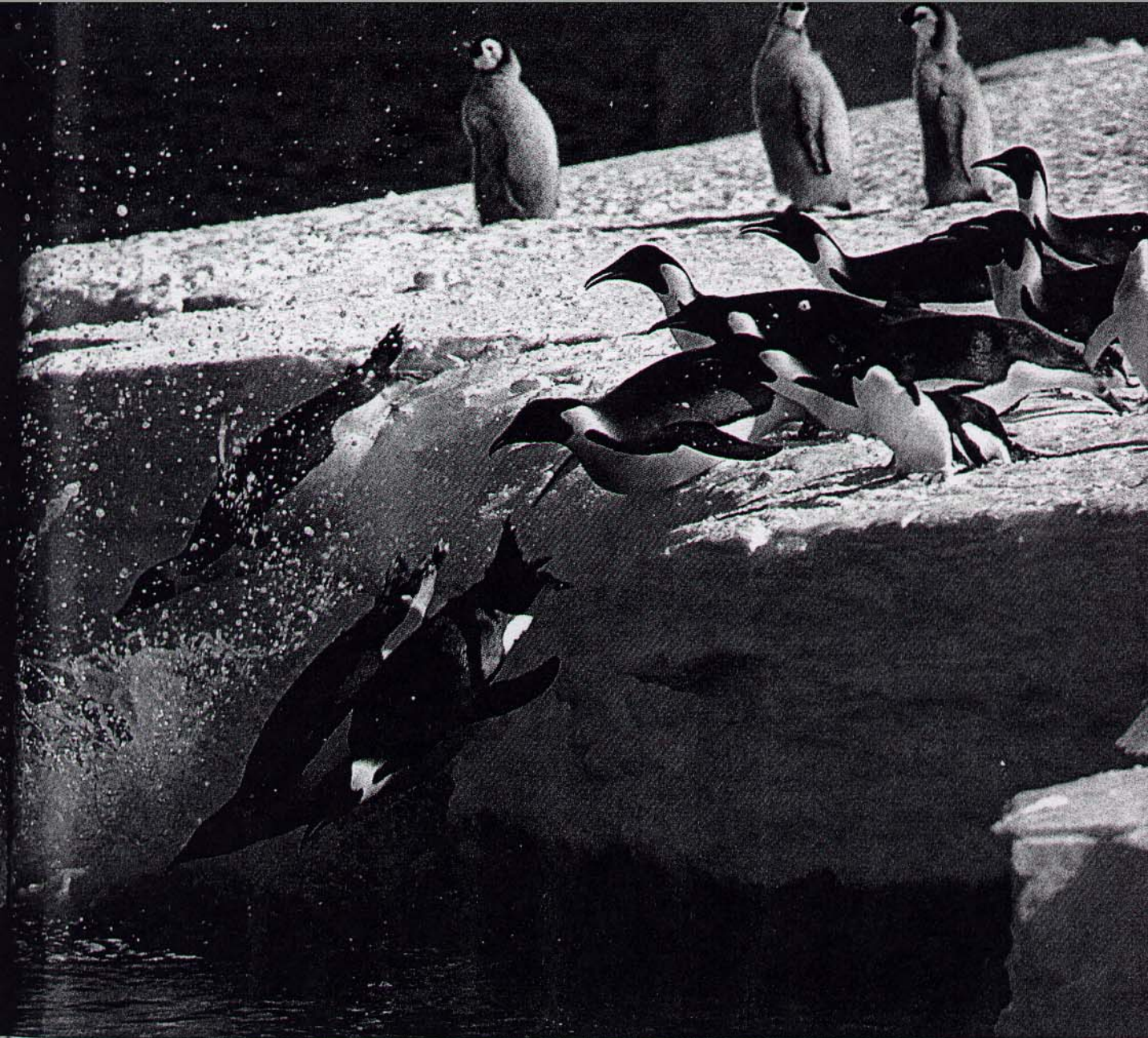
Marine biologists have long wondered about the differences between the



Figure 1. Streamlined and sleek, emperor penguins dive into the icy waters of the western Ross Sea, Antarctica. These birds are among the many marine animals that can dive to depths that far exceed the record of 130 meters for a human dive. This is rather

deepest sea divers and animals restricted to more shallow depths. Initially, their questions focused on the most superficial aspects of the dive: how far and how long? More recently biologists have developed the tools to ask more sophisticated questions. Our own research and that of our colleagues has shifted to issues of the anatomical and physiological traits that allow these animals to do what no human being can ever achieve without mechanical devices. These studies so far indicate that the answer comes

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curious, however, since birds, marine mammals and reptiles, like people, depend on lungs for respiration. Nevertheless, some marine animals can remain submerged for hours, whereas people can remain submerged for about four minutes at best. Furthermore, human divers are plagued by problems imposed by the dramatic changes in pressure as they descend and, even more dangerous, ascend. Some effects of pressure change can be fatal to human divers, but rarely to animals. The differences between the impressive performance of marine animals during a deep dive and the comparatively poor showing of people can be explained by differences in anatomy and the way oxygen is stored and used by the two groups. (Photograph by Carsten Kooyman, courtesy of the authors.)

down to oxygen—the way it is distributed to, stored by and consumed in the body's various tissues and organs.

Expert Divers

Marine divers are found in every ocean from the North Pole to the edges of the Antarctic continent. A couple of hundred million years ago, reptiles dominated the seas with some of the most unusual species of vertebrates that have ever existed. Now they are a remnant of the past, with only one lizard, the

Galápagos marine iguana, seven species of sea turtles and about 50 species of sea snakes being adapted to draw a reptilian living from the sea.

