Lambertsen and O$_2$: Beginnings of operational physiology

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INTRODUCTION

Significant events in history do not occur at random. They occur because individuals confront problems and have the ingenuity and motivation to find solutions. This is the story of how Dr. Christian Lambertsen developed closed-circuit O$_2$ diving for the U.S. military. It was a small episode in World War II, but ultimately significant for environmental physiology and hyperbaric medicine. More importantly, it illustrates how practical problems can inspire fundamental understanding. Much of the military part of the story was classified until the mid-1990s, when Sergeant Brian Danis, U.S. Army, brought it to light through the Freedom of Information Act.

School

Chris Lambertsen grew up during the depression of the 1930s in Scotch Plains, New Jersey. He spent summers at the Jersey shore, building houses with an uncle. Before high school, he had decided on a medical career. After junior college and a two-year scholarship to Rutgers University, Chris entered medical school at the University of Pennsylvania in September 1939.

Classes began with respiratory physiology. To learn about oxygen (O$_2$) and carbon dioxide (CO$_2$), the students breathed hypoxic gas to unconsciousness, hyperventilated to become hypocapnic, and conducted breath-holding contests to feel the effects of hypoxia and hypercapnia. Given his experience at the shore, Chris was impressed by ten-minute breath-hold times after hyperventilation with O$_2$, and found O$_2$ and CO$_2$ particularly interesting for their control of ventilation.

His medical school lessons were useful during weekend underwater excursions at the Jersey shore. With the help of two cousins, he began by re-breathing from a bag, which was connected to a bicycle pump that provided fresh air from the surface. The cousins and pump were soon replaced with a cylinder of compressed O$_2$, but re-breathing was uncomfortable because CO$_2$ accumulated in the bag. When he learned of new anesthesia equipment that used a CO$_2$ absorbent, Chris solved his problem with a small CO$_2$ scrubber, fit between his mouth and the breathing bag.
Henry Bazett, his physiology professor, was enthusiastic and encouraging. Professor Bazett, an Englishman who had studied with John Scott Haldane, understood the problems of underwater respiration. To continue Chris’ work, Bazett requested additional parts from the Ohio Chemical and Manufacturing Company, a maker of anesthesia equipment. Ohio Chemical responded with a job offer to Chris at thirty dollars a week for the summer of 1940. House painting on the Jersey shore stopped abruptly, and Chris took the train to Cleveland, where he and Mr. Sholes, the president of the company, decided that the summer’s objective would be to develop an underwater breathing apparatus for use in lifesaving. The resulting apparatus was constructed over several weeks in Minneapolis, where Ohio Chemical made anesthesia equipment (Figure 1).

It was a semi-closed pendulum, or to-and-fro, rebreather, weighing 12 pounds with a 40-liter \( \text{O}_2 \) bottle. A regulator delivered \( \text{O}_2 \) at about two liters per minute, which was adequate for half an hour of light work. \( \text{O}_2 \) was re-breathed from an oronasal mask through a \( \text{CO}_2 \) scrubber into back-mounted breathing bags. Because the mask and hose were dead-space that retained \( \text{CO}_2 \), an exhaust valve was placed in the mask to release end-exhalation \( \text{CO}_2 \) into the water. \( \text{O}_2 \) added before the scrubber decreased the \( \text{CO}_2 \) in the first part of inhalation.

Chris tested his rebreather in Lake Nokomis, near Minneapolis, and in Lake Erie (Figure 2). One day, while at sixty feet, his eyes and one of his legs began to twitch, and he noted involuntary ‘catches’ in his respiration. Was this \( \text{O}_2 \) toxicity, about which so little was known? A fluttering diaphragm convinced him to abort the dive. In anticipation of such an event, he had attached to himself a line, which was tended by his companion in the boat, Mr. Sholes’ son. The U.S. Navy Diving Manual instructed four pulls in the event of emergency, but when he pulled, the line came down on his head, as they had forgotten to tie it off in the boat.

