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UNDERWATER ANESTHESIA MACHINES? WELL, ALMOST. CLOSED-CIRCUIT REBREATHERS AND THE LEAP FORWARD FOR ADVANCED DIVING, EXPLORATION, AND DISCOVERY

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Anesthesia machines are complex multi-component systems that control the delivery of specific concentrations of gases and allow vigilant monitoring of the patient. There are many variations in design and function, but they generally consist of a breathing circuit, ventilator, anesthetic vaporizer, scavenging system, carbon dioxide (CO_2) absorbent, and multiple physiologic monitoring systems. Classification of the breathing systems range from open and semi-open systems, where gases are not rebreathed, to closed and semi-closed systems in which gases are rebreathed. The closed and semi-closed designs, which are collectively known as circle breathing systems, consist of a circuit where exhaled gases enter a loop to be reused, fresh gas is added, and excess gas is expelled through a waste valve. The gas in the circuit is filtered through scrubbers that remove CO_2 through chemical absorption and monitor levels of CO_2. Fresh oxygen is added to the circuit, and galvanic oxygen sensors analyze the fraction of inspired oxygen, or FiO_2.[1]

Similar in design and function to these anesthesia systems, closed circuit rebreathers (CCRs) are becoming increasingly prevalent in the recreational scuba diving community. Once relegated to only military pursuits and a few advanced civilian divers, the popularity of CCRs has increased sharply in the past two decades. This rise in CCR use is due to an increasing number of manufacturers, decreased production costs, and the increasingly recognized benefits of CCRs compared with traditional open-circuit (OC) scuba diving equipment.

CCRs offer numerous advantages compared to traditional OC equipment. First, CCRs provide divers with warm, humidified breathing gas due to its passage through the respiratory tract and CO_2 scrubbers. Heat and moisture are particularly attractive on long duration dives, where cold compressed gas from OC systems can lead to airway irritation, dehydration, and heat loss. Furthermore, a CCR does not vent gas to the water column, which is advantageous to photographers wishing for close proximity to undersea life or for divers in environments with fragile ceilings, like wrecks or caves. In addition, divers are able to optimize their diving profiles and decompression obligations due to maintenance of a selected partial pressure of oxygen (PO_2) at every depth instead of a varying partial pressure of oxygen like that which occurs with OC gear. Lastly, and most importantly, gas consumption is greatly improved with CCRs. OC systems inefficiently use about 3% of the gas for oxygenation at the surface, while the rest is exhaled as waste. This efficiency decreases to approximately 0.6% at 40 meters and 0.3% at 100 meters.[2] Because oxygen metabolism is independent of depth, breathing gas utilization for CCRs becomes increasingly efficient at deeper depths when compared to OC as oxygen metabolism is relatively constant despite a diver's depth. This feature of CCRs is especially important when diving with helium, which has become increasingly more expensive due to a limited global supply.

A generic CCR consists of a breathing loop, CO_2 scrubber, O_2 sensors, gas cylinders containing pure oxygen and a diluent gas, and a computer to monitor oxygen tensions within the system. The breathing loop includes a counter lung that acts as a reservoir to increase the volume of the loop and to allow the diver to exhale completely before taking the next breath. As the exhaled gas travels through the breathing loop, it passes through a CO_2 scrubber composed of soda lime, which includes calcium hydroxide (neutralizing base),