In our times, the greatest diversification and distribution of sea-living creatures (not counting the fish) is among endothermic birds and mammals. Since they are able to generate and maintain their own body heat, these two groups are not restricted to warm waters. In fact, they have spread into temperate and even polar seas, where they are

most abundant. Among these polar creatures, the quintessential avian diver is the emperor penguin, which can attain depths greater than 500 meters while staying submerged for about 12 minutes. In shallower dives, an emperor penguin may stay submerged even longer, over 20 minutes. Among mammals, the supreme diver is the sperm whale, which can dive down over 2,000 meters, and the northern elephant seal, which can descend to depths below 1,500 meters. The Weddell seal, about

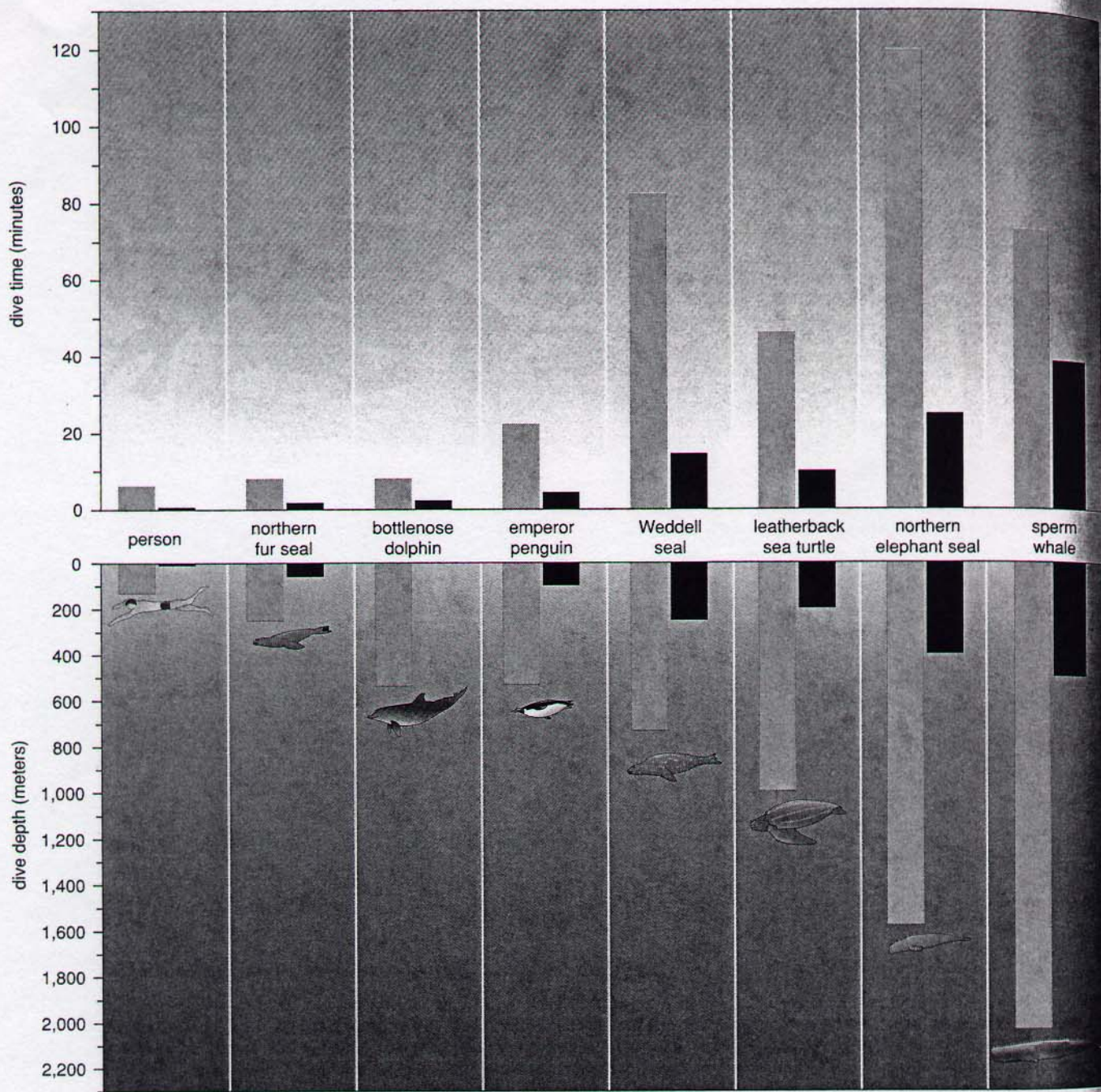


Figure 2. Marine divers are found in every ocean from the North Pole to the Antarctic and include mammals, birds and reptiles. Initial research into these divers focused on the length and depth of the dives. Such studies helped establish that the premier divers were the sperm whale and the northern elephant seal. The world record for a very exceptional human diver is included for comparison.

which most is known and which we study, is somewhat less dramatic in its dives. Still, it can descend to 700 meters, and at times it may remain submerged for 82 minutes, which makes it far superior to people.

How is it that these animals, which also have lungs, are so much better adapted than people to deep-sea diving? One glance at their bodies gives part of the answer. All of the best divers are

very streamlined, almost spindle-shaped. The shape of the penguin is so nearly resistance free that it has one of the lowest possible drag coefficients. Diving mammals have little hair or very short hair, and birds' feathers are modified in such a way that they glide nearly friction-free through the water. Aquatic animals have either shortened hind limbs or none at all. And what would be forelimbs on terrestrial mammals are modi-

fied to become flippers or fins. Aquatic birds use their wings as flippers.

Many of the most important adaptations have taken place internally and have to do with the way diving animals distribute and store oxygen. A universal modification within all deep divers, and perhaps the hallmark characteristic that sets them apart from all land forms, is the distribution and concentration of the protein myoglobin. Myoglobin is found

primarily in muscle, and its main function is to bind oxygen. In some diving animals, particularly those that feed while submerged, the concentration of muscle myoglobin can be anywhere from 3 to 10 times that found in the muscles of terrestrial animals. This suggests that these animals store more oxygen in their muscles than do nondivers and that, somehow, this relates to their ability to dive.

