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Discovery of caisson disease: a dive into the history of decompression sickness

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ABSTRACT
With the Industrial Revolution and the invention of compressed air came mysterious symptoms of unknown etiology. Through careful observation and diligent work from physicians in the 19th century, the true nature of caisson disease was identified and described. By studying thousands of casualties, these scientists were able to identify the cause of caisson disease, develop effective treatment plans for laborers, and institute procedures to prevent this malady. Over the next 100 years, numerous advancements in diving medicine would allow for the creation of the highly accurate dive tables that we have today. Much of our understanding of decompression sickness, however, still stems from the observations and scientific endeavors of the 1800s.

KEYWORDS Aerospace medicine; caisson disease; decompression sickness; diving medicine; hyperbaric medicine; medical history; occupational and preventive medicine

In 1670, Sir Robert Boyle placed a viper into an air-tight chamber and rapidly removed the air with a vacuum. In his journal, he noted that the snake's "body and neck grew prodigiously tumid, and a blister appeared upon the back."[1] This observation would be regarded as the first description of decompression sickness, a dangerous complication of rapid decompression that kills many people each year. While humans have been diving beneath the water for thousands of years, technological advancements of the 19th century opened the door for deeper diving and a greater exposure to injuries from compressed air. With the combined effort of physicians, scientists, and laborers of the 19th and 20th centuries, the root cause of decompression illness was discovered, and a methodology was developed to treat those afflicted with it.

From the beginning of recorded history, people have centered their activities of daily life around oceans and rivers. From drinking water and bathing to military defenses and trade, water has been crucial in shaping the geographic and geopolitical infrastructure of modern society. As early as the 4th century BC, artisanal divers plunged below the surface of the ocean to gather sea sponges, red corrals, and marine food.[2,3] Later, salvage divers would venture to the bottom of rivers and oceans to collect treasures and valuables from sunken shipwrecks. Almost all early evidence of diving injuries is related to drowning, with no notable references to decompression injuries. It wasn't until the Industrial Revolution, with advances and adaptations in the steam engine, that compressed air diving became possible. However, the ability to breathe at greater depths led to unintended consequences and mysterious ailments that are the subject of this paper.

Decompression sickness, or decompression illness, is the result of rapid decompression causing bubbles to form in the body's blood and vital tissues. It is commonly referred to in the context of SCUBA diving accidents, but can affect pilots, parachutists, miners, and anyone who is exposed to rapid reductions in barometric pressure. Inert gases, such as nitrogen, are dissolved in the blood and absorbed by various tissues throughout the body in proportion to the surrounding environmental pressures. If this pressure is reduced quickly, termed decompression, the nitrogen can form bubbles, which wreak havoc on various tissues of the body, causing arthralgias, dyspnea, pruritus, confusion, seizures, and paralysis. If left untreated, most minor cases resolve on their own, but severe cases can cause death if not managed emergently.[4] This disease was a mysterious ailment faced by miners in France in the early 1800s, but today it is well described with scientific tables and complex physics calculations that allow for its prevention. This disease resulted in numerous deaths of industrial laborers, caused disability of physicians, and was the source of many myths and homeopathic remedies.

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TRIGER'S CAISSON

With the Industrial Revolution came the invention of the steam engine, which was eventually adapted to run air compressors. The first to utilize a pressurized chamber for working was Charles-Jean Triger. In 1840, he utilized compressed air to mine coal in the Loire Valley of France, in what he called a caisson (meaning "box" in French).[5] A chamber with an open bottom was lowered down into the ground, and compressed air was pumped into it, forcing water down and out of the bottom. This allowed workers to dig below the water table and into valuable stores of coal. The working chamber was accessed via an airlock at the top of the chamber, and the whole device was regulated by a manually controlled system of inlet and outlet valves. This allowed for the first known injuries from compressed air and represented the start of a decades-long journey to find the cause of the mysterious and deadly "caisson disease."

This mining device was used for approximately 2 weeks, with miners working 7- to 10-hour shifts. Triger, a civil engineer and geologist, would venture down through the airlock and into the pressurized work chamber before each shift to assess the air quality and working environment. During this short project, Triger described experiencing temporary breathlessness and noted two cases of "mal de caisson," which he described as joint pain and soreness that appeared approximately half an hour after returning to the surface. These body aches were treated with alcohol, and the laborers were able to return to work.[5] While rudimentary by today's medical standards, his original description would serve as the first recorded incidence of caisson disease, later to be known as decompression sickness.

