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Hyperbaric Treatment of Compressed Air Workers, Caissons, Tunneling, Bounce Diving, and Saturation Diving

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Continuing Education Activity

This activity addresses the modalities used in the performance of compressed air work; caissons, tunneling, and commercial diving, and the various modalities used to accomplish this work. This activity outlines the indications, mechanisms employed, the potential complications encountered, adverse effects, and health monitoring of compressed air workers.

Objectives:

- Describe the various modalities used during compressed air work.
- Summarize the appropriate use of each type of compression and decompression modalities and articulate the associated health complications related to each.
- Identify the various techniques employed in compressed air work and how each effect these modalities have on the healthcare of these workers.
- Outline strategies that can improve collaborative working relationships among interprofessional teams to help promote the safe care of compressed air workers.

Access free multiple choice questions on this topic.

Introduction

The field of compressed air work (CAW) includes caisson workers, tunnel workers, commercial divers, and inside observers working in multiplace hyperbaric chambers and any environment with increased atmospheric pressure. To summarize, this field includes all workers who perform duties at increased atmospheric pressure. This article will reference all of the workers in these varied environments as compressed air workers (CAWs). CAWs use compressed air during tunneling jobs to prevent flooding by groundwater and/or the entrance of toxic substances such as methane gas. The CAW field has undergone significant change since tunnels and caissons were first constructed in the 1800s.[1] Between that time and the early 1980s, tunnels were primarily excavated by hand by workers exposed to the extremes of increased atmospheric pressure. There was a high incidence of decompression sickness (DCS) among caisson workers (CAWs), commonly referred to as the bends, due to the "bent over" bodily posture workers assumed secondary to the pain in the hips and spine caused by DCS.[1] Pile driving has since replaced much of the need for compressed air caisson work. Skilled and well trained commercial divers perform underwater compressed air work. Their risk of decompression sickness and air gas embolism gets mitigated through the use of well designed academic diving education programs and the use of continuously updated decompression tables and modeling.[2] On-site hyperbaric chambers and medical teams are necessary for specific job sites depending on the conditions and depth of the work. Regulations for compressed air work are on the Occupational Safety and Health Administration (OSHA) website under standard number 1926.803-Compressed Air. Despite all attempts to mitigate risk, tunnel CAWs may still suffer the signs and symptoms of DCS and a variety of other typical construction work-related hazards. This paper will discuss CAWs performance in dry hyperbaric environments, particularly those pertaining to tunnel and caisson work, as well as the different methods of compression used to keep them safe and the job productive and cost-effective.

Indications

The construction of underground passages is becoming significantly more common. Roadways, water siphons, subways, and electrical lines are only a few of the reasons this industry has become so popular. As we run out of usable space on the surface of the earth, underground passages will become even more important to our environment. The modern tunnel boring machine (TBM) has eliminated the need to excavate by hand but has not eliminated the need for CAWs to perform their duties while under the extremes of atmospheric pressure. These workers are still required to enter the face of the TBM to perform inspections, repair tools (rippers and cutters) and all the machinery responsible for the excavation process.[3] The "face" of the TBM refers to the area that is under increased atmospheric pressure in the front of the machine. The amount of pressure required at the face is directly proportional to the depth of the tunnel, groundwater level, and the presence of toxic substances such as methane gas as mentioned earlier. When the tools need inspection or repair, the CAWs are compressed into the face of the TBM via the hyperbaric chambers to perform the duties necessary so the excavation process can be resumed as quickly as possible. The face of the TBM is initially filled with a thixotropic substance known as bentonite. This process is referred to in the industry as "caking the face." They allow the bentonite to solidify over a typical 5- to 6- hour period. Bentonite serves as a filler or grout to aid in blocking ground-water and toxic substances from entering the working face. It also functions to prevent the escape of the compressed air used to stabilize the tunnel face. If not for the bentonite, the air pressure would escape into the crevasses of the soil and rock in front of the TBM rendering the face unstable during the compressed air work or hyperbaric intervention (HI). This process of assuring the maintenance of steady air pressure in the front of the TBM and followed by compressing the workers into the face of the TBM to perform the necessary work duties under pressure, and followed by safely decompressing them or returning them to the habitat, is collectively known as a hyperbaric intervention. These interventions are commonly scheduled as equipment and tools require inspections and maintenance. They are also performed urgently when encountering toxic gases, or faulty equipment needs replacement or repair.[4]