Oxygen Stores

The connection between myoglobin, oxygen and diving ability becomes clear when considered in the larger context of metabolism. Oxygen, of course, is required for respiration. Respiration is often thought to be the physical act of taking in oxygen and expelling carbon dioxide (CO_2). In reality, the oxygen drawn into the lungs is ultimately used in a crucial combustion reaction that turns food into energy inside of cells. Fuel in the form of fatty acids and the sugar glucose is literally burned in the presence of oxygen to form CO_2 and water. The process is analogous to burning gasoline to power the movement of a car, or burning coal to power a train. In these examples, energy production ceases in the absence of oxygen.

In the examples of the car and the train, the burning of the fuel breaks bonds between the carbon atoms in gasoline or in coal. This is done by providing another binding partner for the electrons in the carbon atoms. This partner is oxygen. It is easier for carbon atoms to bond with oxygen than with other carbon atoms. As a result, energy is released when carbon-to-carbon bonds are broken and carbon-to-oxygen bonds are formed. This energy is harnessed to drive the car or power the train. The by-products of this combustion reaction include CO_2 , if there is sufficient oxygen, or carbon monoxide (CO), if there is not. Water is also formed in a combustion reaction when hydrogen atoms in the fuel also bond with oxygen. Clearly, if there is no oxygen around to accept the electrons of the carbon atoms in the fuel, the reaction cannot proceed.

The same is true in the metabolic combustion reaction. The fuel is glucose, a sugar containing six carbon atoms. And just as in all other combustion reactions, oxygen is required to accept the electrons left over at the end of the reaction. The by-products are even

the same: CO_2 and water. There is one crucial difference, however. The energy derived from burning gasoline or coal is used immediately to power the car or the train. This is not true in metabolism, where the derivation of energy and its use do not occur simultaneously.

In the case of metabolism, the energy derived from breaking down glucose is stored for later use. Energy is stored in the bonds of another molecule, called adenosine triphosphate (ATP). These bonds are broken when energy is required inside the cell. The bonds of ATP can be accessed by the cell much more easily than can the bonds of glucose, so it is a more immediate energy store than is sugar.

Breaking the bonds of glucose and storing that energy into the bonds of ATP is a long and complex process. In effect, the glucose is burned very slowly in steps that allow the formation of molecules of ATP at various points. Nevertheless, the reaction does not proceed to completion unless oxygen is present. In the absence of oxygen, only the very initial stages of that process may take place.

In this anaerobic phase of glucose metabolism, only two molecules of ATP are formed (versus 36 for each glucose molecule metabolized in the presence of oxygen), and the end-product is not CO_2 and water, but rather lactate. This accounts for the buildup of lactate in the muscles of athletes who are exerting themselves beyond the rate of supply of oxygen. In this case, the muscles supplement their aerobic respiration with anaerobic metabolism.

Since every cell in the body requires energy and must therefore make ATP, every cell must get an ample supply of oxygen. When people and animals breathe in air, they are taking oxygen into their lungs, the first step in this distribution. Oxygen is transferred from the lung to the blood, which contains the oxygen-carrier molecule hemoglobin. Hemoglobin carries oxygen to all tissues and organs. In muscle, oxygen is transferred from hemoglobin to myoglobin.

The relation between hemoglobin and myoglobin is an interesting one, since the molecules are both function-

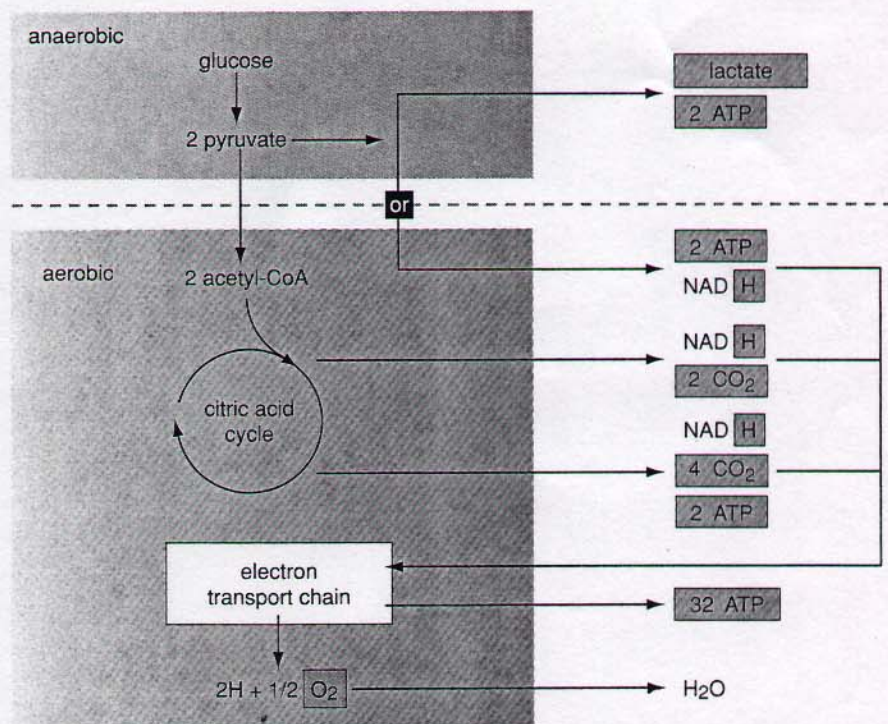


Figure 3. Respiration, which generates energy from food, must continue even while an animal is submerged. Inside cells, the bonds of the sugar glucose ($\text{C}_6\text{H}_{12}\text{O}_6$) are broken, and the energy released is used to produce adenosine triphosphate (ATP). The high-energy bonds of ATP are more readily accessed by the cell than are those of glucose and are used to power many of the cell's metabolic and mechanical tasks. During glucose breakdown, the sugar's carbon and hydrogen atoms eventually react with oxygen to form carbon dioxide (CO_2) and water. The complete oxidation of each glucose molecule generates 36 molecules of ATP. In the absence of oxygen, glucose breakdown is incomplete, yielding lactate in place of CO_2 . The net yield of anaerobic metabolism is only two molecules of ATP for each glucose molecule used.