Triger's caisson was adopted throughout France for various mining projects, and Triger himself continued to use the system to complete other small projects throughout the region. He was unique among employers of his time, as he paid close attention to the safety and well-being of his workers, as is demonstrated by his personal testing of working conditions before each shift. As such, he hired two physicians, B. Pol and T. J. J. Watelle, to oversee the medical needs of his future projects utilizing the caisson. In addition to performing preemployment physicals, Pol and Watelle would monitor and care for the 64 laborers at one of Triger's next projects in Northern France. The Douchy project was reportedly conducted at pressures 3.5 times the normal atmospheric pressure, and Pol and Watelle noted dyspnea, arthralgia, pruritus, and myalgias in many of the workers upon exiting the caisson.[6] Pol himself was stricken with caisson disease and only recovered after a night of severe chest pain, paralysis, emesis, and dyspnea.[7]

While Pol and Watelle correctly attributed the severity of caisson disease to the rate of decompression, they mistakenly thought that the malady was the result of decreased oxygen in the circulation. They postulated that the decrease in the partial pressure of oxygen experienced from returning to the surface resulted in congestion of the blood vessels and meninges, a common finding on many autopsies during this time. Despite being incorrect in their assumption of the cause of caisson disease, in 1854 Pol and Watelle were the first to suggest that recompression might be used to treat those stricken with caisson disease.[2]

For the next two decades, few advancements in the understanding of decompression sickness were achieved. Physicians treated the disease by controlling symptoms with cold water baths, natural oils, cordials, quinine, dry cups/leeches, and even submersion in liquid mercury.[7,8] As more laborers succumbed to the mysterious caisson disease, more physicians began to turn their attention toward its causes and potential cures.

ST. LOUIS BRIDGE

In the summer of 1868, Captain James Buchanan Eads began construction of the St. Louis Bridge. As the chief engineer on the project, he was charged with supervising the construction of a 1500-foot bridge that would span across the Mississippi River. Men would work in 4- to 6-hour shifts, and no injuries were reported until the caissons reached a depth of 60 feet, about half the total depth needed to reach the bedrock 100 feet below the surface of the Mississippi. Most men complained of joint pain or partial paralysis of lower limbs; however, some also complained of headaches and itchiness. Many of the men emerged from the caisson in a bent-over posture, a result of the joint pain, shortness of breath, and abdominal pain. This posture looked similar to the Grecian Bend, a fashionable female posture from the 1820s, and so these men stricken with caisson disease were said to have "the bends."[9]

As one of the caissons neared its maximum depth of 93 feet, six men ultimately lost their lives while working in the compressed air environment. By the end of the project, nearly 25% of all workers would suffer from caisson disease, with 30 hospitalizations, 13 deaths, and two workers becoming permanently disabled. In 1870, Alphonse Jaminet, a local physician, set up an infirmary on a nearby barge to treat the injured workers as they emerged from the caisson. This makeshift hospital with cots, blankets, and a single physician would be noted as one of the first on-site occupational clinics in America. In addition to monitoring men throughout the day, Jaminet also required that laborers stay in his care for "at least one hour after work, while drinking three-quarters of a pint of strong beef tea."[8]

Jaminet himself would venture down into the caisson and experienced numerous effects of compression and decompression. On one occasion, he was afflicted by the bends and was crippled with lower-limb paralysis and abdominal pain for multiple days. In his book about caisson disease, he described his ordeal in great detail: "I was suffering from profuse cold perspiration, every effort to speak caused great suffering and fainting, my pulse was 106 per minute, [and] both my legs and my left arm were paralyzed."[10] Jaminet also noted that his heart rate and respiratory rate would increase in the few moments following his descent into the caisson. For this reason, Jaminet did not allow any stimulant use prior to entering the caisson (notable stimulants of the time included cocaine, alcohol, and hot baths). Upon decompression, he would note ear pain and extreme chills, which would lead him to suggest that men dress warmly for the decompression to ambient air pressure.

While his knowledge of decompression sickness was limited to observations and personal experience, Jaminet developed some of the first therapies to prevent and treat this relatively new disease. Although he incorrectly attributed "the bends" to fast rates of compression, Jaminet instituted standard rates for both compression into and decompression out of the caissons. While the rates of decompression were quite fast compared to today's standards, the idea of controlling the rate of decompression marked a step in the right direction toward preventing decompression injuries.

BROOKLYN BRIDGE

In May 1870, Washington Roebling began construction on the 1600-foot Brooklyn Bridge that would connect Manhattan and Brooklyn. The caissons needed to build this bridge were larger than anything that had ever been built before. At 16,000 square feet, the Brooklyn Bridge caissons were three times larger than those used to build the St. Louis Bridge.

Physician Andrew H. Smith, a throat specialist, was charged with caring for the well-being of the men working on the Brooklyn Bridge. As other physicians had previously noted, Smith observed 86 cases of caisson disease with the common symptoms of joint pain, headache, pruritus, shortness of breath, paralysis, and vomiting. In 1873, he gave a speech to the College of Physicians and Surgeons in New York about this disease, formally calling it caisson disease and later publishing the term in a textbook that same year.

Smith noted that the time of exposure to compressed air was directly proportional to the severity of symptoms of caisson disease. Like Jaminet, he also recorded that workers in the caissons would experience a drastic increase in heart rate, perspiration, and diuresis. He was the first to correctly attribute the increase in heart rate to the increased levels of carbon dioxide, likely from the incomplete combustion within gas lamps in the caisson. Furthermore, Smith noted the hot, humid working conditions at the bottom of the caissons, which he concluded were the cause of the increased sweating and urination.[11]

During the project, Smith did his best to care for those who were afflicted by caisson disease by administering morphine or atropine; however, he was relatively helpless in preventing the disease, as the true cause was still unknown.[11] Smith made an important observation when he noted that most of the 86 workers who experienced caisson disease were overweight, with all deaths described in "obese" patients. These findings would later support the conclusion that obesity increased the risk of caisson disease.