Somehow, he surfaced safely, and with the tests completed successfully, returned to Cleveland, where he remarked to Mr. Sholes that the apparatus might be useful for miners trapped in hazardous atmospheres. Mr. Sholes thought this was a fine idea and had a gas-tight chamber constructed on the loading dock for a demonstration. The chamber was a sealed structure of wood and Plexiglas. It was large enough for a canary, a dog, and Chris, with his rebreather (Haldane had introduced canaries into British mines, for the birds were more sensitive than men to hazardous gases). The structure was flushed with \( \text{CO}_2 \) to remove the \( \text{O}_2 \), and filled with cyclopropane, a highly flammable anesthetic gas.
The demonstration was filmed, with the local press and fire department in attendance. The canary fell off its perch; the dog fell off its shelf. When Chris leaned over to check the dog, he, too, fell over. Something was wrong, and fire axes quickly dismantled the chamber where Chris was found unconscious. No one had realized that cyclopropane would penetrate the latex breathing bags and be inhaled. Mr. Sholes issued a stern reprimand, “Chris, you shouldn't have done that.”

Chris returned to Philadelphia as a local celebrity at the University of Pennsylvania. His photograph (Figure 2) had been distributed nationally by the wire services because in 1940, it was news to spend twenty minutes underwater. Pleased as could be, Professor Bazett and the Dean of the medical school decided a description of the underwater breathing apparatus should be published in the *Journal of the American Medical Association* (1). Bazett submitted a letter of support to the journal that was descriptive and prophetic. He wrote, “The equipment was successful because it was designed by a man who studied the physiological principles carefully and is capable not only of testing it himself but training the users. It could not have been developed by a physiologist unfamiliar with the practical side nor by a swimmer without physiological training” (2).

A former British Army officer, Professor Bazett was concerned by England’s precarious circumstances at the start of World War II, and saw that Chris’s device could have military applications. He wrote to the British Admiralty, pointing out these potential uses: “The apparatus has advantages in lightness and freedom of movement in the water making it adaptable either for use of underwater troops of the trouble-making type or for night-raiding enemy defenses” (2).

Bazett also wrote to the U.S. Navy, and in January of 1941, he and Chris went to Washington, D.C., to visit the Navy Experimental Diving Unit (NEDU). An old professor and a young student, with a gym bag full of tubes and cans, were of little interest to the Navy, considering the challenges presented by the submarine force. In 1939, the Navy had rescued 33 sailors from the sunken submarine *USS Squalus*, using the new McCann Diving Bell (3). After the rescue, the Navy salvaged the *Squalus* with still-experimental helium-O$_2$ diving equipment and decompression schedules. The Navy had also developed the Momsen Lung, a lightweight underwater breathing apparatus for use in escapes from sunken submarines (3). Despite official Navy indifference, a junior medical officer at NEDU, Lieutenant Al Behnke, saw the potential military value of Chris’ device, supported the publication of the journal article, and discussed with him the relative merits of the Momsen Lung.

The NEDU visit reoriented Chris’s mind: lifesaving was out, military applications were in, and a major redesign was in order. Having just read Adriani's paper about CO$_2$ absorption in anesthesia machines (4), he realized that for effective CO$_2$ removal, exhaled gas must have adequate residence time near the absorbent granules. He reasoned that the residence time would increase if one-way valves were placed in the mask tubing so that gas would flow through the CO$_2$ scrubber in one direction only. This ‘recirculating’ design became the Lambertsen Amphibious Respiratory Unit (LARU) II (Figure 3), and the recirculating breathing loop is still used by most rebreathers. The scrubber was large enough to hold the tidal volume of a working diver so that CO$_2$ had additional time during inspiration to diffuse into the absorbent granules. A steel cage around the breathing bag made the unit less fragile.
The Lambertsen Amphibious Respiratory Unit (LARU) II [5].

The LARU-II was almost ready for a demonstration at NEDU, but Chris wanted another test to ensure the system would work at pressure. He located a chamber on Welfare Island in New York City that its operators allowed him to use after five in the evening, with the understanding that “we will assume no responsibility for your well being during or as a result of your work here” (6). He and a physicist friend (Glen Millikan, inventor of the oximeter) took the train to New York in March 1942. Millikan operated the chamber from outside, while Chris conducted equipment tests inside. Recognizing the possibility of an O\textsubscript{2} seizure, Chris attached a line from his mask to an overhead pad-eye in the chamber, and stood during testing. Had he fallen down, the mask would have been pulled from his face. The test procedure was simple: increase the pressure, make notes (e.g. “my left eye itches”) during a 15-minute wait period, and then go deeper.