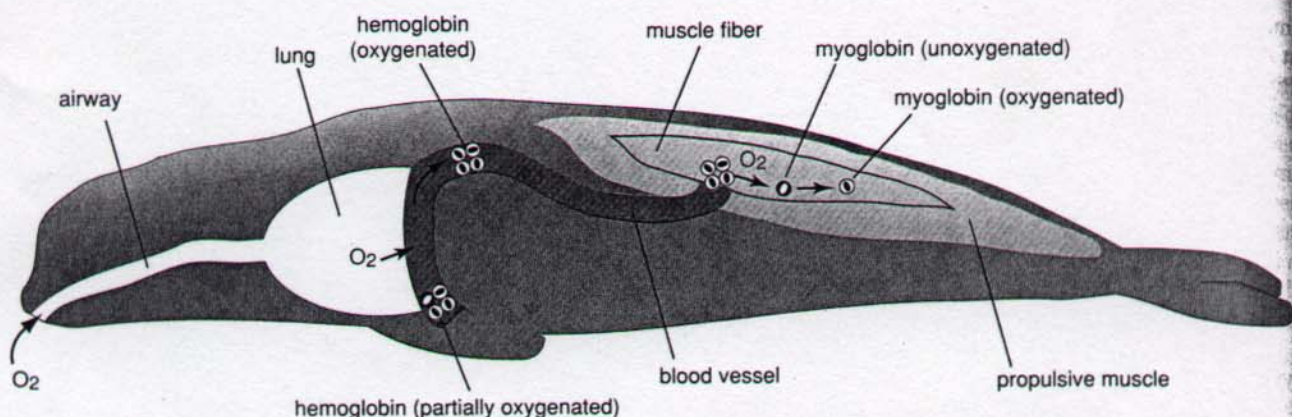


Figure 4. It is crucial that each organ and cell receive sufficient quantities of oxygen. With each breath, an animal takes in oxygen along with nitrogen and other gases in the air. In the seal shown here, as in other animals, oxygen travels down the airway into the lungs and there diffuses into the blood. Once in the blood, it binds to the protein hemoglobin, which carries the oxygen to all of the tissues and organs in the body. In muscle cells, the oxygen is transferred from hemoglobin to a related oxygen-carrying protein called myoglobin. The three largest reservoirs for oxygen are the lungs, blood and muscles, and the distribution of oxygen among these stores is important for diving animals. Diving animals have 3 to 10 times more myoglobin in their muscles than do their terrestrial counterparts, enabling divers to store more oxygen in their muscles than do other animals. A potential consequence of this is that the oxygen in the blood can be used by organs that do not store oxygen, most notably the brain. Still other organs may practically cease operation, so as not to use up oxygen. The abdomens of diving penguins have been found to drop in temperature during a dive, suggesting a slowdown in metabolic activity.

ally related and structurally similar. Myoglobin is a protein in which sits a heme group, an organic structure that contains iron. It is to the heme group, and specifically to the iron in the heme group, that the oxygen binds. Hemoglobin contains four protein subunits, each of which carries a heme group. As in myoglobin, the iron of hemoglobin's

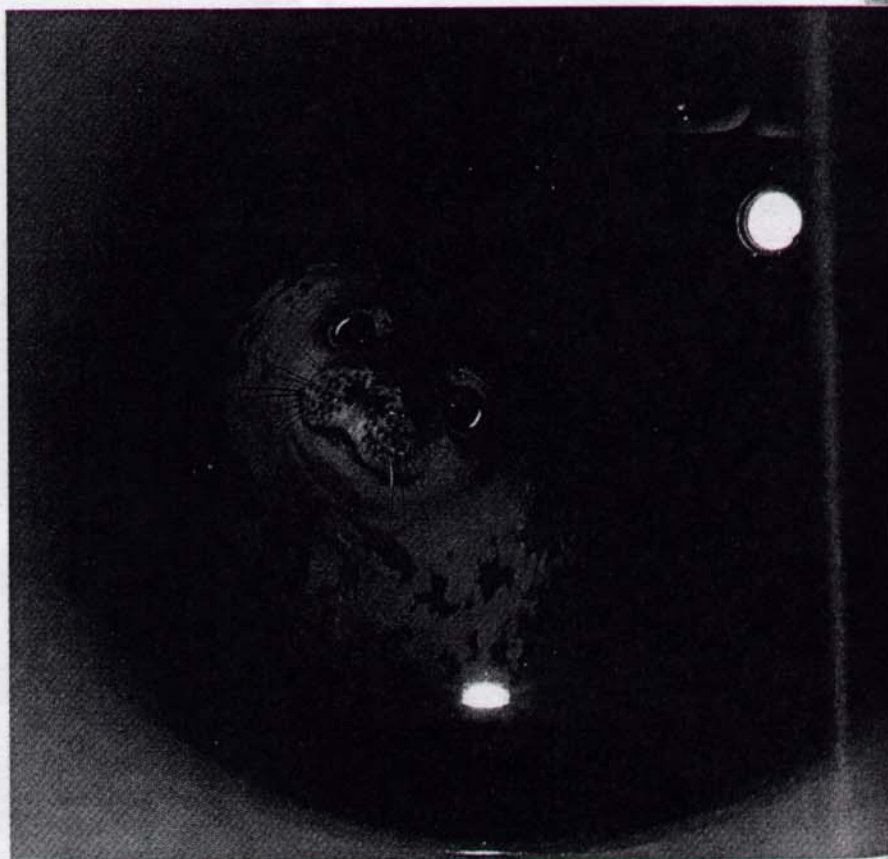
heme group is the site of oxygen binding. Myoglobin has a higher affinity for oxygen than does hemoglobin. When blood passes through muscle, oxygen is transferred easily from the blood to the muscle.