Contraindications

The contraindications to working in the field of compressed air are similar to those of a commercial diver. The diving industry follows the medical health requirements of the Association of Diving Contractors International (ADCI) and the medical evaluations as structured by the Diving Medical Advisory Committee (DMAC). Diver and CAW health examinations should be performed by physicians that have experience in diving medicine and compressed air work, are certified, or board certified in Undersea & Hyperbaric Medicine and preferably have completed a course recognized by the Dive Medical Advisory Committee (DMAC) with the title Medical Examiner of Divers.

The extensive list of contraindications to working in the compressed gas field can is at https://www.adc-int.org/aboutadci and http://www.dmac-diving.orer. Potential complications will be discussed in the complications section below.

Equipment

Modern tunnel boring machines are of variable diameters, work at many depths and require CAWs to assure they continue to function appropriately and timely. The specific equipment used will depend on many factors such as the geology of the ground (rock vs. sand), depth at the face, groundwater levels and the potential presence of toxic substances such as methane gas. Although the tunnels are no longer excavated manually by the CAWs, the tools at the face of these machines (rippers and cutters) require periodic inspection and changing when worn down and no longer effective at performing their cutting and grinding functions; trained CAWs are needed to complete this maintenance.

Many hyperbaric interventions occur at depths that allow repetitive bounce diving multiple times per day with minimal risk. They typically use commercial diving companies to oversee and deliver these services, especially when hyperbaric interventions are necessary to depths greater than 2.5 Bar (82 FSW). There is a hyperbaric chamber ("medical lock"), specially designed and conveniently located to provide hyperbaric medical treatment. Medical locks are typically at the surface near the excavation area. The medical lock is required to treat those CAWs who might suffer from DCS. It is also useful before performing hyperbaric interventions to qualify CAWs with a "test dive" to assess their physical and psychological reactions to working under increased atmospheric pressure. They perform this qualification or "checkout" dive (as they typically referr to it in the compressed air industry) at depths greater than the expected depth expected during the actual hyperbaric intervention. The medical team remains on site during hyperbaric interventions and for 24 hours after the completion of the hyperbaric intervention; this is to assure all CAWs are in good health following compression and do not require hyperbaric medical intervention and treatment before the medical team leaving the job site.

In a technique known as saturation diving, CAWs live at depth (under pressure) in the hyperbaric chamber (called the habitat) located on the surface. The habitat is where the CAWs and divers live when not working. It is pressurized at or near working pressure encountered at the tunnel boring machine face, the expected hyperbaric intervention pressure. CAW teams are compressed into the saturation chamber at the same time and use it as their home base or habitat for the duration of the job. They travel (typically in teams of two or more) to and from the habitat to the work site in the TBM face via this hyperbaric shuttle or transfer capsule. The capsule or shuttle is a mobile hyperbaric chamber. Once the shuttle arrives at the TBM, it's mated with the TBM hyperbaric chamber or "man-lock" via a universal connection or collar. These collars mount on the medical lock, transfer capsule and man-locks (hyperbaric chambers) in the front of the TBM. All these connections occur at atmospheric pressure outside the chambers. Once mated and pressure equalized, the workers transfer from the shuttle into the man-lock built into the TBM during its fabrication. The CAWs pass through the man-lock to the TBM face. At times, small pressure changes are necessary to move from one lock to the next. The TBM chamber undergoes pressurization to the pressure equivalent to that found at the face of the TBM or the "working pressure." The CAWs usually perform a 6- to 8-hour shift and return to the habitat via the shuttle, followed by replacement with the next CAW team from the habitat who exit the shuttle to allow the last working team to return. This process continues around the clock until which time they complete the tasks. This saturation method only requires one compression at the start of the work and one decompression at the end of the hyperbaric intervention. All workers undergo compression at the beginning and decompression at the completion of the hyperbaric intervention. There exist various gas mixtures used during saturation diving. All the gases we breathe become toxic when their partial pressure increases. Different mixtures of oxygen, nitrogen, and helium are most commonly employed to mitigate adverse events of breathing gas toxicity.[4][5] This concept will be discussed later in this article under complications.