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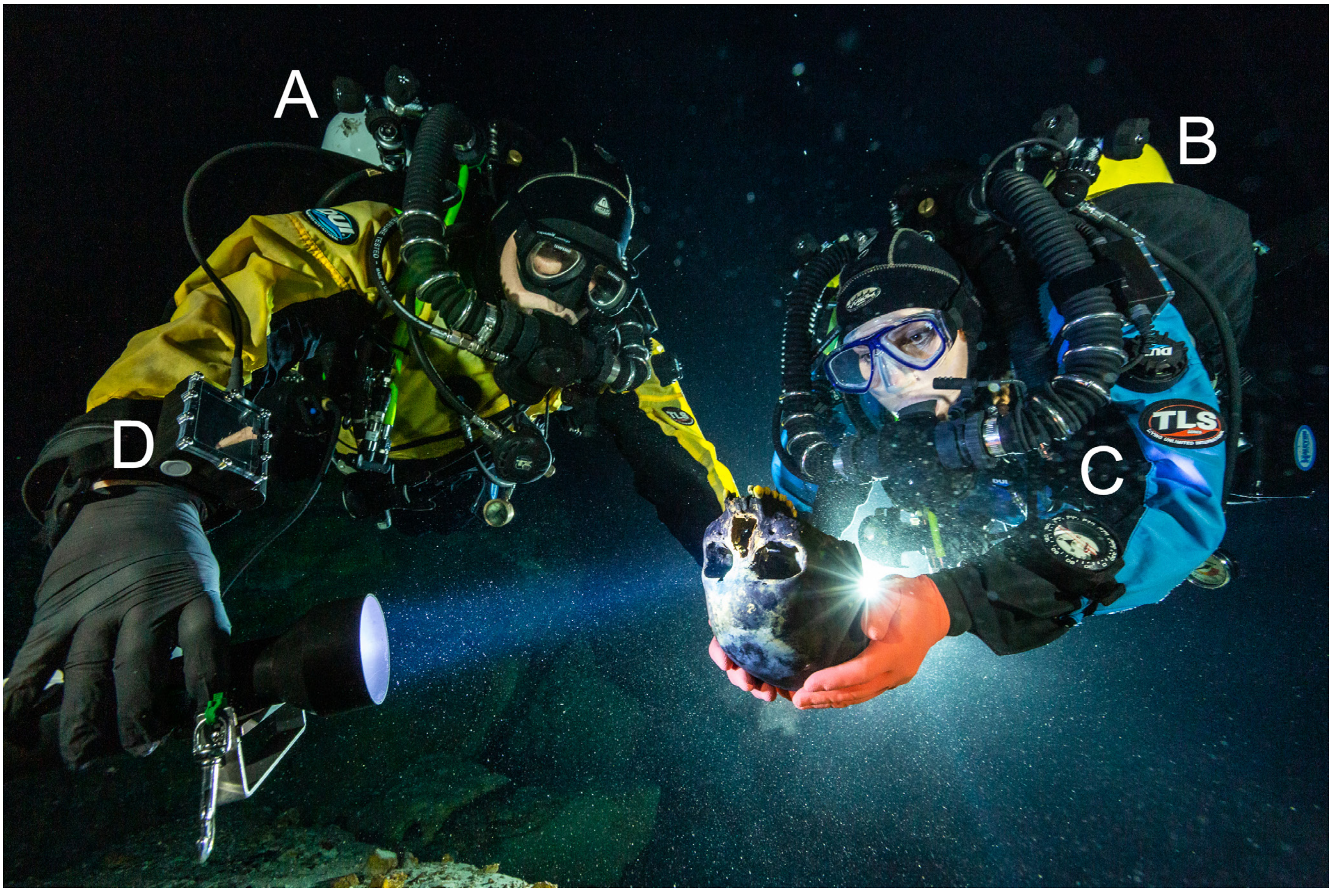

Image 1: CCR divers gently move an artifact found at the bottom of Hoyo Nego, which is part of the Sistema Sac Actun cave system in Mexico. Note the oxygen cylinder (A), diluent cylinder (B), breathing loop (C), and dive computer with PO2 monitoring (D). Photo credit: Paul Nicklen.

water, and a catalyst in the form of strong bases like sodium hydroxide and potassium hydroxide. This reaction creates water and heat, which helps to maintain the warm, humid breathing gas. The PO_2 is analyzed via galvanic oxygen cells that work similar to a battery, producing an electrical current that is proportional to the PO_2 levels. Depending on the system, O_2 is then automatically or manually added by the diver to maintain a desired PO_2 set point. The diluent gas is a variable mixture of air, nitrogen, oxygen, and helium, which is generally only added to the breathing loop as the diver descends due to increased ambient pressure, increasing PO_2, and decreased breathing gas volume. One-way mushroom valves ensure a proper direction of gas flow, which ensures the removal of CO_2 and addition of O_2 before the gas is rebreathed.

Although CCRs used by divers closely resemble the circle system anesthesia machine, there are a few notable differences that set them apart. In general, there are no CO_2 monitors in CCRs, which is significant because hypercapnia is one of the most common etiologies of injuries and deaths for CCR divers.[3] CCRs also lack fail safe/downstream oxygen safety features, such as limiting the addition of non-oxygen gases or automatically using a second oxygen source to maintain a sufficient oxygen tension for metabolism. In addition, CCRs must be compact and mobile to facilitate traveling with these machines and using them underwater. Finally, these machines, which have fragile electrical internal components, must be capable of operating in an inhospitable environment characterized by severe pressure, fluctuations in temperature, water, and humidity.

Despite these current shortcomings and challenges compared to anesthesia machines, CCRs represent a pivotal leap forward in deep and extended range technical diving. For example, Alberto Nava and his dive team utilized CCRs during the exploration of the Hoyo Negro ("Black Hole") section of the Sistema Sac Actun cave in the Yucatan Peninsula of Mexico.[4] At depths exceeding 50 meters of fresh water (mfw), CCRs enabled the explorers extended and more comfortable dive times to delicately collect archeological specimens. In addition to the bones of extinct saber tooth tigers, bears, and wolves, Nava and his team discovered the most complete human skeleton in the Americas exceeding 12,000 years of age [Image 1]. CCRs have also facilitated the exploration of deep cave systems in the state of Florida, scientific research concerning marine species and environments beyond the shallow reef habitat, and the discovery and retrieval of artifacts from deep shipwrecks.[5–7] As Ed O'Brien, the dive safety officer for the famed Woods Hole Oceanographic Institution (WHOI), says, CCRs are a "…gamechanger for us".[7]

As experts in cardiopulmonary physiology and anesthesia delivery systems, anesthetists are in a unique position to influence CCR design and to improve their safety profiles. In a broader sense, anesthetists should consider using their expertise to conduct research in hyperbaric and undersea medicine, which is a small medical specialty with ample opportunities for scientific investigation. Finally, if one is seeking a more diverse clinical practice, he or she could also pursue further training in this field of medicine in the form of a certificate of added qualification program or formal fellowship. In the meantime, even contemporary CCRs continue to extend the boundaries of advanced diving, exploration, and discovery.

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