The Mammalian Diving Reflex
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Fifty minutes without a heartbeat
On a cold September night in Colorado, 21-month-old Gore Otteson fell into a freezing river. When his family pulled him out, he was unconscious, his heart had stopped, and he was no longer breathing. But almost an hour later, Gore was revived at the Denver Children’s Hospital and a few days later, he recovered completely—thanks to his mammalian diving reflex.

Reflexes cause you to snatch a hand back from a hot stove or to startle if someone sneaks up behind you. All mammals have the diving reflex, including humans. The diving reflex is the body’s physiological response to submersion in cold water and includes selectively shutting down parts of the body in order to conserve energy for survival.

We engage the diving reflex in an emergency, unlike seals, whales, and penguins, which use the diving reflex as an adaptation to function in their everyday life. Marine animals possess an extremely sophisticated dive response that enables them to catch fish underwater and to withstand the pressures associated with diving.

The Weddell Seal: The Gold Medal Winner
Robert Maue, a professor of physiology and neurobiology at the Dartmouth Medical School, has studied the diving reflex in the Weddell seal, one of the best divers in the animal kingdom (see Fig. 1). He traveled to Antarctica to study the seals in their natural habitat. “When I was a student down there...they would dive routinely to 500-800 feet, and that was not even the bottom,” commented Maue. Weddell seals have been recorded making dives of up to 80 minutes and down to 2,300 feet.

Because Weddell seals breathe air like all mammals, the diving reflex kicks in to manage the lack of oxygen while underwater. All non-essential processes such as digestion come to a halt, and blood vessels constrict like flood gates, stopping blood flow to outer tissues and organs. The seal’s heart rate slows dramatically, which decreases the amount of blood circulating through its body. Metabolism, the process by which cells create and use energy, declines in the unused parts of its body.

To hunt and chase fish underwater without having to take a breath, the Weddell seal uses pre-stored oxygen in its blood and muscles. These oxygen stores keep the muscles working long after the seal’s last breath. Unlike most tissue, which can survive for a limited time without oxygen, brain cells require fresh oxygen all the time. Decreasing oxygen requirements in other parts of the seal’s body frees up the available oxygen for the brain and keeps it alive.

Maue said that the part that he finds most interesting about the seal’s diving reflex is its complex ability to selectively shut down organs and processes. “It is easy to imagine shutting everything down,” he says. “However,” he continued, “the specialization of the different organs allows differential shut-down.” Unlike other animals, Weddell seals have adapted to shut down their kidney function to save oxygen on prolonged dives. Kidneys are extremely important; they regulate blood pressure, electrolyte content, and the pH balance in the bloodstream.

According to Maue, “Different organisms have different abilities. The [Weddell] seal is the gold medal winner when it comes down to shutting down the kidney function.” The diving reflex adjusts the seal’s metabolism in order to conserve oxygen for its brain, just as it did for Gore.

Human Near-Drowning
The diving reflex exists in humans as a survival mechanism, rather than a means to live every day. Humans “drown” when the automatic reflex to breathe forces us to inhale water into our lungs; suffocation, unconsciousness, and death follow. Medical doctors define “near-drowning” as survival after a person inhales water into his lungs, such as the case with Gore Otteson (see Fig. 2).

Gore Otteson had recently learned to unlatch the screen door at his grandparents’ vacation cabin in the Colorado woods. While getting ready for bed, Gore’s mother put on his pajama shirt and turned to his brother and sister. When she turned back for him with pajama bottoms, he was gone. Twenty-five precious minutes later, her cousin pulled Gore’s body from the cold water.

Dr. Katherine Martien, a Neurodevelopmental Disabilities Specialist in the Pediatrics Department at the Massachusetts General Hospital, compares the human dive response to hibernation. When a grizzly bear hibernates during the winter, it reduces almost all the activity in its body so it can use less energy to stay alive in the cold. Similarly, when a child is submerged in very cold water, the body reacts by decreasing activity, conserving both energy and oxygen.

When Gore fell into the river, his body responded with the diving reflex as soon as the freezing water hit the trigeminal nerve of his face. His body rapidly cooled and his heart rate and metabolism slowed dramatically to
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decrease his body’s oxygen requirement; he lapsed into protective hypothermia as soon as his core temperature fell below 95°F. After an involuntary breath, the cold water that he inhaled helped cool his core temperature even faster, and Gore lost consciousness when his body temperature reached 88 degrees.

There is a very fine line between the circumstances that result in drowning and in “near-drowning.” Near-drowning requires a perfect storm of cold temperatures and young, resilient people; for Gore Otterson, it was a lucky combination. According to Dr. Martien, who has observed cold-water drownings in the emergency room, children exhibit a unique reaction to the cold water.