Most vertebrates that do not have rich stores of oxygen in various tissues are extremely dependent on having a sup-

ply delivered regularly to their tissues via the blood. People fall into this category, and, as we know, we cannot go for very long without breathing. But scientists started to wonder whether the same is true for animals that can store oxygen in their tissues. We would expect diving animals well endowed with muscle myoglobin to be less dependent for the



Figure 5. Metabolic activity in seals can be measured in the wild. Weddell seals dive into holes they have reamed in sea ice (left). The authors mimic such holes by drilling through 2-meter-thick ice with a large ice augur. A plastic bubble is then placed over the hole, which allows the investigators to measure the total amount of oxygen in the bubble before the dive and after the animal surfaces (right). These measurements, as well as others taken from instruments fastened to the seal's body, allow scientists to follow certain metabolic activities before, during and after the dive. (Photographs by Gerald Kooyman.)



duration of the dive on the blood to deliver oxygen. Rather, we think that during the dive, these deep-diving animals rely on the oxygen held by myoglobin. Other organs, notably the brain, do not store large amounts of oxygen. Flow is modulated as needed to other organs, depending on the nature of the dive. Our studies have aimed to measure oxygen uptake and the activity of various organs while animals are diving to see whether our predictions are correct. Investigators have also been measuring the blood flow to see whether, in fact, particular organs are preferentially serviced during a dive.

Taking Measure

No single experimental approach will answer the many questions about how diving animals tolerate the effects of pressure or adapt to the long breath holds required to reach prey. The earliest studies relied on an investigator-controlled, forced submersion conducted within the confines of the laboratory. As facilities for holding marine birds and mammals were constructed, it was possible to train animals to hold their breath within their pools while certain physiological variables were measured. Although this method did not provide the intrinsic stress level of a forced submersion, it did not present a psychological restraint because there was some uncertainty for the animal about how long the submersion would last. If an animal surfaced before the command to do so, there was no reward. Therefore, it had to hold its breath with the possibility that it would be near its limit.

As training methods improved, it became possible to let some species dive in the open sea while certain variables were measured. This is a long and expensive process. It can take weeks to months of training before an animal is ready for the experiment. One of the few laboratories capable of mounting such an elaborate endeavor is the Naval Ocean Systems Laboratory, where Sam Ridgway began and continues work, with many collaborators, on a variety of animals. At this facility investigators can measure tissue-nitrogen levels, metabolic rate, heart rate and other physiological parameters of seals, sea lions and bottlenose dolphins while they dive.

For us, the most rewarding and cost-effective way to study the physiology of diving is to study the animals in the wild. Many of our studies are conducted

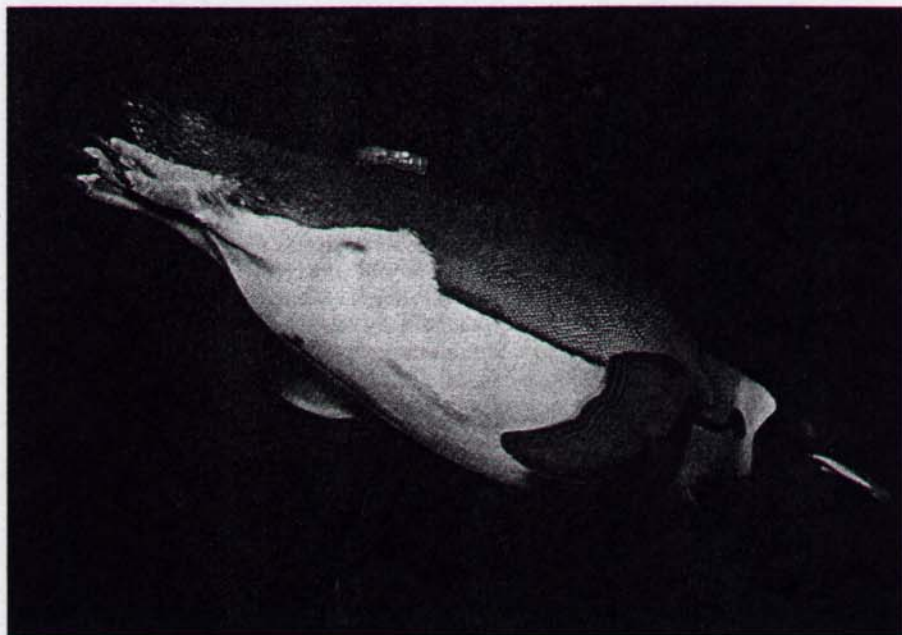
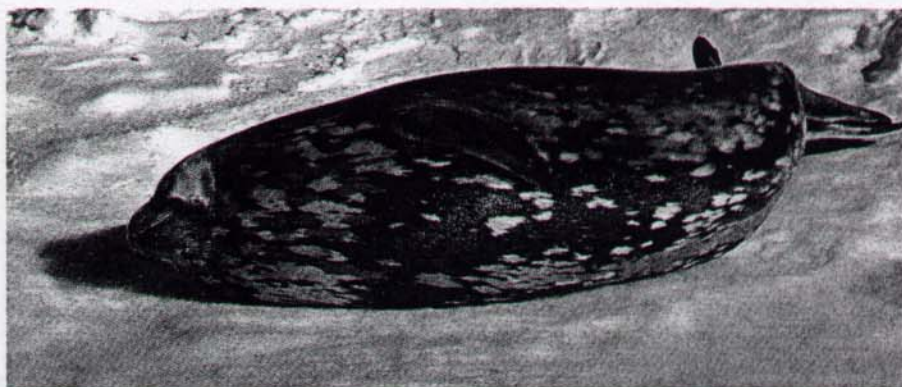


Figure 6. Streamlined bodies of diving animals, such as the Weddell seal (*top*) and the emperor penguin (*bottom*), cut down on drag and swim effort and reduce oxygen-consumption rates. Information about the dive is taken by a recorder, such as the one attached to the penguin's back. (Photograph of seal by Gerald Kooyman, and photograph of penguin by Carsten Kooyman, courtesy of the authors.)

ed in McMurdo Sound, Antarctica. This is quite likely the only practical place in Antarctica for these complex studies, since an ideal habitat is situated fortuitously close to a major research station equipped with superb transport capabilities, both in the air and on the ice.