Personnel

CAWs are a diverse group of individuals working in both commercial diving and tunnel construction industries. There is a significant difference between the two groups of workers regarding training, education, and the medical fitness requirements necessary to work in a compressed air environment. Commercial divers are specially trained to work in extreme atmospheric pressure environments while enrolled in a recognized commercial diving school hosting a formal diving education program. Commercial divers are trained to recognize the potential ill effects of compressed air work, know their limitations, and when to ask for help. They require a stringent medical health evaluation yearly while they work in the commercial diving industry; this is to assure they are fit to work in a compressed air environment and are also physically capable of performing the required duties.

CAWs employed by construction companies are hired to perform many duties, including those not necessarily limited to the compressed air environment. They work in the compressed air environment on an "as needed basis" when there is compressed air work to be performed. They have no training in a formal educational program for compressed air work like commercial divers. They are also not explicitly trained regarding all the potential complications of CAW. Although they are required to submit to a periodic health evaluation, it is not necessarily specific to CAWs as are the health evaluations commercial divers are required to complete. This situation is an important consideration when the on-site dive medical team has the responsibility to clear CAWs for duty.

Commercial dive companies provide hyperbaric chamber operators and the support equipment necessary to carry out specific hyperbaric interventions. The hyperbaric commercial dive team works closely with the onsite hyperbaric tunnel medicine team to provide pre-hyperbaric intervention education, fitness to dive assessments, verify compression and decompression schedules, complete post-dive intervention examinations, provide first aid and emergency critical medical care when necessary. Emergency critical care often initiates with the physician and members of the on-site medical team. They must be able and willing to lock into the hyperbaric chamber to provide emergency care for CAWs who suffer traumatic injuries; especially when the injuries occur prior to meeting the necessary decompression obligation. Having an on-site hyperbaric physician and medical team with appropriate emergency and hyperbaric expertise is critical and should be considered a priority by all companies partnered with the compressed air project. All companies involved are responsible for the health, safety, and well-being of their employees and must minimally abide by the rules and regulations of both NIOSH and OSHA. Even when these federal regulations are followed and put in place, they have not been updated for many years, requiring applications for state dependant for every project.[6]

Preparation

Prior to the beginning of any hyperbaric intervention, all workers get introduced to the work involved at the specific site, the potential hazards of the work required, the compression and decompression profiles, potential adverse events associated with working under pressure and those surrounding the decompression phase of work. This process is conducted in a semi-formal, educational, classroom-type atmosphere and precedes the physical examination and health screen performed by the hyperbaric physician and tunnel medical team. The plan and the importance of not deviating from the plan are discussed. Consequences of deviation of the approved hyperbaric intervention plan can have both legal and health-related consequences. As mentioned, a state-approved variance is usually necessary and requires approval for hyperbaric interventions occurring in the United States; this is primarily due to the outdated OSHA regulations as they apply towards compressed air occupational health and safety and compression and decompression protocols. The decompression schedules currently in use need to be updated to support modern-day hyperbaric interventions properly. Oxygen decompression schedules have been used effectively for CAW decompression since the 1960s. Despite this, modern air/oxygen decompression schedules are not part of OSHA's outdated regulations and policies. Dr. Eric Kindwall initially brought this deficit to the medical communities attention in an article published years ago, and unfortunately, OSHA did not implement his updated oxygen decompression schedules.[6]