The Welfare Island tests were satisfactory, and Chris wrote to now-Lieutenant Commander Behnke, “I will be able to go to Washington any time you suggest. As one of my professors put it, I do not intend to let my medical course interfere with my education” (7). But there were further delays until a former college professor, presently the chairman of the Medical Defense Research Council, encouraged the Surgeon General of the Navy to cut through the red tape. The next visit took place in April 1942, and Chris reported to Mr. Sholes, of Ohio Chemical, “My pressure tests went very well. CO\textsubscript{2} absorption was fine but O\textsubscript{2} poisoning came on at 80 feet. I was almost a goner” (8).

Underwater Troops of the Trouble-Making Type

Four people attended the NEDU demonstration from the British Special Operations Executive (SOE) and the recently formed U.S. Office of Strategic Services (OSS). These were covert agencies in search of an underwater breathing apparatus for reconnaissance and direct action missions. Chris had been rejected by the Navy for hay fever but was recruited by the OSS, and after graduation from medical school in June 1943, was assigned to the new Operational Swimmer Groups (OSG) as a First Lieutenant (1LT) in the Army Medical Corps. His duties were to perfect his underwater breathing apparatus and train the OSG swimmers to use it.

The British SOE was about six months ahead of the OSS in developing swimmers for its Sea Reconnaissance Unit (SRU) (9). The SRU began training in southern California in land warfare, demolitions, small boat handling, surface swimming, and breath-hold diving with the facemasks and swim fins used by California spear fishermen and abalone divers. In January of
1944, the SRU moved to Nassau, Bahamas, for dive training. Since the LARU was not yet readily available, the SRU trained with the British submarine escape apparatus.

While a medical student, Chris trained the first OSS swimmers in May 1943 in the swimming pool of the Naval Academy in Annapolis, Maryland. He conducted an abbreviated course using the LARU-III (Figure 4). Known as L-Units, these small swimmer cadres deployed to England with orders to attack the submarine pens in the Bay of Biscay on D-Day, but the operation was canceled because adequate thermal protection and transport across the English Channel were unavailable. Many of the L-Unit swimmers returned to the U.S. for further training.

**Fig. 4. The LARU-III (C.J.L. photo).**

In May 1944, the first of three full OSS Operational Swimmer Groups (OSG-1) followed the SOE’s Sea Reconnaissance Unit to Nassau for dive training with the LARU-II (the LARU-II was identical to the LARU-III except for a smaller CO₂ scrubber and O₂ supply). 1LT Lambertsen remained in the States to finish production of the LARU-X. Figure 5 shows OSG-1 on the beach with the Duke of Windsor, then the Governor General and Commander-in-Chief (CINC) of the British West Indies.

Upon completion of dive training in July 1944, OSG-1 sailed for Hawaii and was offered by the OSS to Admiral Nimitz for employment. Admiral Nimitz had no need for divers but was pleased to have a group of skilled swimmers for the island-hopping invasion campaign in the Pacific.

**Fig. 5. Operational Swimmer Group 1 (OSG-1) on the beach in Nassau (C.J.L. photo).**

There had been too many U.S. Marine casualties during the amphibious landing at Tarawa in November 1943 because the topography of the underwater approaches to the invasion beaches was unknown. This led to the establishment of Navy Underwater Demolition Teams (UDT). Eventually, each UDT had 100 swimmers whose mission was to chart the water depths and search for obstacles off of the invasion beaches from the high water mark to a depth of 3.5 fathoms (7 m). Just before the invasion the next morning, under the cover of heavy bombardment from the fleet, the swimmers returned with demolitions and cleared the beaches of obstacles for the approaching landing craft. The OSS OSG-1 was immediately assigned to UDT-10, and taught the fledgling teams how to swim with fins and use facemasks. By the end of the
war, there were 20 UDTs with 2,000 swimmers, but OSG-1 never again used their LARU rebreathers.

In July 1944, OSG-2 deployed to Nassau for dive training with the LARU-X, with 1LT Lambertsen as its instructor and physician. The LARU-X (Figure 6) was more robust than the LARU-II and LARU-III. Gone were the steel cage and other components incompatible with seawater. A complete field repair kit was also provided (Figure 7).