In addition to its proximity to a research station, the sound is an outstanding study site because it is overlaid in early summer by a large plate of two-meter-thick sea ice that has formed through the previous winter. Protected from winds and currents, this 60-kilometer-wide by 30-kilometer-long sheet of ice is wedged securely between Ross Island to the east and the Antarctic continent to the west. At 77 degrees South latitude it takes until February for the ravages of the sun to erode and weaken the ice enough for waves and wind to fragment the sheet

into floes that become part of the late-summer pack ice.

The integrity of the ice is particularly important since the two species we study—the Weddell seal and the emperor penguin—both commonly dive under ice. We can exploit both their diving habits and the ice sheet to prepare our study site. We drill holes through the ice to introduce the diving animals. The holes are placed at great distances from one another, making it unlikely that an animal introduced into one hole will surface at another. This allows us to measure accurately the length and depth of the dive by attached recorders that are easily retrieved. We measure the time it takes the animal to descend and ascend, the animal's swim speed and how long the animal remains at depth. We also look at the animal's heart rate, taking care to measure how it changes through

		total oxygen (milliliters per kilogram of body weight)	percent of total		
			lungs	blood	muscle

	people	20	24	57	15
	California sea lion	40	21	45	34
	bottlenose dolphin	36	34	27	39
	emperor penguin	55	19	34	47
	Weddell seal	87	5	66	29
	leatherback sea turtle	18	26	63	11

Figure 7. Magnitude and distribution of oxygen in the various stores varies among species. For each species shown here, the total oxygen store is given, as well as the concentration typically held in each of the three stores—lungs, blood and muscle. People maintain a lower supply of total-body oxygen than do most of the diving animals. In addition, the largest oxygen stores for people are the lungs and blood, whereas the blood and muscle are the primary stores in most diving animals.

the course of the dive, which gives us some notion of the circulatory patterns.

Since we want to know something about the animal's metabolism, we further prepare the study site to allow us to measure oxygen concentrations. (So far, we can do this only with the seals.) We place a plastic dome over the hole, allowing us to measure the oxygen content within the dome before the animal dives as well as after it has surfaced. By measuring the oxygen concentrations within the dome while the seal is surfaced, we can make some calculations about its metabolic rate and pulmonary function. We can also make some calculations about the seal's oxygen capacity and usage.

Two Means to an End

Overall, our measurements have indicated that each species has a unique solution to the challenges of diving. The one thing all of these animals share, however, is a very streamlined body. This not only reduces drag and swim effort, it also lowers oxygen-consumption rates.

In addition, some penguins further lower their oxygen consumption by reducing the temperature of various regions of the body that may not need to function at the levels required while the animals are above water. Recent studies by Yves Handrich and colleagues at the Centre National de la Recherche Scientifique in Strasbourg, France, indicate

that during a dive, the temperatures of the abdomens of king penguins drop several degrees while the animals feed on cold prey. The abdomens may not return to normal temperatures for many hours. This may result in an important

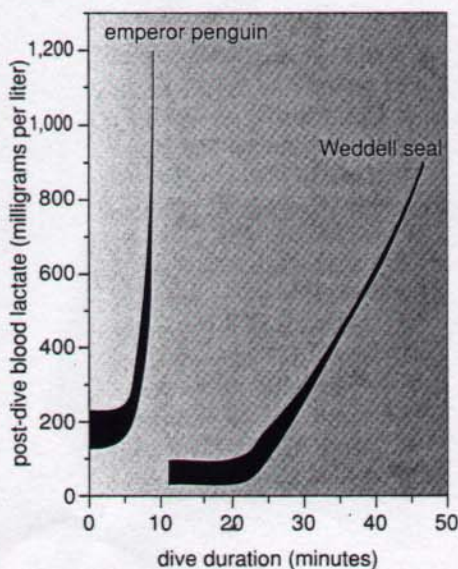


Figure 8. Since lactate is a by-product of anaerobic metabolism, the authors measure the time it takes for lactate to appear in an animal's blood and have defined this time as the "aerobic diving limit." In natural dives, the authors saw a rise in blood-lactate levels in only about 5 percent of Weddell-seal dives, and 21 percent of emperor-penguin dives. They are now trying to define the parameters that most contribute to the aerobic diving limit.

regional metabolic saving that influences the overall rate of oxygen use while diving.

The magnitude and distribution of oxygen in the various stores—lungs, blood and muscle—vary among species. People have a total oxygen capacity of 20 milliliters per kilogram of body mass. In contrast, Weddell seals have a total capacity of 87 milliliters of oxygen per kilogram of body mass. Penguins fall between the two, with a total oxygen capacity of around 55 milliliters per kilogram of body weight. Most of the oxygen in seals is in the blood and muscle, with the lungs storing less than 5 percent of the animal's total oxygen. In fact, the seal's lungs are almost fully collapsed soon into the dive, at which point the lungs cease to exchange gas.

Emperor penguins and other birds have a different distribution of body oxygen stores. Birds have several large air sacs, suggesting that their respiratory system contains a greater proportion of the total body oxygen than it does in most diving mammals. In addition, the blood volume and hemoglobin concentrations are only slightly elevated over flying birds. On the other hand, the myoglobin concentration in emperor penguin muscle is 10 times greater than in terrestrial birds. For this species, the muscle-oxygen store exceeds the blood-oxygen store.

The differential distribution of oxygen in emperor penguins and Weddell seals implies that oxygen is also used differently by the two during a dive. In seals, the blood-oxygen store dominates, and the lung-oxygen store plays a minor role in breath-hold endurance. In penguins, lung-oxygen stores are more important than in seals, but the muscle-oxygen store is the largest.

One of the more difficult and contentious issues to come out of all this is whether and when the diving animal exhausts its muscle-oxygen stores. One would expect that as an animal used up its store of oxygen it would be compelled to switch from aerobic to anaerobic respiration. Since the end-product of anaerobic respiration is lactate, we would expect to see a rise in muscle lactate with the increasing reliance on anaerobic metabolism. Previously, investigators had reported seeing such a surge in blood levels of lactate at the end of each laboratory experiment in which the animal was forcibly submerged, no matter how short the breath-

old. Scientists interpret this surge to mean that lactate is released into the blood from the muscles, where it has been accumulating over the duration of the dive.

When we measured lactate levels in naturally diving Weddell seals, we saw something quite different. We saw an increase in only about 5 percent of the dives, and these were of the most extreme length. We have defined the time it takes for an animal to express the rise in blood lactate as the "aerobic diving limit," and are now trying to define the parameters that most contribute to that limit. We think that the oxygen in each compartment is used at different rates during a dive. Furthermore, we think

that because the muscles in diving animals contain so much myoglobin, it is less important for blood to flow to muscle than it is for flow to be maintained to organs that do not have an oxygen store, most notably the brain. But an animal has only so much oxygen in the blood and muscle, and in order to conserve these resources other activities must reduce their requirements. We hope that by determining precisely how and where oxygen is being used, we can find answers to such questions.

Pressure

It is clear that the oxygen supply imposes the time limit of the dive. An emperor penguin's dive lasts about 10 to 12 minutes, during which the bird could reach a depth of 600 meters, slightly greater than the maximum observed value. Longer dives fatigue the animal and compromise the reserve energy that might serve to elude a predator. These possibilities suggest that dives in excess of 600 meters would pose unacceptable risks.

But other factors, notably pressure, might also limit the maximum depth. Pressure is certainly a factor limiting human dives. Among the most dangerous effects of pressure on people is decompression sickness. People get the bends most often when they are breathing compressed air at high pressures. At these pressures, a human diver takes in additional oxygen and nitrogen gas, which remains dissolved in the blood until the person starts to ascend. By this time, most of the oxygen is used up. But not the nitrogen. As the pressure decreases, the dissolved nitrogen may form bubbles in the blood and other tissues. Nitrogen bubbling in tissues, particularly in the joints causes pain and sometimes neurological problems as well as other complications. In addition, nitrogen bubbles in the blood form emboli that may block circulation and cause physical damage to organs or tissues. The emboli may also prevent oxygenation of tissue.

Even though birds and mammals are not breathing an external supply of air, the gas volume they carry in the lungs or air sacs, the depth of their dives and the durations are adequate for high concentrations of nitrogen to develop within the blood and tissue.

In fact, laboratory studies on elephant seals by us and Antarctic field studies of freely diving Weddell seals by Konrad Falke and his colleagues at

Harvard University have shown that blood-nitrogen levels rise very little no matter how deep the dive. As noted before, when the animals reach a relatively shallow depth of only 50 to 70 meters, their lungs collapse and do not become reinflated until after the animal ascends to shallow depth. This means that over the better part of the dive the lungs are not functioning; they do not exchange gas, and much of the nitrogen in the lungs never enters the blood supply. We presume that other marine mammals experience similar

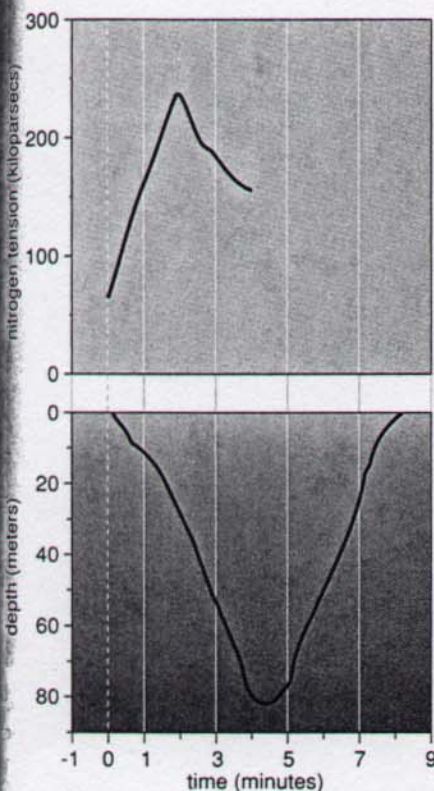


Figure 9. High concentrations of nitrogen are hazardous to human divers. Nitrogen, which is a component of air, passes into the blood as do oxygen and other gases. As the diver rises toward the surface and the pressure decreases, the dissolved nitrogen may form bubbles in the blood and other tissues, which results in joint pain, neurological disorders and other complications. These effects, referred to as the "bends," do not seem to trouble diving animals. Shown are data taken during a Weddell seal dive. The concentration of arterial nitrogen (top graph) reaches its peak long before the animal achieves maximum depth (bottom graph). Nitrogen concentration then seems to decline to an equilibrium between arterial and venous blood until the seal ascends.