The intensity of the human dive response is relative to the temperature of the water; colder water, of course, cools the body faster. Dr. Martien explained that the more intense the dive response, the better the tissues are preserved, and the better the chance of recovering. “Children who go through the ice,” she said, “those are the kids who have the best chance because it drops their core temperatures so quickly.”

Children have a survival advantage over adults in cold water. Their bodies have a higher surface area-to-volume ratio than adult bodies, so they cool more quickly—the same way that a cupcake just out of the oven cools faster than a sheet cake. They also have the innate ability to absorb more oxygen into their bloodstream than adults do, so, when they go underwater; there is already more oxygen available.

Youthful tissue also has a better chance of recovering from oxygen deprivation because it has not been previously damaged by disease or bad habits, like some adult tissue. Dr. Martien explained that “youthful tissue can withstand metabolic stress better…and drowning is the ultimate metabolic stress.” In addition, children are more resilient; they can create new brain connections more easily than adults. This aptitude for forming connections is the same reason why young children are so good at learning languages, but it also enables them to bounce back from brain damage because they can repair the connections.

Treating Near-Drowning

As medical professionals better understand the mechanisms involved in near-drowning, they can better address them when treating a patient. Dr. Martien, also an instructor at the Harvard Medical School, points to the key role of lactic acid for patients recovering from cold-water drowning hypothermia.

When cells are deprived of oxygen but continue to carry out metabolism, they produce lactic acid as a waste product. For example, when you push through a hard workout, the heart cannot pump enough blood to fuel muscles with oxygen for metabolism. As a result, the oxygen-deprived muscles produce lactic acid, which irritates muscles and makes them sore the next day.

Because the dive response shuts down metabolism in the body, it prevents the buildup of lactic acid in oxygen-deprived cells. However, some lactic acid is still produced, but it remains locked up in the cells because there is no blood flow to carry it away. If the lactic acid is suddenly released as the body warms up and the blood vessels de-constrict, it can build up and acidify the blood to toxic levels.

When doctors warm up hypothermic patients after near-drowning, they must accommodate the protective effects of the dive response, such as the decrease in metabolism and the increase in lactic acid. To prevent blood from becoming deathly acidic when warming up a patient, doctors use various chemical compounds to buffer the blood and prevent it from becoming too acid. After establishing a heartbeat, they warm patients from the core so that the blood is already flowing in the extremities when the lactic acid is eventually released.

“You’re walking a little bit of a tightrope,” said Dr. Martien as she highlighted the difficulty of warming up a hypothermic patient. The challenge is getting the blood flowing to move the lactic acid without letting all the lactic acid rush to the body’s core and to the heart. In the context of near-drowning, Maue adds that “the key [to survival] is probably coming out slowly. The body likes to stay in balance, so you have to give the body a chance to catch up. Brining [the core temperature] up slowly allows everything to stay in balance.”

Maue also explains how research on the seals’ dive reflex in the Antarctic has implications for human health. “How [seals dive] gives you insights into how humans do it—you learn about what kind of changes take place, so you know to warm up the kid slowly or to pay attention to lactic acid. Now research on seals is relevant to drowning victims.”

An Incredible Recovery

Fortunately for Gore, the Denver Children’s Hospital staff responded appropriately to his near-drowning experience and decided to keep him in a protective hypothermic coma, so his brain did not have to compete with the rest of his body for oxygen; each breath went directly to his brain cells. His brain could heal in peace and quiet, with all the oxygen it needed. Finally, when it was time to warm Gore up after 48 hours, they started slowly. If 21-month-old
Gore had warmed up too fast, his metabolism would have kicked in before his cells had enough oxygen, and the lactic acid stores would have rushed into his blood, poisoning him.

Doctors all across the country have been using therapeutic hypothermia to treat cardiac arrest and surgery patients, not just drowning victims, Dr. Martien noted. For example, the body is cooled quickly during cardiac surgery using either cooling blankets or cold intravenous fluid. For near-drowning victims like Gore, Dr. Martien raises the question, “should they have cooling blankets on ambulances?” Preventing the body from warming up too fast may be as important for survival as the initial dive reflex itself.

Fifty minutes is an extraordinarily long time without a heartbeat when that child comes back to life and completely recovers without any sign of brain damage. The news story is astounding, but the internal mechanisms that saved Gore’s body and his brain are just as amazing—and also just one example of how evolutionary adaptations directly impact survival. The dive response is a direct product of the strong forces of natural selection, continually ensuring that humans survive.

References: