Without Air

Breath-hold divers compete in one of the most intense and dangerous conditions on the planet—underwater. Breath-hold divers take huge risks participating in their sport.

Stéphane Mifsud of France holds the record for the longest breath-hold dive. He held his breath for 11 minutes and 35 seconds. Irreversible brain damage normally sets in at six minutes and solidifies at eight to ten minutes. But Mifsud survived with no noticeable brain damage. This amazing feat truly show the accomplishments of humankind to explore the boundaries of our limitations. But does breath-hold diving pose any risks to the brain? Does the lack of oxygen cause brain damage?

—From Chapter 8 "Brain Damage"

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Michelle Kathryn Duklas was born in 1991 and raised in the suburbs of Toronto along with her two younger siblings. Michelle graduated in 2013 from the University of Toronto with a double major in Political Science and Professional Writing & Communication.

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Duklas Without Air The World of Breath-hold Diving

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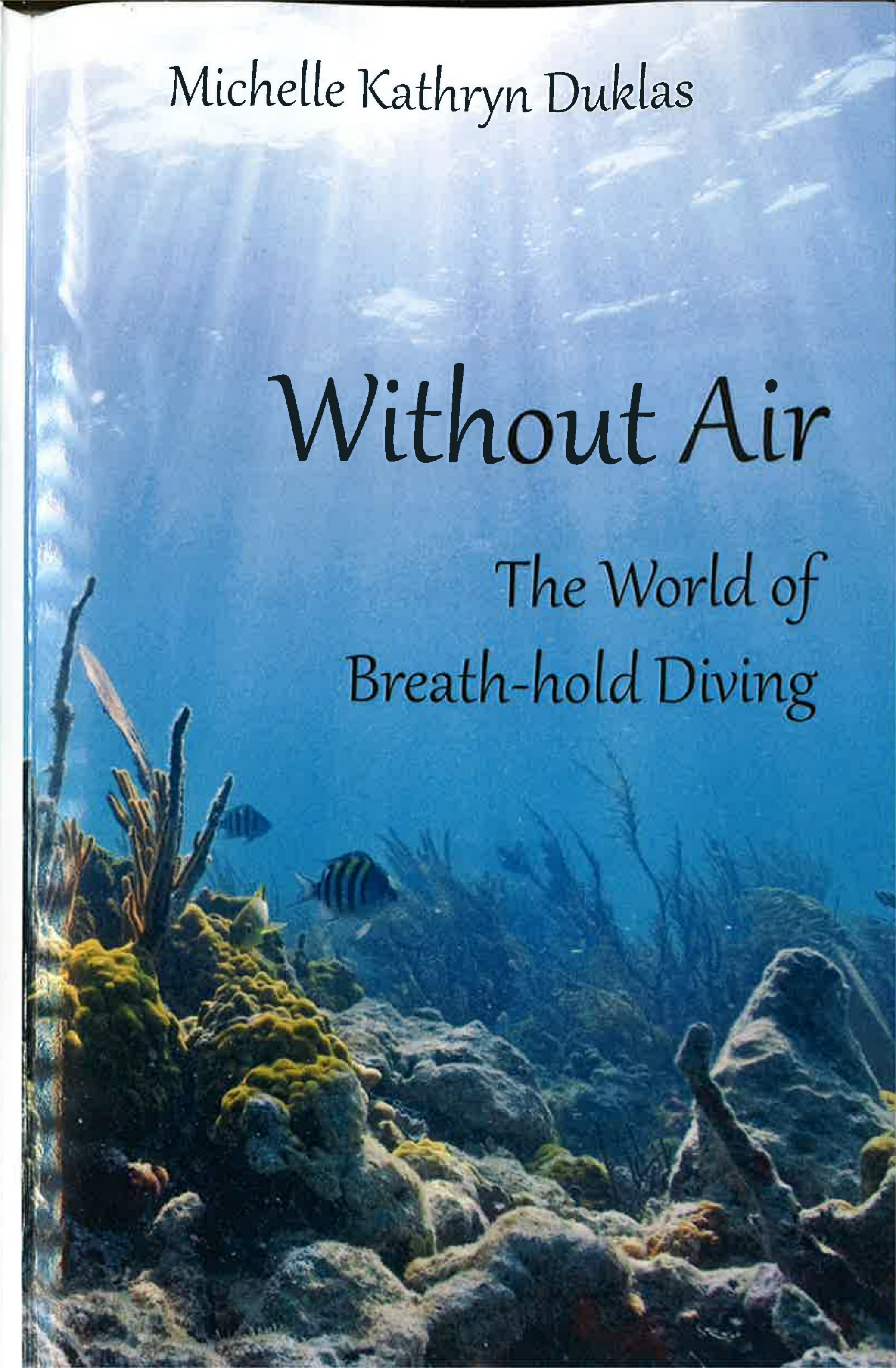

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The World of Breath-hold Diving

Michelle Kathryn Duklas

Life Rattle Press
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This book is research-based science writing. Some of the case studies sourced in this book omitted the names of their subjects. In those cases, I have added names to create more fluency in the writing.

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I dedicate this book to my parents, Irene & Julian Duklas

Dad, thank you for fostering in me a hunger for knowledge
Mom, thank you for teaching me the importance of caring for others

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Contents

Prologue

Every time someone finds out that I've written a book, I always get the same two questions: "Oh, what's your book about?" and "How on earth did you pick that topic?"

I think I've repeated my answer close to fifty times. No one I talk to has ever heard of breath-hold diving before. So sometimes I simply answer that I've written a research-based book about science. Usually the word "science" scares people off and I can avoid further questioning.

Although I'm relieved when the questioning ends, it's sad that people find themselves scared by scientific concepts. Science is a critical part of our lives. We depend on science for our transportation, our food, and for communication and computation, in addition to many other things. Understanding how things work helps us gain a better appreciation for the things themselves. In the case of this book, my hope is that you'll learn more about the human body.

This prologue is for the people to whom I've given a vague answer. I hope to clarify for you what exactly I wrote about and how I arrived at the topic.

Without Air started to take shape through my work in the Professional Writing and Communication program at the University of Toronto. One year before this book came together, I took a course called Science and Writing. For that class, my professor, Dr. Guy Allen, asked us to each pick a science topic to research and write about.

As a former competitive swimmer and lifeguard, I gravitated towards research involving medicine and swimming. Through my lifeguard training, I have learned that rescuers should always attempt CPR or hook the victim up to an AED (automated external defibrillation) machine because there's always the chance that the victim could survive.

For this reason, I initially wanted to research the mammalian diving reflex. I have always been fascinated by stories of children who have survived underwater for long periods of time and recovered with minimal brain damage or injuries.

However, when I started looking into the area of drowning victims making full recoveries, I discovered that the bulk of the research came from the late 1960s and early 1970s. For my class, I needed to find current research, something from 2010, 2011 or 2012.

As I typed in the keywords of "underwater," "drowning," and "survival" into the search engines of all the leading science journals, I found an area I could pursue.

Research was flourishing in the field of breath-hold diving. I had never heard of the concept. I knew nothing about the annual breath-hold diving competitions or about the long legacy of Japanese and Korean Ama divers.

I learned that breath-hold divers have a deep desire to explore the limits of the human body. As I read through the studies conducted by researchers around the world, I was amazed by the fearlessness of the men and women who pursued this sport.

Breath-hold diving is simply a term to describe diving underwater while holding one's breath. Scientists and divers alike use the term to differentiate between scuba divers and breath-hold divers. All divers who hold their breath underwater can be classified as breath-hold divers. Consider that next time you're at the pool!

Those breath-hold divers who participate in competitions are sometimes referred to as freedivers. As the name suggests, freediving means going underwater without an oxygen tank or any other breathing apparatus.

Most sporting organizations classify freediving as an extreme sport, because of the heightened risk for serious injuries and fatalities.

Freediving has eight disciplines. Competitions are regulated by the Association Internationale pour le Développement de l'Apnée (AIDA), a French-led organization that promotes freediving. AIDA runs yearly world championships for breath-hold diving.

The eight disciplines are as follows:

No Limit: This discipline is only used for record attempts and does not run as part of the annual world championships. There are few rules. Divers use a weight to descend and any method of their choice to ascend (usually a balloon). The sole motive for this discipline is to dive deeper than anyone has ever dived before. Herbert Nitsch holds the world record at 214 metres. Nitsch set the record in June 2007.

Variable Weight: Divers use weights to descend in this discipline. The preferred choice of weight is usually a sled. Divers then use their own strength to swim to the surface. Herbert Nitsch has held the world record (162 metres) since December 2009.

Constant Weight: In this discipline, competitors must maintain a constant weight. They can use fins to swim both down and back up. Alexey Molchanov set the world record at 126 metres in November 2012.

Constant Weight Without Fins: This discipline is identical to the Constant Weight competition, except divers cannot use fins. William Trubridge has held the record (101 metres) since 2010.

Free Immersion: This discipline allows divers to use a rope. Normally, the rope directs divers down to their depth and back up to the surface. In most disciplines, touching the rope (except to stop descending) is not permitted. In Free Immersion, divers use the rope the entire time. William Trubridge holds the record at 121 metres. He set the record in 2010.

Dynamic With Fins: One of the two disciplines that must be held in a swimming pool, Dynamic With Fins measures the horizontal length divers can swim underwater. Fins are permitted in this competition. The pool must be a minimum of 25 metres long. In 2010, Goran Čolak set the record at 273 metres.

Dynamic Without Fins: This discipline is the same as Dynamic With Fins, except that divers cannot use fins. Dave Mullins holds the world record at 218 metres. Mullins set the record in September 2009.

Static Apnea: This discipline calculates how long divers can hold their breath underwater. This discipline can run in either open water or swimming pools. Stéphane Mifsud holds the world record at 11 minutes and 35 seconds.

Most of my book focuses on freediving, but I also mention other types of breath-hold divers, such as spearfishers and Ama and pearl divers.

Without Air takes the reader through the history of freediving and an introduction to some of the disciplines within freediving. I discuss some of the main techniques divers use before diving underwater and some of the dangers associated with breath-hold diving. I conclude my book with some stories about breath-hold divers, including a real-life mermaid and the Korean *Halmangbadang*.

Michelle Kathryn Duklas
February 2013

Chapter 1

The Beginning of Breath-hold Diving as a Sport

Courtesy Wikimedia Commons

Raimondo Bucher, at left in 1942 with his first underwater camera, called the "Robot." At right, Bucher wears a home-built diving suit and holds an underwater camera.

In 1949, Italian fighter pilot and spear fisher Raimondo Bucher founded the modern sport of freediving. He announced that he would dive to a depth of 30 metres on one breath of air. Bucher successfully completed his dive outside Naples. He later confessed that his motive for the dive was a 50,000-lire bet, worth $800 USD in current figures, he had with a fellow diver Ennio Falco.

Courtesy Wikimedia Commons

Raimondo Bucher, shown here in 2002 at a conference in Parma, Italy.

Of course, breath-hold diving existed before 1949. It was a way that some used by the Japanese and Koreans earned a living. Those divers would hold their breath as they dived to collect food, shells, and pearls to sell.

The feat no one thought possible

In 1962, Enzo Maiorca, another Italian freediver, became the first person to descend below 50 metres. At the time, medical experts and scientists warned that humans could not survive below 50 metres because of the enormous pressure. Scientists predicted that at 50 metres, human lungs would burst. Maiorca proved them wrong.

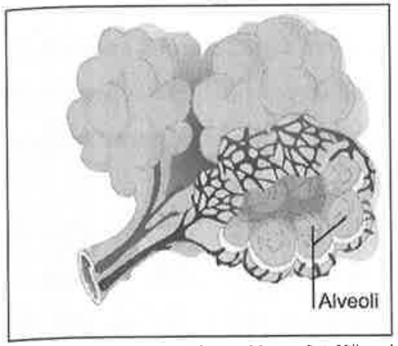
Croft: A revolutionary

In the late 1960s, American Robert Croft joined the sport of freediving, and revolutionized it. A former submarine personnel trainer with the United States Navy, Croft felt the urge to test his limits beyond the 36-meter deep training tank. He also wanted to discover more about human capabilities. He became the first person to dive to 70 metres. Croft developed and honed the skill of lung packing, called *glossopharyngeal insufflation*. Glossopharyngeal insufflation involves a motion, similar to swallowing, that forces more air into the lungs.

Croft allowed researchers to perform tests on him as he trained and competed. Scientists confirmed many of their theories about the mammalian diving reflex and blood shift phenomenon because of him.

What is the mammalian diving reflex?

The mammalian diving reflex theory explains how humans survive underwater longer than expected. When a person's head descends below the surface of cold water, the heart slows. This decrease in heart rate, called *bradycardia*, saves oxygen. Blood vessels in the extremities of the body, such as the hands and feet, close off. This leaves more oxygen for the body's vital organs.



Courtesy Mariana Ruiz Villarreal

The alveoli in the lungs play an integral role in preserving a person's life during deep sea dives.

What is the blood shift phenomenon?

The blood shift phenomenon occurs in the last stage of the mammalian diving reflex. When bradycardia cuts off most of the blood flow to the body's extremities, more blood circulates in the core. This increased flow should cause the blood vessels to bulge and burst, but they don't.

During the blood shift, the body allows blood plasma to fill the lungs' alveoli. Alveoli are cells in the lungs that normally fill with air as humans breathe. The blood shift fills the alveoli with blood, so that as divers descend deeper and deeper below the water's surface, the blood-filled alveoli prevent their lungs from squeezing to the point of bursting. This is similar to imagining what happens to a balloon. To burst a balloon, you stand on it, or squeeze it. But filling the balloon with hard objects such as marbles makes it much harder and almost impossible to burst.

As the diver ascends, the process reverts and the lungs drain the blood back into the circulatory system.

Courtesy Georges Biard

Luc Besson at the 2000 Cannes Film Festival.

When did freediving become popular?

Freediving became more of a world-wide phenomenon after Luc Besson's 1988 film *The Big Blue*. The movie covered the 20-year rivalry between Enzo Maiorca and French freediver Jacques Mayol.

The beginning of AIDA and the freediving world championships

In 1992, French freedivers Roland Specker, Loïc Leferme, and Claude Chapuis started Association Internationale pour le Développement de l'Apnée (AIDA), or the International Association for Apnea Development. *Apnea* is the medical word for breath-holding.

In 1996, AIDA held its first world championships in Nice, France. The most recent AIDA World Championships, in 2012, was held in Nice as well, marking the 20th anniversary of AIDA. Croatia won the men's gold, and Japan won the women's gold medal.

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Chapter 2

Constant Weight No Fins

Courtesy Paolo Valentini

William Trubridge operates a freediving school and annual competition both called Vertical Blue at Dean's Blue Hole in Long Island, Bahamas.

William Trubridge holds the current record for "Constant Weight No Fins" at 101 metres. He set the record on December 16, 2010 in Long Island, Bahamas.

"Constant Weight No Fins," is a regulated freediving discipline. Competitors dive as far as possible without an oxygen tank and fins. Unlike "No Limits" where divers can use weights and balloons, in "Constant Weight No Fins," divers must maintain a constant weight. Competitors swim downwards following a rope. Divers can't hold onto the rope (except to stop descending and start ascending). Freedivers consider this discipline the most difficult because of the physical stamina required. The dive requires a lot of swimming.

What takes place during a "Constant Weight No Fins" competition?

During a world championship, the competition starts the night before the dive. Divers secretly write down how far they will attempt to dive the following day and submit that number to a group of judges. This part of the process involves guessing what number the other divers will submit. Submit a dive too deep, and you may not make it. Submit a dive too shallow, and someone else will beat you.

Courtesy Igor Liberti

William Trubridge swims towards the surface of Dean's Blue Hole, the deepest known blue hole in the world with an entrance below sea level. A blue hole is an underwater sinkhole. Trubridge achieved his world record of 101 metres at Dean's Blue Hole, in Long Island, Bahamas.

"It's like playing poker," New Zealand freediver William Trubridge says. "You are playing the other divers as much as you are playing yourself."

On the day of the dives, judges announce all the divers' submissions before the competition starts.

During the actual dive, competitors must meet many different requirements before the dive is counted as legitimate. Divers descend to the depth that they submitted the night before, and must grab one of the tags attached to a metal plate. By presenting these tags to the judges, they prove that they made it to their submitted depth.

What about if something goes wrong? After all, these divers descend quite deep underwater.

Many different back-up protocols exist so divers can focus on their goals, rather than worry about safety. The major rule in place is that divers must be fully conscious upon reaching the surface of the water. Upon surfacing, judges watch the divers carefully. They look for any signs of post-blackout mechanical movements (PBMM), where the divers' heads bob or drop repeatedly as they go in and out of consciousness. Passing out results in immediate disqualification. For this breach of the rules, divers earn a red card and their dive is not counted.

What is allowed?

Bleeding, for one thing. It's normal for divers to burst blood vessels in their nose and ears during dives.

"The judges don't care how someone looks," CarlaSue Hanson, the media spokesperson for AIDA says. "Blood? That's nothing. As far as the rules go, blood is OK."

Requiring divers to remain fully conscious prevents them from setting unreasonable goals for themselves. Even if they reach those goals, their dive won't count unless they can (1) remove their face mask, (2) show the "okay" sign with their hands, and (3) verbally say "I am okay" all within 15 seconds of finishing a dive. Upon successful completion of those three steps, the diver earns a white card, which validates the dive.

"The rules are there to make freediving safe, measurable, and comparable," says Hanson. "They are set up to ensure that, through the whole dive, the diver is in full control. That's what competitive freediving is all about: control."

What is the biggest concern for freedivers?

A primary concern for freedivers is blackouts. In the case of a blackout, if it occurs around the 18-metre mark, rescuers will pull the unconscious diver to the surface. If divers black out so deep that the rescuers can't reach them, a sonar system attached to the competitor will detect the blackout (i.e. because the diver is not surfacing as fast as he or she should) and the lanyard attached to the diver's ankle will allow surface rescuers to reel the diver up as quickly as possible, in a way similar to reeling in a fish.

Fortunately, the freediving community doesn't look very highly upon those divers who black out.

"Blacking out is like shitting yourself," Sebastian Näslund, Swedish freediver and multiple record-holder says. "It's an embarrassment to you and everyone else around you."

Despite the fact that competitors feel that they aren't putting their life in the hands of a merciless deity when they descend underwater, they are required to sign waivers emphasizing that they understand the potential consequences: heart attacks, blackouts, lung injuries and drowning.

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Chapter 3

Hyperventilation

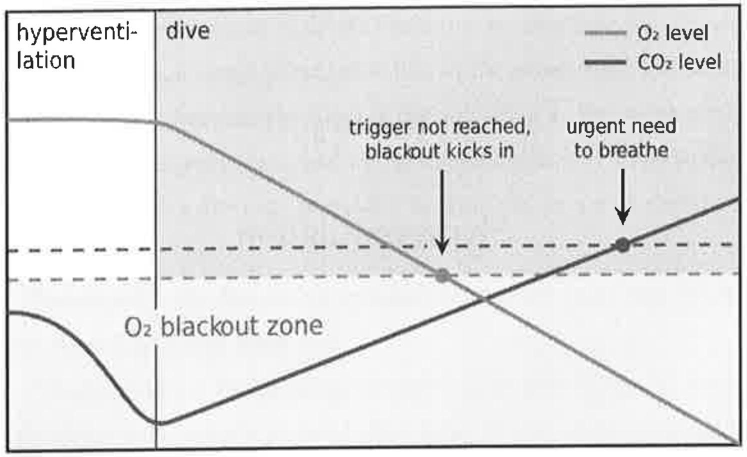
If you attend a spearfishing competition, a freediving championship or watch an Ama or pearl diver at work, you'll notice that many divers hyperventilate before they go underwater.

Hyperventilation involves breathing faster than usual and deeper than usual. The medical term for hyperventilation is *hyperpnoea*.

What does hyperventilation do for a breath-hold diver?

Hyperventilating for a short period of time can help a breath-hold diver remain underwater longer than he normally would. Hyperventilation decreases carbon dioxide levels in the bloodstream. High carbon dioxide levels, not low oxygen levels, trigger the need to breathe.

Inexperienced divers will notice that their lungs start to burn quite quickly, even after 15 seconds underwater. Their bodies are very sensitive to carbon dioxide levels. By hyperventilating and decreasing carbon dioxide levels in the blood, divers can trick their brains into holding off the physical triggers, such as an urgent desire to breathe. The body must replenish its carbon dioxide levels. This takes time and usually doesn't occur until the body is very close to running out of oxygen.



Courtesy Wikimedia Commons

In this image, the oxygen line dips below the blackout line before the carbon dioxide rises high enough to trigger the urgent need to breathe. This happens because hyperventilation lowers the body's carbon dioxide levels.

Does hyperventilation have any special qualities?

In 1987, the Center for Research in Special Environments at the State University of New York at Buffalo performed a study on hyperventilation. The researchers wanted to know if it was the act of hyperventilation or simply the low carbon dioxide levels achieved that led to a less intense urge to breathe. After testing five male breath-hold divers, they discovered that hyperventilation provides no useful benefit outside of decreasing carbon dioxide levels in the blood.

Hyperventilation and euphoria

When practiced right, hyperventilation can lead to a sense of euphoria and well-being. This can trigger feelings of confidence in divers, and

lead them to stay underwater much longer than they should.

Does hyperventiliation store oxygen?

Hyperventilation does not store extra oxygen. In fact, if divers hyperventilate for too long, they rob their bodies of valuable oxygen needed to complete a long or deep dive. They can also develop symptoms such as dizziness and muscle cramping.

Can divers predict how many times they should hyperventilate?

It is also impossible to calculate how many inhalations is "safe" and won't induce blackouts. A study published in *Respiration Physiology* in June 1973 reported that after studying eight breath-hold divers, the researchers could not predict how many hyperventilating breaths each of them should take before diving.

In 1970, French researcher Raymond Sciarli proposed observing how long a diver hyperventilated. He suggested that researchers note when the divers lost consciousness, and then to recommend hyperventilating for one third of that time.

The researchers in the 1973 study put Sciarli's theory to the test. They found that the divers suffered underwater blackouts after hyperventilating for different lengths of time. In some cases, hyperventilating didn't even increase the time a diver could spend underwater.

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Chapter 4

Diving Bradycardia

A trained breath-hold diver jumps into the water. He pulls himself underneath the surface and starts to swim. He holds his breath. His heart races. After fifteen seconds of swimming underwater, his heart rate drops. Why did this happen?

Patrick Butler and Anthony Woakes from the University of Birmingham in England researched the connection between the diving reflex and exercise. The diving reflex triggers a physical reaction within a diver that helps them survive longer underwater. Butler and Woakes found that in the first ten to 15 seconds of un-

Courtesy James Heilman

Courtesy Wikimedia Commons

These charts show abnormal heart rhythms. The image on the left shows bradycardia, a heart rate lower than 60 beats per minute. The image on the right shows tachycardia, a heart rate over 100 beats per minute. The average adult human heart beats 60 to 80 times per minute.

derwater swimming, a swimmer's heart rate exhibited *tachycardia*. Tachycardia refers to a heart rate higher than the average resting heart rate of 72 beats per minute. After 15 seconds, the swimmer's heart rate started to decrease. It dropped lower than before the swim occurred. Low heart rate is called *bradycardia*.

How is bradycardia triggered?

Direct contact with cold water to the forehead, eyes and nose, combined with breath-holding triggers bradycardia. A regular heart rate is 72 beats per minute. Diving bradycardia usually reduces the heart rate to 45 to 60 beats per minute. Elite breath-hold divers and young children can develop bradycardia below 20 beats per minute. Elite athletes can train their heartbeat to slow down to 20 beats per minute through gradual training. Young children, on the other hand, seem to have a natural bradycardic response. This gives them a better chance at surviving a possible drowning.

The longer a dive, the more pronounced the diving bradycardia. This occurs because the body reacts to lower oxygen levels. Lower oxygen levels trigger chemical receptors in the body's arms and legs to activate. These receptors release chemicals, slowing the heart even more.

How does diving bradycardia benefit a swimmer?

Courtesy Wikimedia Commons

A diagram of three blood vessels. Notice that the image in the middle has a smaller opening. This does not allow as much blood to pass through the blood vessel.

Diving bradycardia triggers vasoconstriction. Vasoconstriction causes the blood vessels of the heart to tighten and con-

tract. Vasoconstriction redistributes blood flow. Vasoconstriction reduces the amount of blood—and therefore oxygen—sent to the body's arms and legs. This saves oxygen for the heart and the brain. By saving oxygen for the heart and the brain, the body extends the time before serious damage, such as brain damage, occurs from a lack of oxygen.

What is the best temperature to trigger bradycardia?

Water temperature affects the severity of diving bradycardia. The lower the water temperature compared to the air temperature, the more severe the bradycardia. Immersion in water between ten degrees and 15.8 degrees elicits the strongest bradycardic response and the most noticeable decrease in heart rate.

Water temperatures under ten degrees induce tachycardia, called a 'cold shock response,' instead of inducing bradycardia. The cold shock response triggers the body to breathe. The urge to breath decreases the amount of time swimmers can hold their breath for.

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Chapter 5

Glossopharyngeal Insufflation

A 22-year-old male breath-hold diver, let's call him Greg, hyperventilates. Greg inhales completely, opens the airway to his lungs and forces additional air into his lungs through a manoeuvre that resembles swallowing. He pumps his cheeks and tongue to push more air into his lungs. Greg holds his breath. Ten seconds later, he loses consciousness.

Fortunately for Greg, he's at a clinical research lab at Lund University in Sweden. He's there for a study researching a breathing technique divers use before attempting breath-hold diving. The lead experimenter, Johan Andersson, intervenes and opens Greg's airway by tilting Greg's head backwards. Thirty seconds after breath-holding, Greg spontaneously regains consciousness. He exhibits no symptoms and no after-effects from the incident. What happened?

Freedivers aim to hold their breath for as long as possible underwater, daring to test their body's limits. One of the obstacles in their way is pressure. Water pressure puts more pressure on the human lungs than air pressure does. When a freediver descends deep underwater, the air in their lungs condenses due to the excess pressure.

Divers use a method colloquially called "lung packing" to increase the amount of oxygen they intake. Lung packing takes practice.

What is glossopharyngeal insufflation?

Scientists refer to lung packing as *glossopharyngeal* (glo-SO-fa-ryn-GEE-uhl) *insufflation* (GI). GI overfills a competitive breath-hold diver's lungs above total capacity by up to 47%. GI increases the available oxygen divers have to store in their bodies. These divers equalize the pressure inside and outside their bodies by slowly releasing air from their lungs as they surface.

Packing blackouts

GI also leads to a loss of consciousness that breath-hold divers call a "packing blackout." Packing blackouts occur because the body loses the oxygen it needs to function properly. GI raises the pressure inside and around the lung. It also compresses the heart, in some cases the left side of the heart, or in other cases the whole heart.

Injuries from GI

Divers who perform GI risk developing high blood pressure in their pulmonary arteries. This leads to the enlargement of the heart. Breath-hold divers can experience the bursting of their blood vessels into the lungs. Such injuries occur when divers swim deep underwater. Their lungs squeeze because of the pressure difference, their blood vessels rupture, and blood pours into their lungs.

Can GI prevent barotraumas?

In a 2005 study published in the *European Journal of Applied Physiology*,

Swedish scientists Peter Lindholm and Sven Nyren argue that GI might decrease the risk of developing barotraumas. A barotrauma occurs underwater and refers to any injury that occurs due to pressure, such as burst eardrums or arteries.

Lindholm and Nyren write that when divers pack their lungs beyond total lung capacity, they may protect their lungs from damaging as they descend underwater. Because depth leads to greater pressure, the deeper a diver swims, the more their lungs squeeze. If their lungs have more air inside, the air will prevent their lungs from squeezing excessively.

To increase lung volume above normal total lung capacity, divers performing GI must overcome pressure in the lungs and expand the rapidly stiffening lung. This requires substantial pressure. Discomfort limits the air that a diver can pack into his lungs beyond total lung capacity, but consistent training can loosen the lungs and alleviate discomfort.

Why do divers practicing GI have a high risk of fainting?

Ralph Potkin from the University of California at Los Angeles examined five elite breath-hold divers. After performing GI, the divers' heart rates increased from 53 beats per minute to 100 beats per minute and their blood pressure decreased from 112mmHg to 75 mmHg. The spike in heart rate and decrease in blood pressure can lead to light-headedness and loss of consciousness.

GI causes the heart to pump less blood through the arteries and leads to low blood pressure. When less blood flows through the arteries, the heart can't deliver enough oxygen to the brain and other vital organs. The person loses consciousness from a lack of oxygen, a condition called *hypoxic syncope*.

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Chapter 6

Passive Equalization

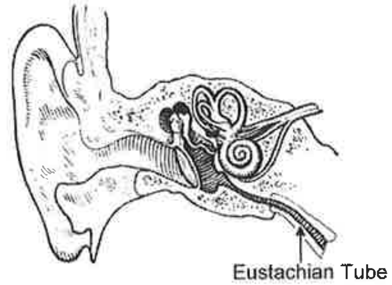
Preventing Barotraumas 200 Metres under the Sea

Belgian freediver Patrick Musimu breathed in, filled his lungs with air and descended below the surface of the water. He held onto a metal sled and propelled downwards. He wore a belt attached by a metal ring to a rope that led down into the darkness. After two and a half minutes, he reached 209 metres below the surface of the water. Musimu broke the world record by almost 40 metres when he reached that depth in 2005.

That far below the surface, the high-pressure difference should have given him an excruciating headache. He may have even lost consciousness. But Musimu trained to avoid pressure differences when breath-hold diving. He used a technique called passive equalization.

What is passive equalization?

Some breath-hold divers use a technique called passive equalization to balance the pressure inside and outside their bodies. They keep their nostrils open as they descend and allowing water to enter their nose and fill the maxillary sinuses and Eustachian tubes. The maxillary sinuses are cavities inside a person's cheekbones. These cavities, normally filled with air, drain into the nose. A person sick with the common cold may feel pain in this area as it fills up with mucus. The Eustachian tubes connect the middle ear to the back of the throat.

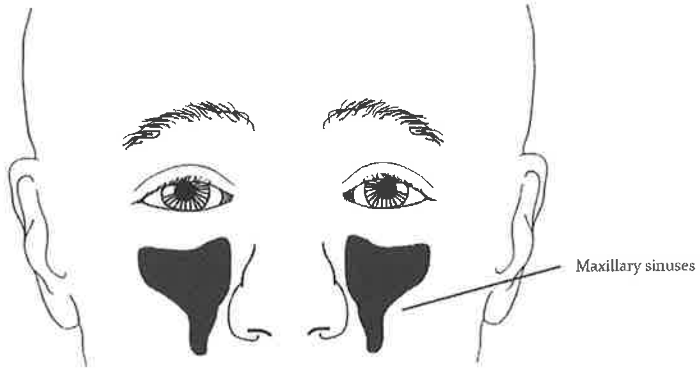


Courtesy Pearson Scott Foresman

The Eustachian tubes normally remain closed in humans, but can open slightly to equalize the pressure between the middle ear and the air (or water) outside.

These areas can fill with water during passive equalization because as divers descend, the air volume in their body cavities decreases. Water rushes in to fill the empty space. Swimmers usually stop this from happening by breathing a constant stream of air out of their nose.

Passive equalization requires training. Normally, introducing water into the nasal cavity and middle ear produces sneezing and pain, as the body tries to rid itself of the water. It may even cause panic in the diver. It takes frequent training and focused mind power to counter this bodily reflex.

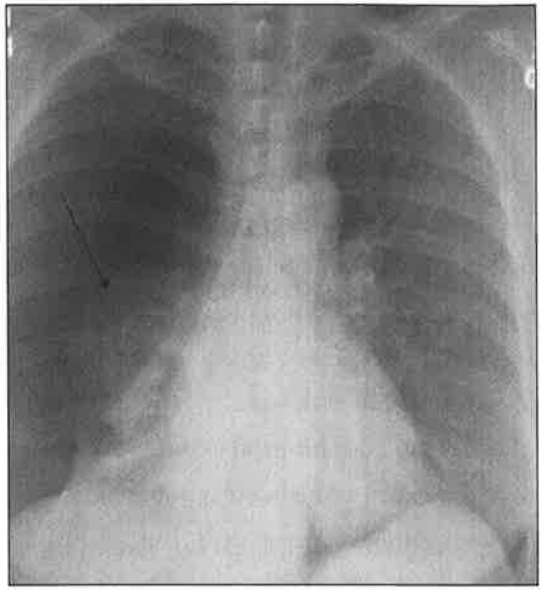


Courtesy Michal Komorniczak

The maxillary sinuses are the largest of the paranasal sinuses. The paranasal sinuses are air-filled cavities located in the head.

Why do divers need to equalize the pressure inside and outside of their bodies?

If pressure does not remain equal inside and outside the body, barotraumas form and injure body tissues. Barotraumas, also called pressure injuries, occur because air compresses, but bodily tissues don't. The pressure outside the body increases, but air space inside the body decreases as the body descends further underwater. Nosebleeds, a common form of barotraumas, often occur in breath-hold divers. More serious forms of barotraumas include burst eardrums and collapsed lung(s).



Courtesy James Heilman

An X-ray of a collapsed lung. The black arrow points to the edge of the collapsed lung.

Does passive equalization have risks?

Breath-hold divers risk infection when they use passive equalization. Breath-hold divers perform their dives in open water. Open water, such as lakes and oceans, provide a perfect breeding ground for pathogens such as bacteria. Water takes two or more hours to completely drain from the nasal cavity and middle ear after passive equalization. During this time, the pathogens can reproduce and infect the body before the cavities empty completely. In addition, passive equalization destroys the naturally forming mucus in the middle ear. This mucus protects the ears from most pathogens, but when destroyed, the body limits its effectiveness at keeping pathogens at bay.

Current Research

Musimu, along with colleagues Simon Germonpré and Constantino Balestra, published a study reporting on his research in June 2011. Germonpré and Balestra took an MRI scan of Musimu's nasal cavity and middle ears. They scanned his head both before and after Musimu filled the cavities with water.

Musimu filled his nasal cavities with water by pouring regular tap water into each of his nostrils and moving his head around until he filled up both nostrils.

Tragedy

One month after the *British Journal of Sports Medicine* published his article on passive equalization, Musimu's wife and daughter found him dead after training alone in his home pool. Medical examiners did not release the official cause of death to the public. Musimu was 40 years old.

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Chapter 7

Taravana & Decompression Sickness

On the Tuamotu Islands in French Polynesia, pearl divers scouring the depths of the Takatopo Lagoon often suffer from *Taravana*, a Paumotan word meaning "to fall crazily." Pearl divers affected by Taravana display neurological symptoms such as dizziness and impaired vision—for example, they see their hands as disproportional to their bodies. Taravana isn't limited just to French Polynesia, though. In the Western world, we call this

Courtesy Albert Herring

A pearl farm off the cost of the Tuamotu Islands.

condition decompression sickness.

For much of the last century, scientists thought that breath-hold divers couldn't develop decompression sickness because they didn't spend enough time underwater. In the last decade, scientists found evidence that breath-hold divers do suffer from decompression sickness.

What is decompression sickness?

Decompression sickness, also known as the bends, occurs when nitrogen gas forms bubbles in the bloodstream. When a diver ascends too quickly to the surface, the cardiovascular system doesn't have time to rid itself of the nitrogen. Nitrogen builds up in the lungs, bloodstream and body tissues. Decompression sickness is a relatively rare condition most commonly associated with scuba diving.

Decompression sickness has a variety of symptoms. Symptoms include nausea, vomiting, headaches, lethargy and partial loss of limb movement. More serious effects may include severe chest pain, paralysis, coma and death.

Decompression sickness and breath-hold diving

The risk of suffering from decompression sickness increases based on dive depth, how fast the diver descends, how fast the diver ascends, and how long the diver waits between dives. The wait time between dives has a huge impact.

In 1965, Dr. Paulev, from the University of Aarhus in Denmark, published a revolutionary discovery. Paulev, a Danish naval medical officer, helped train Navy recruits in a submarine escape training tank at Haakonsvern. Haakonsvern is the main naval base for the Norwegian navy, located near the large city of Bergen.

The recruits performed a breath-hold dive in a submarine escape training tower, simulating the rescue technique used to escape from a disabled submarine. Paulev accompanied the divers as he trained them to perform the breath-hold dive. The divers began at the bottom of the tower, climbing in through a pressurized tank at the bottom. Their training required them to swim to the top of the tower. They did this while constantly releasing a stream of air out of their mouths so as to avoid damaging their lungs.

Courtesy Wikimedia Commons

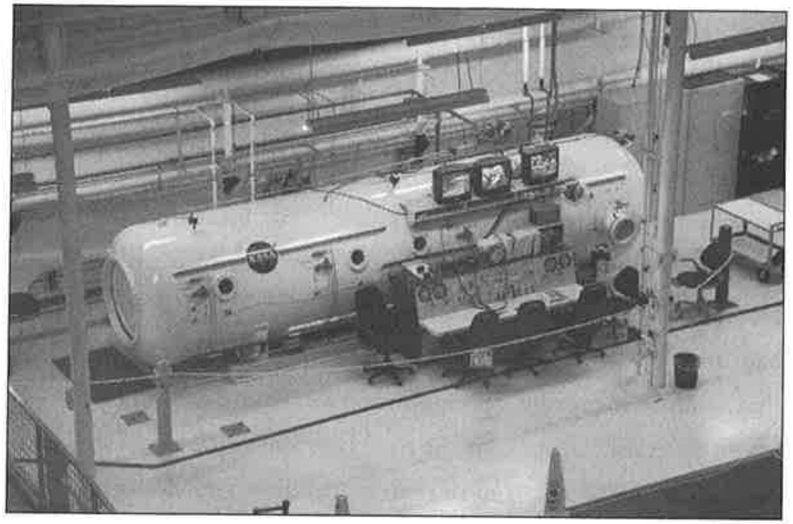
Divers inside the Submarine Evacuation Training Tower (SETT) in Portsmouth, United Kingdom. Since the discontinuation of training for submarine disasters in March 2009 (due to the increase in submarine safety), the SETT has been used primarily for freediving practice and underwater equipment testing.

Afterwards, Paulev felt symptoms of decompression sickness. He measured the nitrogen in his blood and realized that the amount of nitrogen in his blood equalled that of a continuous dive, despite the fact that he had breathed in between each dive. In his paper, Paulev explained that in order to prevent decompression sickness, divers must rest between dives for longer than the time they spend underwater. Divers can eliminate the nitrogen in their blood through exhalation.

Pearl divers in Polynesia commonly develop decompression sickness because they dive to depths of 30 metres every two minutes for a total of five hours. These divers don't spend enough time between dives to rid their bodies of the nitrogen that builds up in their blood and tissues and thus develop symptoms.

Paulev's study created controversy when he first published it. Other scientists didn't want to believe that divers could develop decompression sickness even if they weren't breathing compressed air from a scuba tank. In the past two decades, other scientists have started to accept Paulev's findings.

Breath-hold divers may experience worse decompression sickness than scuba divers. Breath-hold divers tend to ascend at more than 1.5 metres per second—much faster than the recommendations set out by medical professionals for scuba divers. Because breath-hold divers need to reach the surface quickly to breathe, they have less time to rid their bodies of nitrogen than scuba divers do.



Courtesy Michael Renlund

This image shows the NASA decompression chamber at the Neutral Buoyancy Lab. Decompression chambers expose people inside to 100 percent oxygen and flush out nitrogen from the bloodstream.

How do doctors treat decompression sickness?

To treat decompression sickness, divers inhale 100 percent oxygen in a hyperbaric chamber for the amount of time prescribed by a physician. The oxygen enters the bloodstream and flushes out the nitrogen through divers' lungs when they exhale.

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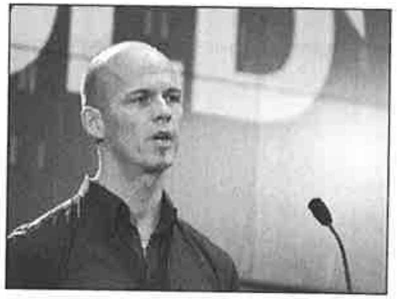
Chapter 8

Brain Damage

Breath-hold divers compete in one of the most intense and dangerous arenas on the planet—underwater. Breath-hold divers take huge risks participating in their sport.



Courtesy Eirik Solheim

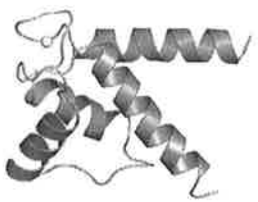
Forty-two-year-old Herbert Nitsch works as a pilot, but his real passion is in breath-hold diving, where he holds the title "Deepest Man on Earth."

AIDA monitors world records for breath-hold diving. Austrian diver Herbert Nitsch holds the record for the deepest breath-hold dive at 214 metres below the surface of the water. Stéphane Mifsud of France holds the record for the longest breath-hold dive. He held his breath for 11 minutes and 35 seconds. Irreversible brain damage normally sets in at six minutes and solidifies at eight to ten minutes. But Mifsud survived with no noticeable brain damage. These amazing feats truly show the accomplishments of humankind to explore the boundaries of our limitations. But does breath-hold diving pose any outstanding risks to the brain? Does the lack of oxygen reached through breath-hold diving cause permanent brain damage?

Dr. Johan Andersson and his colleagues Dr. Mats Liner and Dr. Henrik Jonsson published a study in 2009 about brain damage risks caused by breath-hold diving. Dr. Andersson and his colleagues hypothesized that they would find increased levels of S100B proteins in breath-hold divers with the lowest levels of oxygen in their system.

What is S100B?

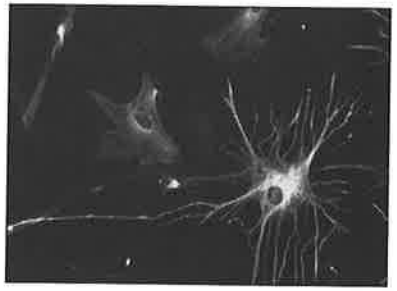
S100B is a member of the S100 family. S100 proteins get their name because they dissolve in 100% saturated ammonium sulphate solution.



Courtesy http://www.ebi.ac.uk/

Image of an S100 protein.

Star-shaped glial (GLEE-al) cells in the brain, called *astrocytes,* produce S100B. Glial cells work as the "glue" of the brain. Glial cells hold neurons in place and provide them with food and oxygen.

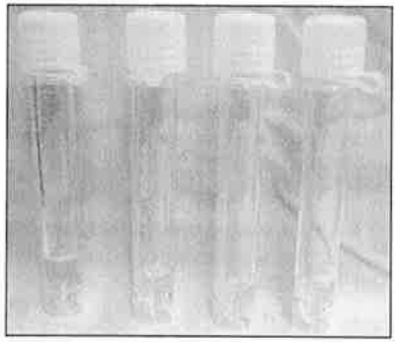


Courtesy Bruno Pascal

This picture of a human astrocyte comes from a 23-week-old fetal brain.

Inside the cell, S100B regulates metabolism. Outside the cell, S100B induces cell suicide, called *apoptosis* (AY-pop-to-sis).

Doctors measure S100B to diagnose brain damage. Doctors find the



Courtesy James Heilman

Vials filled with cerebrospinal fluid.

highest levels of S100B in people with brain trauma. Brain trauma usually occurs in victims of strokes, brain tumours, severe head injuries or multiple sclerosis. Patients with the highest levels of S100B in the fluid surrounding the brain and spine, called *cerebrospinal fluid,* have the worst brain damage.

S100B and Breath-Hold Diving

S100B levels spiked significantly in seven of the nine breath-hold divers in the 2009 study by Dr. Andersson. The increase ranged from 17 percent to 167 percent. These divers participated regularly in breath-hold competitions. The levels of S100B dropped back down to normal within an hour and a half after the divers resumed breathing.

Dr. Andersson and his colleagues explain that S100B levels spike because the body lacks oxygen. Scientists don't know how S100B levels increase in the bloodstream. Dr. Andersson speculates that the blood-brain barrier leaks S100B into the bloodstream. The blood-brain barrier separates cerebrospinal fluid from the bloodstream. The blood-brain barrier protects the brain from bacteria and other large and harmful molecules in the blood.

This study provides good news for freedivers and other breath-hold divers. Andersson's study found levels of S100B much lower than those in brain-damaged patients and ischemic stroke victims.

Still, Andersson, Liner and Jonsson's paper warns athletes to take precautions. Continuous training can lead to S100B build up and damage the brain over time.

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Chapter 9

Meningitis and Breath-hold Diving

A 63-year-old British tourist, let's call him John, travelled to the British Virgin Islands for a two-week vacation. John spent his holiday breath-hold diving in the ocean, admiring the yellow, red and orange coral and the puffer fish and barracudas. He dived to depths of ten to 12 metres up to twice a day while on vacation.

Just before he returned home, he developed a slight earache. After he returned to the U.K., John's earache worsened. Discharge poured from his left eardrum and a red rash formed on his left ear. He had difficulty hearing.

Four days after returning, John developed a severe headache. He started feeling tired and lethargic. He developed a fever. His neck grew stiff. Bright lights hurt his eyes. He had difficulty walking and he could not straighten his legs without pain. John checked himself into the hospital. What happened?

Doctors ran multiple tests. Initially, they presumed that John simply had decompression sickness, a common side effect of diving. However, more testing revealed that John's kidneys weren't functioning properly.

Courtesy Wikimedia Commons

A positive Babinski reflex. The big toe jerks upward when a reflex hammer is run along the bottom of the foot.

Doctors tested John for the Babinski reflex. The Babinski reflex tests for signs of spinal cord or brain infection. The doctors ran a reflex hammer up the bottom of John's foot. A negative, or normal, response occurs if the patient's toe curls downward towards the bottom of his foot. His largest toe jerked upward. John had a Babinski reflex.

The doctors performed a lumbar puncture to detect meningitis. They inserted a long thick needle into John's spine between the vertebrae in his lower back. Regular cerebrospinal fluid should be clear, like water. John's lumbar puncture revealed cloudy cerebrospinal fluid. He had bacterial meningitis.

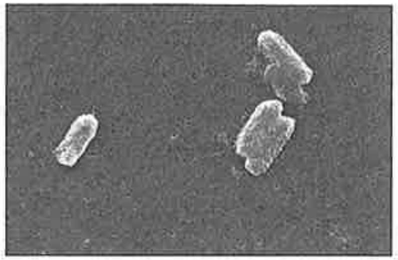
Courtesy Gabriel Rodriguez Alberich

Image of a doctor performing a lumbar puncture.

Doctors used the sample of the cerebrospinal fluid to grow a bacterial culture and determine what type of bacteria John had. They also prescribed antibiotics. John's fever dropped and his temperature returned back to normal within 24 hours. Four days after his admission to the hospital, the cerebrospinal fluid culture grew into Citrobacter koseri.

What is Citrobacter koseri?

Citrobacter koseri bacteria commonly grow in water and soil. In humans, they multiply in the intestines and cause infections in the urinary tract, lungs, abdomen and central nervous system. C. koseri meningitis commonly infects children, but it rarely occurs in adults.



Courtesy Centre Disease Control and Prevention

An image of a Citrobacter bacteria. This image shows the Citrobacter freundii, a member of the same genus as C. koseri. These bacteria rarely cause problems for humans.

Adults develop C. koseri meningitis if their immune systems have been suppressed. Immune system suppression allows for the spread of bacteria through the bloodstream. The bloodstream carries the bacteria to the brain. Here it crosses the blood-brain barrier, invades brain cells and causes symptoms, like those that John displayed. Meningitis can also take hold in adults who have recently undergone brain surgery or who have brain tumours.

Courtesy Wikimedia Commons

An MRI scan of a person diagnosed with meningitis. The best test for diagnosing meningitis is a lumbar puncture. MRI scans may not always be accurate because everyone will show signs of major swelling.

Citrobacter koseri meningitis and freediving

Diving leads to pressure changes in the middle ear. The pressure changes can give the C. koseri bacteria access to the brain. Barotraumas injure tissues throughout the body, but most commonly in the head and chest. Barotraumas occur when the pressure cannot equalize inside and outside the body. The middle ear and the surrounding areas swell with blood.

C. koseri from sea water likely gains access to the middle ear when the naturally secreted mucus from inside the ear deteriorates. From there, the bacteria can infect the upper wall of the ear and spread to the brain.

What happened to John?

With treatment, John's inflammation decreased and his kidneys recovered. Fourteen days after admission, the hospital discharged him. John had slight stroke-like symptoms on the left side of his body and mild hearing loss. These symptoms are permanent. Doctors discouraged him from future participation in any diving-related water sports for the rest of his life.

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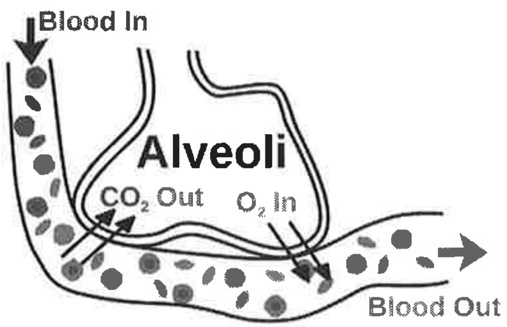
Chapter 10

Ultrasound Lung Comets

A doctor presses an ultrasound probe against his patient's chest. He looks at the monitor in front of him. He sees the lungs. Then he sees something strange. It resembles a comet. The 'comet' stretches from the top of the lung to the bottom. What is this strange phenomenon?



Courtesy Wikimedia Commons

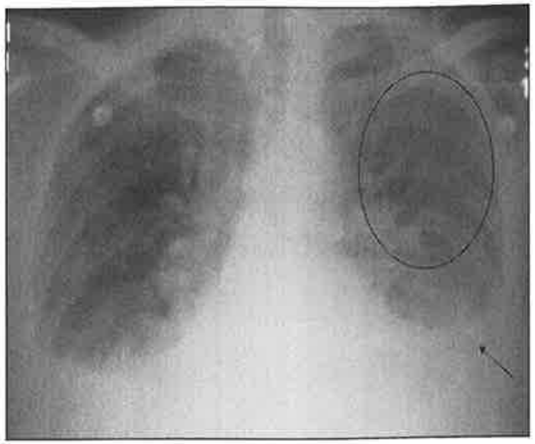
The blood-gas barrier, also called the alveolar-capillary barrier, prevents air bubbles from forming in the bloodstream, and prevents blood from entering the lungs. As blood passes by alveoli, carbon dioxide leaves the bloodsteam, and oxygen enters.

Transferring oxygen from the lungs to the bloodstream

The human body contains a fascinating mechanism for transferring oxygen to the bloodstream.

This thin membrane, called a blood-gas barrier, transfers oxygen from the lungs into the bloodstream.

When humans hold their breath underwater it triggers a diving reflex. The diving reflex includes a heart-brain circuit, where the majority of the body's blood flows in a circle from the heart to the brain. The heart-brain circuit ensures that the body's most precious resource—the brain—has oxygen for as long as possible. However, the heart-brain circuit puts pressure on the blood vessels closest to the heart, including the lungs. The blood vessels expand. When a vessel reaches its limit, it undergoes stress failure. The vessel bursts and blood flows into the lungs, causing acute pulmonary edema.



Courtesy James Heilman

This images shows an X-ray of a person with pulmonary edema. The circle shows the enlarged veins and the arrow points to a pleural effusion (a buildup of fluid between layers in the lung).

To diagnose acute pulmonary edema, doctors perform ultrasound tests. Ultrasound detects high frequencies within the body using sound waves. On an ultrasound, acute pulmonary edema shows up as an ultrasound lung comet (ULC). However, since even a small amount of lung fluid can produce a large "comet tail" image, ULCs cannot indicate significant pulmonary edema.

What are ultrasound lung comets?

Ultrasound lung comets (ULCs), named for their shape, signal extravascular lung water (EVLW). EVLW, a misnomer, does not signify the presence of water in the lungs. Rather, it refers to fluid build-up, such as blood or mucus. The build-up thickens the tissues at the bottom and sides of the lungs.

Why is EVLW harmful?

EVLW indicates acute pulmonary edema. Divers with acute pulmonary edema have trouble breathing and usually cough a lot. Their breathing will usually be shallow. EVLW distresses the membrane that prevents water and blood from entering into the lungs. This disrupts the oxygen exchange from the lungs to the bloodstream. When the heart does not receive the proper amount of oxygenated blood from the lungs, it has difficulty pumping blood. The presence of EVLW leads to a decrease in the amount of blood that the heart pumps through the arteries.

ULCs and Breath-hold Divers

Kate Lambrechts and her colleagues in Brussels, Belgium analyzed ultrasound lung comets (ULCs) in breath-hold divers and published their findings in February 2011. Forty-two healthy people performed breath-hold diving in different conditions.

For the test, atheletes performed dynamic surface apnea. The athletes breathed in deeply and swam as far as they could horizontally under water just below the surface. They also did no-limits freediving, consisted of a weighted sled for descent as far down as they could go and an inflated air balloon to aid surface ascent. Dynamic surface apnea requires stressful physical effort while no-limits free-diving requires little physical activity and focuses on the ability to cope with high water pressure and descending and ascending as quickly as possible.

The divers performed static (staying still) breath-hold dives in two ways. One time they lay face-down in the water and held their breath as long as possible. On another day, the same subjects made ten successive static dives of 30 seconds with 30 seconds of rest between each one. Both of these types of breath-holding don't require any physical activity. Despite this, during the "struggle phase" of the dives, seven of eight of the subjects underwent intense involuntary diaphragmatic contractions.

What is the struggle phase?

The "struggle phase" occurs at the end of dives. As the name suggests, the struggle phase mentally challenges a breath-hold diver. Divers enduring a struggle phase feel intense involuntary diaphragmatic contractions.

The diaphragm muscle separates the lungs and heart from the intestines. The diaphragm helps the lungs move oxygen in and out of the body. The diaphragm contracts to let oxygen enter the lungs. Underwater diaphragmatic contractions mimic the lung movement that takes place when humans breathe. This movement creates an intense longing in the diver to breathe.

Hold your hand over your nose and mouth and try to breathe in. After doing this for only a few seconds, you will start to feel lightheaded and crave oxygen. Imagine this feeling underwater. This can lead to a sensation of panic and fear and the diver often stops breath-holding and surfaces.

Diaphragmatic contractions progressively increase in frequency and intensity the longer a breath-hold diver fights to stay underwater. The struggle phase facilitates the movement of fluid into the lung.

What did the study find?

Lambrechts evaluated the number of ultrasound lung comets (ULCs) appearing in each participant's chest using an ultrasound scan of the chest before and after each diving session. ULC scores increased significantly for most subjects. Breath-hold diving has a significant effect on EVLW accumulation.

What causes EVLW accumulation?

Lambrechts hypothesized EVLW would accumulate in divers performing deep water immersions because the blood vessels would burst from the stress and pressure of deep dives. Lambrechts found no significant difference between the two groups in terms of the increase in ULCs resulting from two types of dives: active surface apnea and no limits freediving. For this reason, she concluded that deep diving during breath-hold diving does not automatically lead to EVLW accumulation.

Just a few months later, Alain Boussuges and his colleagues found similar findings in their study of ULCs in underwater fishermen. They noticed that repeated breath-hold diving could also increase the risk of developing ULCs. Boussuges speculates ULCs develop in underwater fishermen because they swim vigorously underwater.

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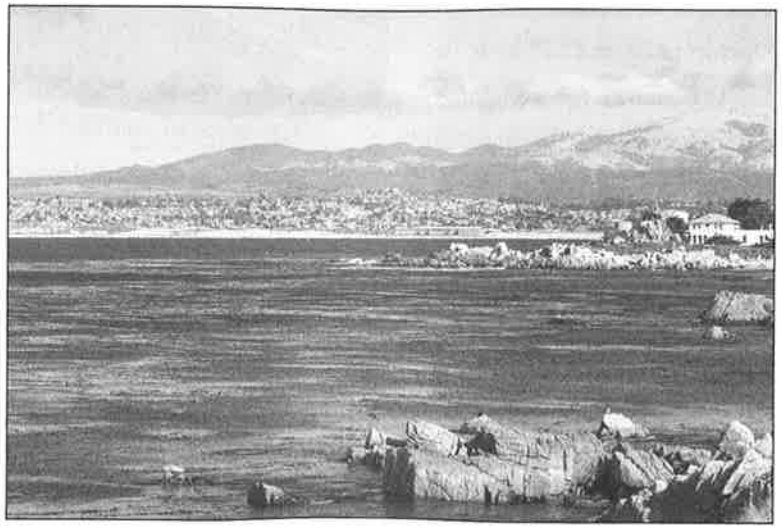
Chapter 11

Lung Cancer Survivors Discouraged from Breath-hold Diving

David, a 60-year-old breast cancer survivor, dives in the frigid waters of Monterey Bay, in northern California. He holds his breath for a minute and a half each time he descends.



Courtesy Wikimedia Commons

A picture of the southern side of Monterey Bay.

He swims along the bottom of the 13-metre-deep waters. His daring adventure turns scary as he emerges from his fifth dive.

He surfaces and notices a slight pain in his chest. He wheezes. Over five minutes, he coughs up four tablespoons of blood.

Ten months before David's diving adventure, doctors surgically removed a serious and advanced form of cancer in his left breast. Following his surgery, doctors treated him with chemotherapy to ensure that all the cancer was gone. A former smoker, David quit when he learned he had cancer.

Four hours after David coughs up blood, he checks himself into the hospital. Although he reports feeling well and doesn't appear distressed, the emergency room doctors perform tests. They want to know what happened.

A chest x-ray shows irregularly shaped patchy spots on the upper part of his chest that weren't there six months earlier. Doctors perform a CT scan.

Courtesy Nithin Rao

Image of a CT scanning machine.

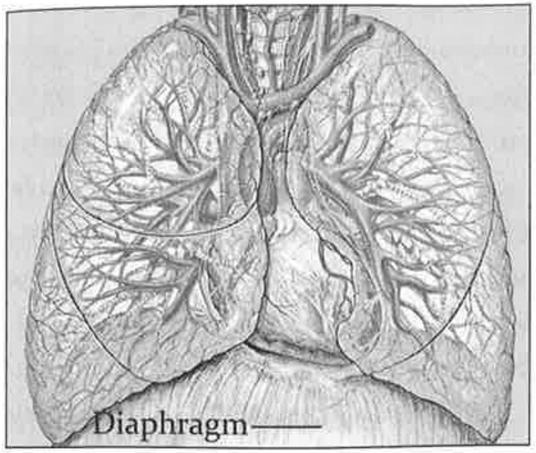
CT stands for computed tomography. CT scanning machines take dozens of x-rays from different angles and a computer puts them together in 3D. David's CT scan shows *ground glass opacification* and *subpleural reticular opacities* on the left upper part of his chest. Ground glass opacification refers to hazy spots that appear on the inside of the lung. These hazy spots show up when there is something besides air in the lung. It could be blood, pus or mucus, in addition to other substances. In David's case, the hazy spots likely represent blood. Subpleural reticular opacities form a mesh-like spotting on the outer parts of the lung.

Luckily for David, the CT angiogram doesn't show a pulmonary embolism. Pulmonary embolisms are blood clots that have travelled from other parts of the body. If doctors were to diagnose David with a pulmonary embolism, it would mean his cancer had returned.

Doctors admit David to the hospital for observation. He stops coughing up blood. Doctors release him two days later. The doctors assume his breath-hold diving caused tiny blood vessels in his lungs to burst and bleed. Doctors rule out high pressure as a cause for the burst blood vessels. David dived only 13 metres deep.

Markus Gutsche and Ware Kuschner, doctors from Stanford University, pose their own hypotheses, published in the *Journal of Clinical Medicine and Research* in 2012. Gutsche and Kuschner believe David's blood vessels contracted because David swam in cold water. David likely exerted a lot of energy as he completed the five dives. He stayed underwater for up to a minute and a half at a time. These long swims caused his heart rate to increase. Increased heart rate and smaller vessels drive blood pressure up. Increased blood pressure can cause the blood vessels to fail. The thinner the blood vessel walls, the higher the risk a person has of bursting blood vessels.

Another hypothesis that the authors present is diaphragmatic movement against a closed glottis. Basically this means that David's body "attempted" to breathe while he kept his mouth and nose shut. Diaphragmatic movement commonly occurs among divers. It's a natural reaction for humans if we find ourselves running out of air. This type of movement causes negative pressure in the chest. This is similar to a vacuum, where the air is sucked out of a space. Negative pressure can cause blood vessels to bulge and fill in the space where the air used to be. Too much negative pressure and the blood vessels can expand to the point of rupture.



Courtesy Patrick J. Lynch

The diaphragm aids in breathing. When it contracts, it makes room in the chest for the lungs to expand and air to enter the lungs.

Two months later, David returned to the hospital for a follow-up. This time around, the CT scan didn't show ground glass opacification. However, the CT scan still revealed subpleural reticular opacities and mild scarring from his previous chemotherapy treatment.

Doctors advised him not to breath-hold dive anymore, because it could increase his risk of coughing up blood again.

Gutsche and Kuschner conclude that divers with a history of chemotherapy or some form of chest cancer should avoid breath-hold diving because these divers risk coughing up blood and damaging their lungs.

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Chapter 12

Breath-hold Diving and the Risk of Paralysis

Sixty-three-year-old Diane works as a seafood gatherer. She holds her breath underwater for three minutes at a time as she collects different types of seafood. Most days, Diane works for three hours. Today, she collects enough seafood to please her boss.

On her way home from work, Diane's neck starts hurting. Her shoulders ache. Diane doesn't know what's wrong. She always waits five to seven minutes in between each of her dives to prevent decompression sickness. Decompression sickness results in symptoms similar to those Diane faces. Two hours after Diane finishes work, she can no longer stand on her feet.

Calling an ambulance, Diane checks herself into emergency. When she arrives, emergency doctors discover that Diane can't move her legs. Although she can move her arms, she has difficulty. Diane retains her sense of touch, but she can't feel pain below her neck.

Doctors perform an MRI scan. MRI stands for magnetic resonance imaging. Doctors use MRI scans when they want to analyze tissues such as muscles or nerves because MRI machines pick up detailed

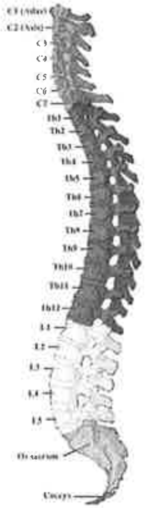
Courtesy John A. Beal

The dura mater helps protect the central nervous system.

distinctions between different tissue densities.

The MRI shows a large acute epidural hematoma. An acute epidural hematoma occurs when blood pools in the spinal cord between a membrane called the dura mater and the bone that makes up the spinal vertebrae. An epidural hematoma puts pressure on the spinal cord. As a result, the body can no longer function the way it should. It becomes hard, if not impossible, to move.

In Diane's case, her hematoma stretches from the third cervical spine (C3) to the fourth thoracic spine (Th4). Diane's hematoma extends over one third the length of her spine.



Courtesy Gray's Anatomy of the Human Body

There are 24 vertebrae in a human spine.

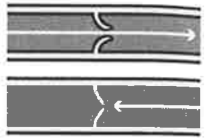
Doctors schedule emergency surgery for Diane. The surgery, called a level total laminectomy, involves opening Diane's spine at the thickest part of the hematoma. The surgeon removes pieces of the spinal bone to relieve pressure and sucks away the excess blood from around her spinal cord. Diane needs two of these surgeries.

After Diane's procedure, she regains her ability to move. Her paralysis disappears.

Doctors and medical specialists refer to Diane's condition as a non-traumatic spinal epidural hematoma (NTSEH). Non-traumatic hematomas are not preceded by a trauma, or injury, such as a fracture or a

dislocation of the spine. Most NTSEHs occur as a result of clotting disorders, a malformation of the spine or a tumour.

NTSEH severity depends on the location of the hematoma and the amount of pooled blood. NTSEHs require early diagnosis and surgery for successful treatment. The sooner the surgery, the better chance for recovery.



Courtesy Wikimedia Commons

Venous valves allow blood to flow in one direction, but not in the other.

In Diane's case, structural damage didn't exist. She didn't have a clotting disorder, a malformation of her spine or a tumour. In these cases, the cause of the NTSEH is usually venous bleeding. The veins in the area where Diane's hematoma formed don't have valves. Valves protect veins from pressure build up. Because epidural veins don't have valves, they can't relieve underwater pressure.

Breath-hold divers use a special breathing technique to extend the amount of time they spend underwater. During the breathing maneuver, Diane's abdomen and chest filled up with a lot of air—more than normal. This increased amount of air caused the pressure in her body to increase. The veins in her chest and abdomen squeezed. This forced blood up those veins and into other areas of her body, like her spinal cord.

Imagine a long balloon, like the kind used to make balloon animals. If you squeeze one end of the balloon, it expands at the other end as the pressure inside the balloon increases. Eventually, if you squeeze hard enough, the balloon pops. The same thing happened to Diane's blood vessels. The pressure increased to the point where her blood vessels burst.

Diane started diving at the age of 16. In her lifetime, she dived around 12,000 times and spent 600 hours underwater. Emergency room doctors tell Diane that the repetitive stress she put on her body probably injured her vessel walls and caused NTSEH.

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Chapter 13

Shallow Water Blackout in Spearfishers

Most of this book focuses on competitive freedivers and the health risks that they face. However, there are other breath-hold divers who do not compete in freediving. One of these groups is spearfishers.

Spearfishing involves breath-hold diving and catching fish using a harpoon, a spear, or a speargun. Competitions exist world-wide, where spearfishers congregate to see who can catch the most fish within a certain time period. Extra points are given for certain kinds of fish and the size of the fish.

The greatest risk that spearfishers face is shallow water blackout. Shallow water blackout happens when divers return towards the surface of the water. Their lungs expand. The deeper the diver, the more pressure on their lungs. As they start to surface, the pressure decreases and their lungs increase in size (return towards normal). Unfortunately, this process creates a vacuum that sucks the oxygen out of the bloodstream and back into the lungs. The lack of oxygen in the bloodstream causes the diver to black out. Upon blackout, the diver starts to sink. If divers

Courtesy Brocken Inaglory

A spearfisher looks for fish off the coast of Hawaii.

experiencing a blackout aren't rescued, they will drown.

Blackouts are sudden and instantaneous. The low level of oxygen forces the brain to shut off as the tissues start to die.

Blackouts normally strike within five metres of the surface of the water. This makes death due to shallow water blackouts so tragic and upsetting. The majority of drowning victims that suffer from shallow water blackouts are usually intermediate divers. Beginners are not usually subject to blackouts because they can't hold their breath that long underwater. Intermediate divers push their boundaries and often ignore the warning signs that tell them something might be wrong: tunnel vision, shakes, starry vision or momentary memory loss. They can pretend that those symptoms have other causes. Perhaps they're shaking because they're cold. Perhaps their vision is tunnelled due to intense concentration. Perhaps they've just forgotten something. Advanced

divers also have a high risk of blacking out. However, they are usually more knowledgeable about recognizing the signs.

One of the most important things for spearfishers to do when ascending is to weigh themselves for positive buoyancy using their weight belts. If they do this correctly, divers will float, even if they lose consciousness. Upon reaching the surface of the water, the vacuum effect stops, and the divers may have enough oxygen left so that their brain starts to function again.

If divers doesn't have the buoyancy to float, they can still survive. A protective mechanism called the laryngospasm reflex seals up their throats so that water can't penetrate into the lungs. However, this mechanism only lasts so long. Eventually, the seal relaxes and water floods into the lungs. This causes the tissues to swell. If divers are rescued at this point, they may survive, but will require intensive hospitalization

Courtesy Guy Keulemans

Spearfishing off the coast of Ryukyu Island in Japan offers the unique experience of finding fish that are not normally seen in other parts of the world.

and months of recovery.

Rescuers have a limited period of time to rescue a diver. Permanent brain damage starts to set in around the six-minute mark, and usually becomes full-blown around the eight- to ten-minute mark. The heart continues to beat long after brain damage happens. If rescuers perform CPR, the diver often emerges in a coma or a vegetative state.

Terry Maas, author of *BlueWater Hunting and Freediving*, emphasizes that CPR should always be performed on drowning victims, because cold water can preserve the brain for longer, and the victim may experience a full recovery. This is especially important considering that the majority of "amazing" recoveries take place in younger victims and many shallow water blackout victims are young.

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Chapter 14

Cold Water Can Lead to Death in Breath-hold Divers

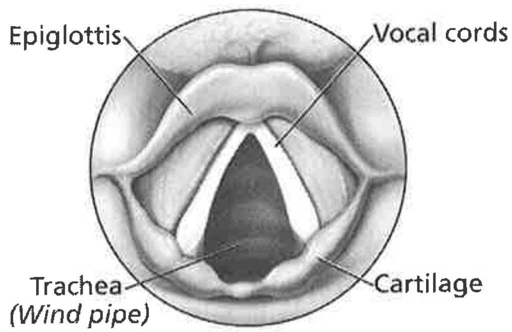
Coroners diagnose most deaths that occur in cold water as hypothermia. Hypothermia refers to a decrease in the core temperature of the human body. Early summer is the most dangerous time of year in the northern hemisphere for deaths occurring in water, because air temperatures rise well before water temperatures. Naive and untrained swimmers believe the water to be warmer than it actually is, and, therefore, go swimming.

Sixty-seven percent of drowning deaths occur in strong swimmers and 55% of these are within three metres of safety.

Coroners identify cold-water deaths where the victim died quickly as drowning. When no water can be found in the lungs, coroners mark down the death as hypothermia or "dry" drowning.

Why does "dry" drowning occur?

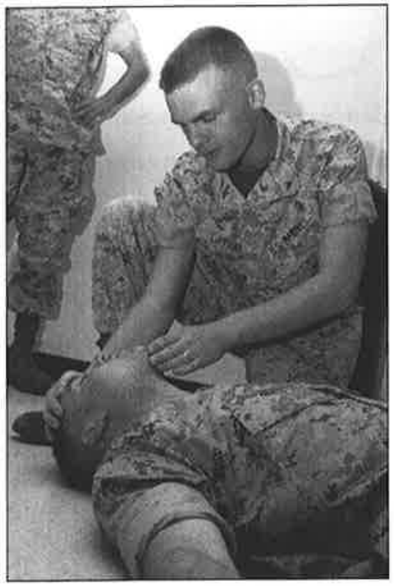
"Dry" drowning occurs because of a natural human reaction. When people inhale water into their lungs, the vocal cords contract and close



Courtesy Alan Hoofring

During a laryngospasm, the vocal cords close together. This seals the wind pipe and prevents water from entering the lungs.

to prevent further damage to the lungs. Doctors call this condition a laryngospasm. The person cannot breathe. Panicking and sucking in makes the problem worse, because the vocal cords contract even more. Unfortunately humans naturally panic and suck in when faced with this circumstance.



Courtesy Cpl. Justin M. Martinez.

A U.S. Marine demonstrates how to perform a head-tilt chin-lift. This technique opens up the airway and allows the vocal cords to relax.

Laryngospasms are useful. Breath-hold divers have documented dozens of cases of fellow divers who have survived underwater blackouts because of the body's amazing capability to protect the lungs against water inhalation. In 2003, Canadian diver Mandy-Rae Cruickshank, blacked out 15 metres below the surface of the water. Laryngospasm saved her life because it

prevented her lungs from filling up with water and rescue divers pulled her up to the surface. After performing a head-tilt, where paramedics tilt the chin towards the neck and then backwards, her airway cleared and she started breathing again.

Shattock and Tipton remain unconvinced

Michael Shattock from King's College in London and Michael Tipton from the University of Portsmouth in the United Kingdom find the diagnoses of hypothermia and "dry" drowning in quick cold water deaths unconvincing. If the victim dies in less than half an hour, severe hypothermia hasn't set in. It takes longer than half an hour for a person to die of exposure to the cold.

Shattock and Tipton believe there is no evidence that "dry" drowning even exists. Medical professionals remain divided on the issue. Currently, 10 to 15 percent of all drowning deaths are attributed as "dry" drowning.

Instead, Shattock and Tipton suggest that cardiac arrhythmias could cause cold-water deaths.

Coroners don't normally consider arrhythmias when looking at post mortem results. Arrhythmias, which are electrical disturbances to the heart, are not detectable in autopsies. Arrhythmias can cause a person to become immobile. The incapacitation can lead to water inhalation. The death looks like a drowning as a result.

What happens when a person jumps into a body of icy water?

When a person jumps into a body of icy water, their body elicits a cold shock response. The cold shock response is a pattern of reflexes driven by receptors on the skin. Signs of a cold shock response include tachycardia (increased heart rate), gasping, uncontrollable hyperventilation, increased blood pressure and starting to see black around the edges of the eyes.

The diving response also leads to bradycardia. Bradycardia is a lowered heart rate. During the diving response, the veins in a person's body constrict to preserve oxygen. The primary function of the diving response is to extend underwater time and allow a person to reach air.

On one hand, the body sends a signal to the heart to beat faster and on the other hand it sends a signal to beat slower. When tachycardic and bradycardic rhythms meet, the body develops an arrythmia. This process is called a shock response.

Do underwater mammals experience arrhythmias as well?

Diving animals rarely experience arrhythmias because they don't get a shock response. Shock responses occur upon impact with cold water. This literally shocks the body into an arrhythmia. Shattock and Tipton insist that both the diving reflex and shock response are needed to cause arrhythmias, and this observation solidifies that hypothesis.

How common are cardiac arrhythmias during breath-hold diving?

Cardiac arrhythmias have often been reported during breath hold diving, especially in cold water. For example, the incidence of cardiac arrhythmias during dives undertaken by Korean women increases from 43% in the summer to 72% in the winter, according to a study published in Diving Medicine in 1976 by S.K. Hong.

Recommendations from Shattock and Tipton

The authors recommend that in situations where coroners have excluded hypothermia and other cardiac problems due to circumstantial or

pathological evidence, they should consider cardiac arrhythmia as a potential cause of death. Coroners should also consider cardiac arrhythmia as a possible initiating event in some cases of apparent drowning.

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Chapter 15

A Brush with Death: Addicted to Breath-hold Diving

Imagine performing a dangerous activity over and over again, despite understanding its consequences. Most people refer to such behaviour as an addiction.

Courtesy Jean-Marc Kuffer

A freediver participates in the dynamic apnea event at the 2nd Great Camberwell Breath-hold Freeding Competition, held in London in May 2009.

In 2009, Per Westin, a 39-year-old Swede, broke the world record in dynamic apnea. During dynamic apnea, one of the disciplines in competitive breath-hold diving, the diver attempts to swim horizontally underwater for as long as possible. Westin set a new world record at 202 metres. In an Olympic-sized swimming pool, that's just over four lengths of the pool. Most swimming pools, however, are 25 metres long.

As a former competitive swimmer, I found myself particularly interested in Westin's record. I wondered how far I could swim underwater. On a damp Monday morning in October, I took to the pool to see how far I could swim. I made it just over one length of the pool—around 27 or 28 metres. At that distance, my lungs screamed for air and I had problems moving my limbs the way I wanted to. I couldn't imagine swimming over eight pool lengths. But then, I'm not trained in any special breath-holding techniques. And I didn't use fins, as Westin did.

Courtesy Jean-Marc Kuffer

In dynamic apnea, divers use monofins to increase their speed. Using monofins, divers can reach speeds of up to 12 km/h.
In this picture, an unnamed diver competes in dynamic apnea at the 2009 Camberwell competition in London.

Glossopharyngeal insufflation

Westin started breath-hold diving many years ago. Ever since he started, he's performed a maneuver called glossopharyngeal insufflation or GI. GI involves hyperventilating and then swallowing air in order to increase the amount of oxygen in the lungs.

But GI comes with consequences. On four separate occasions, Westin suffered symptoms of an air embolism. Bubbles of air find their way into the bloodstream and wreak havoc on the body. In Westin's case, he started coughing up blood. He felt dizzy. He had trouble keeping his balance. He started seeing black spots instead of his regular 20/20 vision. His limbs and torso felt limp and painful. His head pounded. He developed an excruciating headache. Most of his symptoms went away around ten minutes after they started, but his headache remained overnight.

After experiencing symptoms so severe, I expected Westin to decide to retire. After all, these symptoms happened four times.

A near drowning experience

Soon after his four episodes, Westin experienced an even greater scare: a near drowning.

The accident happened when Westin competed in a dynamic apnea event. He performed GI by filling his lungs with more air than they should hold. He jumped in. He slithered through the water as he dolphin-kicked his way to the other end of the pool. He touched the smooth surface of the pool wall. His body started to go numb. He swam up towards the surface. Reaching for the ladder, he tried to pull himself out of the pool.

To his surprise and dismay, he couldn't hook his fingers around the ladder rungs. In addition, the rest of his body refused to respond to him. He drifted towards the bottom of the pool. Fully conscious, he waited for thirty seconds before a lifeguard jumped in and rescued him. Even as the lifeguard pulled him out of the water, he couldn't move any of his muscles. He felt paralyzed. He was paralyzed.

Twenty minutes after the rescue, his limbs recovered their function. The usual headaches that accompanied his previous air embolism attacks hit him at full force. The paramedics who arrived to bring him to the hospital started him on a pure oxygen treatment for his lungs and a special oxygen treatment for his blood. Normal blood oxygen levels should be in the range of 95 to 100 percent. Westin's blood oxygen level reached a low of 75 percent. Medical standards rate 75 percent oxygen saturation as "extremely poor." Oxygen saturation this low can cause brain damage and blindness.

At the hospital, doctors performed chest X-rays. The X-rays showed that Westin had likely swallowed pool water. Some of the water ended up in his lungs as he attempted to breath at the surface. Westin remained in the hospital for 12 hours so his blood oxygen level could return to normal. During this time, doctors performed a complete neurological examination. The examination showed that Westin didn't have any brain damage as a result of his near-drowning.

It wasn't long after Westin's discharge from the hospital that he went back to the pool. It's hard for me to imagine how someone who came so close to death could return to the sport that nearly ended his life. But he did.

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Chapter 16

The Death of a Freediver Leads to Safety Reviews

Audrey Mestre was born in France in 1974 and immigrated with her family to Mexico in 1990. While attending La Paz University in Mexico, she studied the blood shift phenomenon, a unique and strange physical change observed in deep-water dives. It was through her work that she met her husband Francisco Ferreras, a professional freediver. She moved to Miami to live with him and they began the International Association of Freedivers (IAFD) in 1996 in direct opposition to the French-run Association Internationale pour le Developpement de l'Apnee (AIDA). IAFD had limited success compared to AIDA and required constant media attention for funding. Ferreras often arranged dangerous stunts for his organization to attract donors.

The goal: Breaking the world record

In October 2002, Ferreras organized a record-breaking dive for his 28-year-old wife Audrey. At the time, she was one of the world's best female freedivers. He arranged for her to descend to 171 metres below the water's surface, off the coast of the Dominican Republic. The distance is roughly equivalent to ascending and descending a 55-storey building. A successful dive to that depth would break the No Limits world record for both genders, which was set by American freediver Tanya Streeter in August 2002 at 160 metres.

The dive: issues that led to deadly consequences

The dive, which occurred on October 12th, 2002, didn't happen as planned. Audrey Mestre dived on a day when the weather was much rougher than she was used to. She reached the record-breaking depth of 171 metres. The ascent to the surface, however, proved fatal.

Courtesy David K. Staub

The Chicago Temple Church in Illinois, USA is 173 metres tall. If this building was placed underwater, it is approximately the same length that Mestre dove underwater.

When dives like these occur, there are always underwater scuba divers present to ensure that a standard level of safety is maintained. During Mestre's dive, the diver at the bottom realized that

she was having trouble maintaining consciousness. He managed to reach her at 89 metres. Her husband, Ferreras, donned scuba gear and dived under when he realized that Mestre was no longer alert. By the time Ferreras pulled his wife to the surface, she had been underwater for eight minutes and 48 seconds. It was impossible to revive her.

Spectators and media on-lookers failed to realize what had happened at first. As Mestre was hoisted onto a rescue boat, the crowd cheered.

"People just didn't make the transition from festivity to horror," said Paul Kotik, a journalist who witnessed the dive.

Findings from the IAFD official report

According to the official report released by the IAFD, numerous factors contributed to Mestre's death. The cable used to guide her descent and ascent was a newer style of cable, thinner than most. The strong winds and currents gave the cable some slack and made it more difficult for her lift bag to move along the cable. The lift bag got caught as she ascended, most notably at 164 metres, where she couldn't ascend for 30 seconds.

Also, the type of weight used at the bottom of the cable to keep the cable in a vertical position was not heavy enough for the weather conditions that day. The cable did not remain completely vertical, but rather moved sideways slightly, which meant that Mestre did not ascend on a complete vertical path, but rather on an incline. This made it much easier for her lift bag to get stuck along the way.

Teflon brushing is attached on the lift bag where it meets the cable to reduce friction as the bag glides up the cable. The Teflon brushing on Mestre's lift bag was worn down and caused her bag to get stuck more easily.

Also, her lift bag did not fully inflate as she attempted to reach the surface. It did fill to a sufficient amount, but a subsequent test of the bag revealed that it had leaked, and it is very likely that the air tank was not fully filled with air before her dive.

Another safety measure not taken was the presence of a doctor. Once Mestre was pulled to the surface, she would have had a much higher chance at surviving had a medical professional been present. The only training anyone on board had was in dentistry.

The autopsy performed in the Dominican Republic ruled that the death was accidental, and the final cause was asphyxia by submersion.

Anger from the freediving community leads to Ferreras's retirement

Freedivers from around the world heavily criticized onsite security measures in an emotional debate on the Internet. There was a lot of anger directed towards Mestre's husband Ferreras, accusing him of tampering with the equipment. Some people argued that Ferreras had purposefully used a leaking lift bag because he didn't want Mestre to succeed. As a result of the anger expressed by the worldwide freediving community, Ferreras quit freediving. No criminal investigation was ever opened into Mestre's death and most people's accusations remain unfounded.

Safety improved after Mestre's death

Audrey Mestre's death triggered safety investigations by AIDA and the IAFD. The IAFD mandated the use of lead bottom weights, rather than the concrete one that had been used during Mestre's attempt. They went back to using thicker cable, and required more precise oceanographic data before permitting record attempts. AIDA's investigation led them to introduce the mandatory use of a safety lanyard and back-up lifting systems.

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Chapter 17

Real-Life Mermaid

What is it that makes some people naturally talented at holding their breath? Is it practice? Is it genetics? This is a classic case of nature versus nurture.

Thirty-two-year-old American freediver Amelia de los Rios fits in well on the "nature" side of the argument. She realized at a young age in Bogota, Colombia that she had a talent for holding her breath.

"My dad was really good at holding his breath and used to swim across pools in one breath," de los Rios says. "One day I grabbed his back and held on and crossed the pool with him with no problem. I knew there was something special about my lungs."

De los Rios's brain takes longer to let her know that she's run out of air. She says, "Truth is, when you feel like you need to breathe, you still have plenty of oxygen left in you, but your body keeps asking and asking."

Lung size matters

In a study done by Swedish scientists Erika Schagatay, Matt Richardson and Angelica Lodin-Sundström in June 2012, they conclude that the amount of air that divers intake before diving has a direct correlation with the amount of time they can spend underwater without blacking out.

The larger a diver's lungs, the better they perform in breath-hold diving. Those divers who aren't born with large lungs train their lungs to stretch. They use methods such as stretching exercises and lung packing techniques to increase their lung size.

De los Rios's talent for breath-hold diving gave her the opportunity to compete for Team USA at the 2012 AIDA Team World Championships in Nice, France.

When de los Rios isn't training with Team USA, she works in Hawaii as a mermaid at Pacific Beach Hotel's Oceanarium Restaurant. She swims in a 280,000 gallon indoor oceanarium, entertaining guests while they eat.

"People think I'm being silly or cheesy when I tell them I'm a mermaid," she says. "Then when they come to see me, they say, you really are a mermaid!"

Back in June 2012, De los Rios enrolled in a freediving course in the Philippines to learn how to improve her skills. On her second day, she surprised everyone by holding her breath for five minutes and 50 seconds.

"I guess [it's] pretty good," she says. She attempted to hold her breath longer and she managed to get to six minutes.

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Chapter 18

Breaking the World Record

In June 2012, German freediver Tom Sietas broke the World Record for the longest time spent underwater. In Changsha, China, Sietas held his breath for 22 minutes and 22 seconds. He beat his previous record of 20 minutes and 21 seconds.

Sietas's record is not included in AIDA's records because Sietas breathed pure oxygen in before he began his record. It is much easier to maintain consciousness underwater with a bloodstream full of pure oxygen. The record for breath-holding without pure oxygen beforehand is 11 minutes and 35 seconds, set in 2009 by French freediver Stéphane Mifsud.

Metabolism rate linked to oxygen consumption

Sietas did not eat for five hours before he attempted his world record. The lack of food slowed his metabolism down. Sietas needed a slower metabolism when he held his breath because metabolism involves using up oxygen to keep the body functioning. The slower the metabolism, the longer a person can stay conscious on one breath.

Sietas's advantage

Sietas's lungs are at least 20 percent larger than the average male's. This gives him an advantage when he holds his breath because he can pack 20 percent more air into his lungs.

When freedivers hold their breath underwater, their bodies starts to use up the oxygen that they breathed in. As oxygen decreases, freedivers start to experience symptoms of hypoxia.

What is hypoxia?

Hypoxia is a medical term for a lack of oxygen. Symptoms of hypoxia include loss of motor control, also called a "samba" by freedivers because of the body tremor that develops along with head bobbing. Other symptoms include loss of vision, hearing, colour perception and the ability to think clearly. If freedivers remain underwater, they will eventually black out and lose consciousness.

Ten percent of divers attempting to hold their breath for as long as possible (called static apnea) are disqualified because they show symptoms of hypoxia.

How do divers try to prevent hypoxia?

To prevent symptoms of hypoxia, divers tend to hyperventilate before they immerse themselves underwater. Hyperventilation increases the amount of oxygen in the lungs and in the bloodstream by up to 40 percent. However, hyperventilation leads to a high risk of passing out before the diver even descends below the surface of the water.

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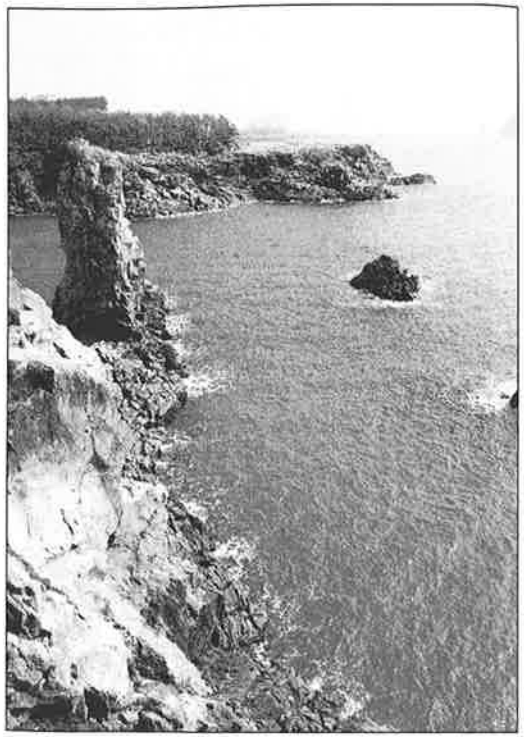
Chapter 19

The Haenyo Divers of Korea

Haenyo (pronounced hen-yuh) divers hail from the beautiful Jeju Island, 85 kilometres south of mainland Korea. *Haenyo* is a Korean word meaning sea women. These women are the breadwinners for their family. They collect conch, octopus, urchin, and abalone.



Courtesy Martin Chen

The view from Jeju Island, in South Korea.

Courtesy Wikimedia Commons

Haenyo divers don't carry around oxygen tanks with them when they dive because it hinders their ability to work underwater. It's also expensive to buy scuba equipment.

An innovative idea

In the 19th century, seafood became expensive to catch because the Korean government charged high taxes. Only men paid taxes, so a group of bright women got together and decided that they would do the diving. They avoided paying taxes and made money for their families.

The haenyo don't use oxygen tanks. The tanks would thwart their efforts and slow them down. Instead, they wear wet suits and goggles. They dive 18 metres to collect the lucrative seafood.

Many of the haenyo are now well into their seventies and eighties. It's a lifestyle that's hard to give up, despite the dangers.

And there are dangers. These women have to avoid the sting of jellyfish and the bite of a shark in the Korean Strait. They must hold their breath for up to two minutes while they collect their prizes.

The future of the haenyo

Their future is bleak. Back in the 1970s, the haenyo grew rich because of the high market price of abalone and conch. They sent their daughters to university on the mainland. Advancements in education led the haenyo's children to seek jobs in business and science rather than in diving. In the 1950s, 30,000 haenyo lived on Jeju Island. Now, there are just 5,000 and most are over 60 years old.

Courtesy Wikimedia Commons

Most Haenyo divers are between 50 and 60 years old.

Strong hip and leg bones in deep divers

Researchers classify haenyo divers into three different groups: high, middle, and low. The high group consists mainly of younger women who dive the deepest. In a study completed in 2006 by Hwansik Hwang, Jongmyon Bae, Seungwook Hwang, Hoonki Park, and Inyoung Kim of South Korea, high group divers have stronger hip and leg bones than non-divers. High group divers require a lot of strength to swim far down. The deep water exposes their muscles to high pressure continuously.

The Halmangbadang

Encouraged by these results, the researchers looked at the middle and low diving groups.

These divers are older women, called *Halmangbadang* or "sea grandmothers." Middle and low group divers have a special part of the sea reserved for them—the shallower areas. When the researchers studied the Halmangbadang, they found something troubling. These women spent too much time in buoyant waters. The buoyancy increased bone mineral density loss.

What are the dangers of low bone mineral density?

Low bone mineral density (BMD) correlates to an increased risk of osteoporosis and fractures. BMD refers to the amount of mineral in the bone, calculated using dual-energy X-ray absorptiometry (DXA). DXA shoots X-rays at a person's bones. It determines the health of the bones based on X-ray absorption.

Just as astronauts lose bone density when they go into outer space, Halmangbadang lose bone density because they spend a great deal of time in very buoyant waters where they don't do much weight-bearing activity. Bone density builds up when we put weight on the bones. Exercises like walking and handstands help our bones to get stronger.

Conclusion

Hwang and his associates therefore conclude that while diving to deeper depths can have a positive impact on bone density, staying in shallow water has the complete opposite effect.

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Without Air

Breath-hold divers compete in one of the most intense and dangerous conditions on the planet—underwater. Breath-hold divers take huge risks participating in their sport.

Stéphane Mifsud of France holds the record for the longest breath-hold dive. He held his breath for 11 minutes and 35 seconds. Irreversible brain damage normally sets in at six minutes and solidifies at eight to ten minutes. But Mifsud survived with no noticeable brain damage. This amazing feat truly show the accomplishments of humankind to explore the boundaries of our limitations. But does breath-hold diving pose any risks to the brain? Does the lack of oxygen cause brain damage?

—*From Chapter 8 "Brain Damage"*


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