In 1871, after personally inspecting the working conditions in one of the caissons, Roebling suffered an extreme case of decompression illness and was left paralyzed for the rest of his life.[8] As digging continued, he became concerned with the rising number of injuries and deaths and eventually halted digging at 78 feet, just shy of the anticipated 100 feet needed to reach bedrock. Despite recommendations against doing so, Roebling decided to place the Manhattan bridge pylon on sand, and the Brooklyn Bridge was opened in May 1883.

PAUL BERT

French physiologist Paul Bert was instrumental in discovering the root cause of decompression sickness. As a physiologist, he was interested in studying high altitude ballooning and built many chambers to experiment with barometric pressure. In 1870, he conducted numerous experiments on the rapid decompression of mice, dogs, and birds. After extended periods in chambers pressurized to 10 times that of normal atmospheric levels, these animals were rapidly decompressed in a matter of minutes or seconds.

In his book *La Pression Barométric*, Bert described "air" in the venous system and right side of the heart of these animals and demonstrated that this gas was predominantly composed of nitrogen. He shared the landmark discovery that "sudden decompression … [allows] nitrogen, which was dissolved in the blood and tissues as a result of the pressure, to return to the free state."[12] He was the first to demonstrate that caisson disease was the result of nitrogen bubble formation throughout the human body, a result of the rapid decompression from hyperbaric conditions. Bert also observed that the negative effects of decompression were often delayed by 10 to 30 minutes, although he could not understand why.

In addition to identifying the cause of caisson disease, Bert also proposed interventions to prevent and treat cases of it. He suggested "to slow down the speed of decompression to allow the excretion of gaseous nitrogen through the lungs … to have the subject breathe pure oxygen if minor symptoms appear … [and] to recompress immediately then slowly decompress in case of paralysis."[12] These practices of slow decompression, oxygen administration, and recompression are mainstays of the current treatment of decompression illness over 150 years later.

JOHN SCOTT HALDANE

John Scott Haldane is credited with creating the first accurate decompression tables for those working in compressed air environments. Haldane was an accomplished physiologist in the field of gas physiology. In 1905, he was able to demonstrate that the respiratory drive is dictated by the pH of the blood, and in 1919, he was the first to treat victims of carbon monoxide with pure therapeutic oxygen, still a cornerstone of modern emergency treatment of carbon monoxide poisoning.

Haldane was familiar with Bert's research on the physiological effects of decompression. In conjunction with the Lister Institute of Preventative Medicine and the Royal Navy, Haldane constructed a hyperbaric chamber to better study caisson disease. In the early 1900s, Haldane conducted hundreds of experiments in his chamber, on both nonhuman and human animals. He noted that most of the observed symptoms were from effects on the nervous system, and he was even able to directly observe nitrogen bubbles in the white matter on microscopy. As white matter is predominantly composed of fat, Haldane correctly hypothesized that there is a correlation between the severity of caisson disease and the amount of fat within the victim. From this and other studies, restrictions were placed on those who could work in caissons, specifically that "really fat men should never be allowed to work in compressed air, and plump men should be excluded from high pressure caissons."[13]

From 1903 to 1904, Haldane conducted hundreds of experiments in his chamber resulting in the conclusion that the amount of nitrogen absorbed within a given body tissue was determined by the fat content of that tissue and the blood flow through it. He also introduced the idea of supersaturation, that tissues of the body could hold nitrogen for a limited amount of time after decompression before forming bubbles. This observation addressed Bert's findings of delayed onset of symptoms following rapid decompression. Finally, Haldane developed the theory of tissue half-times, that is, the time that is needed for the slowest tissue to desaturate to half of the partial pressure of its supersaturated state.[14]

Haldane developed a method to avoid caisson disease that revolved around tissue half-times. Under his model of "staged decompression," the worker would be decompressed to half of the pressure that they had been working at and then slowly decompressed at 10-foot intervals thereafter.[15] Today's dive tables are far more sophisticated than Haldane's first decompression tables, with numerous advances in gas physiology, computers, and mathematics.[16] Nonetheless, Haldane's theory of tissue half-times is still a foundation of modern diving medicine.

CONCLUSION

With the Industrial Revolution and the invention of compressed air came mysterious symptoms of unknown etiology. Through careful observation and diligent work from Pol, Watelle, Jaminet, Smith, Bert, and Haldane, the true nature of caisson disease was identified and described. By studying thousands of casualties, these physicians and scientists were able to identify the cause of caisson disease, develop effective treatment plans for laborers, and institute procedures to prevent this malady. Over the next 100 years, numerous advancements in diving medicine would allow for the creation of the highly accurate dive tables that we have today. Much of our understanding of decompression sickness, however, still stems from the observations and scientific endeavors of the 1800s.

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