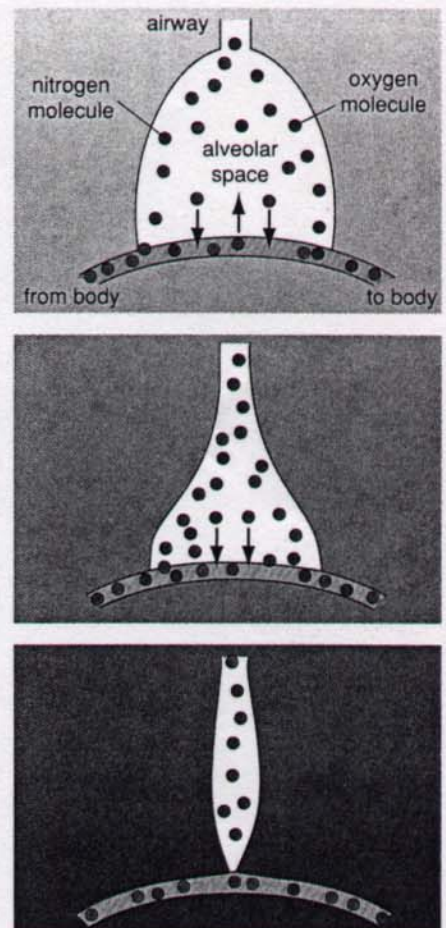


Figure 10. Dynamics of the lung help explain how seals avoid the bends. At the surface (top), the lungs are fully inflated, and gases pass freely between the lungs and the blood. As the seal descends, the lungs start to collapse (middle). Alveolar gas pressures rise because of the impinging ambient pressure. At that point, nitrogen diffusion is unidirectional into the blood, and the blood-nitrogen concentration reaches a maximum. As the seal continues to descend, the lung collapses completely, entirely curtailing any gas exchange between the lungs and the blood (bottom). This limits the amount of nitrogen in the blood and helps the seal avoid the risks of elevation of nitrogen pressure.



Figure 11. Like seals, emperor penguins ascending from a dive do not experience the bends. Yet, the structure of the bird's lungs is entirely different from seals, and the model proposed for seals is not applicable to diving birds. The way in which birds avoid high nitrogen concentration is unknown. (Photograph of ascending birds by Gerald Kooyman and surfacing bird by Paul Ponganis.)

lung collapse while at depth. Falke and his colleagues have shown this to be the case in freely diving seals.

How birds avoid the bends is not so clear. Their lungs may not collapse during a dive, and, since atmospheric air

is nearly 80 percent nitrogen, their air sacs would in fact serve as a very good nitrogen store. Laboratory experiments with diving Adelie and gentoo penguins, two medium-sized species, indicated that gas exchange did continue throughout the dive. The oxygen in the lungs became progressively depleted, and the nitrogen in the blood rose to levels that were borderline for decompression sickness. We think that these animals avoided decompression sickness by diving for only a short time. In the wild, most penguins do not dive deeply enough or for long enough pe-

riods to incur a risk from nitrogen uptake on a single dive.

Emperor and king penguins are another matter. They do dive deeply and for relatively long periods of time, and the way they avoid nitrogen-related problems is still under investigation.

Clearly, the work we have described only begins to touch on the complexity of the physiology of deep-sea diving. This research will benefit greatly from new technologies that allow us to monitor more closely the organ functions of diving animals. Such instrumentation will enlarge our understanding of the

physiological adaptations to diving, such as how organs survive low blood flow and the consequent oxygen depletion. These kinds of studies may aid in treatment of shock, stroke and organ transplants. Nevertheless, the discoveries so far made about diving animals have increased our admiration and enjoyment of them. They are a world treasure. Future studies will no doubt enhance this view of their value.

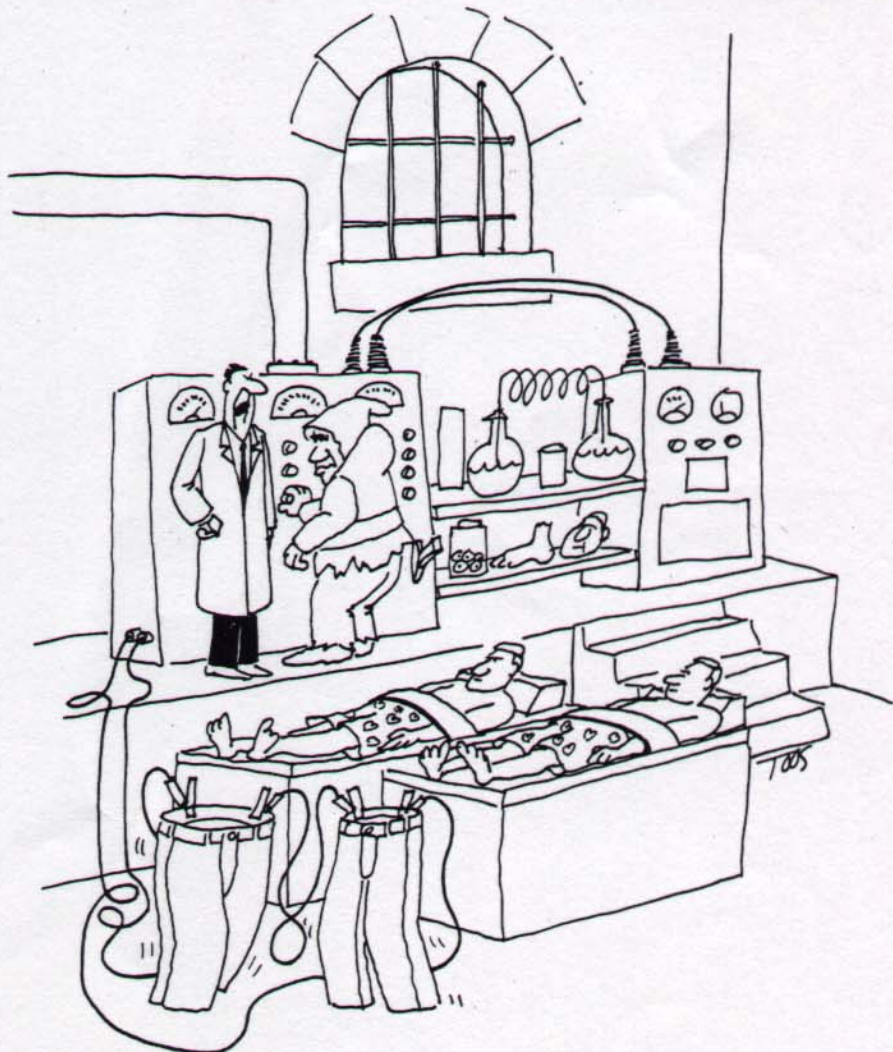
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"You idiot!, I meant transfer their genes."