Lambertsen trained the OSS operational swimmers and observed each pair of students’ performances. One day, he sank inertly to the bottom. Assuming this was part of the drill, the students continued to swim until, finally realizing something was wrong, they brought their unconscious instructor to the surface. He had taught them to purge their breathing bags with O$_2$ before diving to prevent dilution hypoxia, as O$_2$ was metabolically absorbed. This time, the instructor had neglected to purge his own bag, an object lesson that everyone remembered especially well. Upon regaining consciousness, Lambertsen went back into the water with the next pair of students to maintain their confidence and preserve the momentum of training.

The OSG-2 training activities not only taught diving but also tested equipment built by the OSS. In addition, it developed operational tactics for night reconnaissance and demolition. Figure 8 is a neutral buoyancy container for towing weapons or demolitions. Figure 9 is a limpet mine and firing device that a swimmer could attach to the hull of a ship.
With OSG-2 well-trained and equipped, the OSS was asked to demonstrate its secret capabilities to the Navy in an exercise at Guantanamo Bay Naval Base, Cuba, in September 1944. Swimmers infiltrated the bay at night by submarine, and were inserted by rubber boat. The submarine torpedo nets around the harbor proved to be no obstacle (Figure 10). Swimmers went over (Figure 11) and under the nets (Figure 12), dropped them to the bottom with demolitions, and once inside the harbor, found it easy to put limpet mines on target ships.

L-Unit personnel returned from England to train with OSG-3 at Nassau in October 1944. By this time, however, the war in Europe had moved to the continent, and there were no suitable targets for the U.S. OSG and British SRU. The Pacific theater offered more opportunities, but General MacArthur, CINC of the Pacific, had little use for ‘special’ units like the SRU and OSG, which he viewed as private armies. Admiral Mountbatten, CINC of the Southeast Asia Command (SEAC), felt differently, and the SRU and OSG were assigned to him. He referred to them as his pirates (9). OSG-2 operated with the SRU in the Burma campaign. Lambertsen, now a Captain (CPT), deployed with OSG-2 and then joined OSG-3 in Ceylon (today, Sri Lanka) to conduct training in swimmer delivery operations (Fig. 13).

**Sleeping Beauty**

The Bay of Biscay operation for the L-Units during the Normandy invasion of Europe had been canceled, in part, because divers with fins could cover not much more than a mile while operational infiltrations required much lengthier transits. The SOE
had developed a number of experimental underwater craft, including a motorized submersible canoe known as the Sleeping Beauty (Figure 14).

The Sleeping Beauty was 13 feet in length and accommodated a single pilot. Its range on the surface was thirty nautical miles at a speed of three knots, and it could dive to a depth of fifty feet (10). The SOE concept of operations for the Sleeping Beauty had the pilot approach a target vessel on the surface to a range of several hundred yards, submerge for the final approach, hang the vehicle from the target’s bilge keel, and attach a limpet mine (Figure 15).

The L-Units had returned to the United States in January of 1944 with a top secret Sleeping Beauty for testing and evaluation, and Lambertsen had an opportunity to study it in Washington. When he arrived in Ceylon in January 1945, he found two units available to him, and began an intensive program to train OSG-3 in the operation of the Sleeping Beauty. An SRU detachment on another part of the island was also training with the submersible canoe, and the two units got together to compare the LARU-X with the Amphibian-II breathing apparatus, which the Royal Navy had developed independently (Figure 16).

Throughout the war, British swimmers and divers occasionally became unconscious and were lost for no apparent reason, a phenomenon they called ‘shallow water blackout.’ From his own experience, Lambertsen knew that dilution hypoxia from inadequate purging of nitrogen in the breathing bag was one cause of unconsciousness. He demonstrated this to the SRU, using their officer in charge as an example (Figure 17). Other potential causes of shallow water blackout were CO₂ intoxication and O₂ toxicity, both of which could be brought on by CO₂ retention, as he would show in subsequent years (12). These were more likely with the Amphibian-II because its pendulum breathing circuit, as in the original LARU (Fig. 1), was predisposed to CO₂ retention. The British
Navy eventually restricted O\textsubscript{2} diving to 30 feet (10 m) and introduced rigorous nitrogen purge procedures (13), but the use of pendulum rebreathers continued in use until the 1980s.

CPT Lambertsen’s training program for the Sleeping Beauty included the development of new tactical procedures that were based on its use to deliver operational swimmers. Instead of taking the submersible directly to a target, the pilot would navigate to within several hundred yards, park or moor the canoe on the bottom, swim to the target, place demolition charges on it, and swim back to the Sleeping Beauty. These procedures represented the birth of the swimmer delivery vehicle (SDV) concept. Before further development or operational employment, however, the war ended, and President Truman disbanded the OSS and sent home its skilled operational swimmers. SDV work did not begin again until 1948, with the Navy’s Underwater Demolition Teams. It did not reach fruition until 1982, when the Navy’s SEAL Delivery Vehicle Teams were commissioned.

**Post-War**

CPT Lambertsen was assigned to an Army hospital as a medical officer upon his return to the United States. Recognizing that the operational underwater swimmer program had abruptly ended with the demise of the OSS, he had the secret LARU-X declassified, and delivered two units each to the Navy, Army, and Coast Guard (being careful to obtain written receipts) with letters of explanation to senior officers. The commandant of the Coast Guard himself responded quickly, and Lambertsen was assigned to train a cadre of instructors for the possible use of O\textsubscript{2} rebreathers in rescue and recovery at sea. One day, after drifting deeper than intended, he found himself at 100 feet (30 m) with a fluttering diaphragm. His last action before an O\textsubscript{2} seizure was to inflate his breathing bags in order to become positively buoyant. He awoke with a buzzing in his head, staring into the eyes of a Navy chaplain.

**Fig. 18.** Lambertsen on assignment to the U.S. Army Corps of Engineers (C.J.L. photo).

An Army observer assigned during the Coast Guard training recommended that Lambertsen work with the Corps of Engineers to determine the feasibility of O\textsubscript{2} diving for river operations. During three months as a civilian, he tested British, Italian, and U.S. diving equipment, and developed river combat diving procedures. Figure 18 shows Lambertsen with a reel of telephone cable on his back, prior to a submerged passage across the Ohio River.

The U.S. Navy was the last service to seek advice. Actually, it was not the official Navy but Lieutenant Commander Douglas (Red Dog) Fane, U.S. Naval Reserve, the most senior UDT officer after the war. He was in charge of two small underwater demolition teams in Little Creek, Virginia. The Navy had proposed a change to the UDT name and mission. To prevent
this, Fane wanted to put the UDT underwater, as divers. In 1947, he invited Lambertsen, now a civilian instructor in pharmacology at the University of Pennsylvania Medical School, to Little Creek to train a selected group of UDT swimmers in tactical diving with the LARU and Sleeping Beauty (14). Butler describes this story in detail (15).

O2 Research

When Lambertsen was released from active duty with the Army in 1946 as a Major, he returned to the Pharmacology Department at the University of Pennsylvania, where he had worked as a medical student. His four or more episodes of O2 toxicity, including one seizure, had stimulated his curiosity concerning the underlying mechanisms of central nervous system (CNS) O2 toxicity. This was a fortuitous time. Seymour Kety had recently developed a method for measuring cerebral blood flow and metabolism by using nitrous oxide uptake and washout from the brain (16). With a grant from the Office of Naval Research, Lambertsen turned the doors around in an altitude chamber to convert it into a pressure chamber. In the chamber, he used Kety’s methods to study the effects of hyperbaric O2 and inspired CO2 on cerebral blood flow and O2 consumption both in normal subjects and schizophrenic patients (12, 17, 18). Electroconvulsive therapy (ECT) was a common treatment for schizophrenia at the time. Using high-pressure O2, rather than ECT, to induce convulsions was conceived as an alternative, if experimental, therapy.

These studies revealed that hemoglobin never de-saturated while subjects breathed high-pressure O2. This interfered with the ability of the blood to transport CO2 and caused the CO2 tension in the brain to rise abnormally (17, 18). The elevated CO2 tension stimulated ventilation, which reduced the CO2 tension in the arterial blood. CO2 was demonstrated to be a potent vasoactive signal to the cerebral circulation (12). Cerebral vasoconstriction and decreased blood flow induced by hyperventilation reduced O2 delivery to the brain. A possible explanation for Lambertsen’s observations while O2 diving with the Navy and OSS was the idea that hyperventilation could abort the signs and symptoms of CNS O2 toxicity. Conversely, the chamber studies with the schizophrenic patients showed that inspired CO2 accelerated the onset of O2 toxicity.

These were the beginnings of Chris Lambertsen’s systematic study of the physiology of O2 and its toxicity. Inspired by practical wartime experience, he developed a career of expanding interest and influence that continues to this day.

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