Technique or Treatment

A technique referred to as bounce diving is commonly used in standard commercial wet diving and also for dry diving the tunneling industry when hyperbaric interventions are required. Bounce diving requires several teams of CAWs, working in succession over a 24-hour period. The hyperbaric chamber is used to compress the workers into the face of the TBM to perform their duties. The chambers are built directly into the front of the tunnel boring machines (TBMs) during fabrication. The time spent performing their duties in the face of the TBM is commensurate with the depth and time of the work and the decompression tables used. Upon completion of their shift, they decompress in the hyperbaric chamber. During compression and decompression, the CAWs are observed by a team of skilled hyperbaric chamber operators and the on-site hyperbaric medical teams. Some construction companies have used dive medical technologists (DMTs) to perform on-site medical duties. The company allocates them to multiple duties such as driving the chamber and entering the chamber while at depth to attend to medical emergencies. Some actually expect the chamber to be decompressed by the DMT from inside the chamber simultaneously while performing the emergency medical duties. This practice should be considered unsafe and avoided as it is not the optimal fashion to provide hyperbaric medical services. There should be an experienced dive medicine physician and medical team on-site separate from chamber operation duties. The team should be composed of emergency medical technologists (EMT) with hyperbaric or dive medic certification (CHT) and/or emergency trained nurses (CEN) with hyperbaric certification (CHRN) to assist the physician in performing diver health evaluations. The National Board of Diving and Hyperbaric Medical Technology (NBDHMT) and the Baromedical Nurses Association (BNA) provide these certifications. This method of working with the onsite medical team is the preferred and safest method to provide the required healthcare to the CAW teams. Using a highly qualified medical team on-site comes with a higher cost factor for the construction company but will prove to be a money-saving endeavor if a significant emergent medical problem was to occur.

The term "bounce diving" makes reference to daily compression and decompression of the CAWs; similar to that performed in commercial wet diving. The hyperbaric intervention begins with a rapid compression to the working depth. The rate of compression is commensurate with the CAWs ability to equalize middle ear pressure, and not to exceed the predetermined minimum time limit of compression to the working depth. This is followed by a short working period and longer decompression to surface. A variety of gases may be employed for this purpose. The most common being oxygen when the decompression depth reaches 60 FSW equivalent. At this point of decompression, oxygen is breathed intermittently during a series of decompression stops. This continues until the CAWs reach the surface.

The required pressure to maintain a balance between the earth and the face of the TBM is known before hyperbaric interventions and adjusted based on the earth conditions. A diving plan is put in place that will include a compression rate and working time to pressure based on the working depth. They use a variety of accepted diving decompression tables that may include the use of a variety of gas mixtures depending on the depth of the work and necessary time for decompression. The decompression tables used will vary depending on the preference of the dive company and hyperbaric physicians responsible for setting the best bounce-dive schedule in an attempt to mitigate the potential for decompression sickness. The French decompression tables for tunnel bounce diving are preferred as they are more conservative than the U.S. Navy Treatment Tables (USNTT). They also employ a combination of air-Oxygen decompression using a sealed mask to shorten decompression time and add a significant level of safety (risk mitigation) to the decompression schedule. Air-only decompression tables are used by some companies but are discouraged. The benefits of using oxygen as a supplemental gas for working at pressure and for decompression are well known and will decrease the incidence of DCS[7]. Using oxygen during decompression decreases the overall decompression time and enhances work productivity[6]. Of note, bounce diving requires more skill of the CAWs, hyperbaric and medical teams as it holds more potential risk for decompression sickness for the CAWs and is more demanding from the perspective of dive operations despite being the most common of all hyperbaric interventions.

More practical ways of performing hyperbaric interventions are being investigated. One such option is mixed gas saturation diving and its physiologic and pathologic effects on CAWs and commercial divers[7][8]. Saturation diving, although a more expensive service to provide from the operational perspective, might actually decrease cost based on increased work production, and less time spent performing the hyperbaric intervention. Saturation interventions may also decrease the incidence of DCS based on the need for one decompression at the end of the intervention. Although a practical concept of increased work productivity and overall decreased in cost assumptions, to date, no prospective or retrospective research has been published. This is probably due to the newness and underutilization of saturation interventions. Much of this data is interpolated from wet commercial diving data that is often proprietary to each individual dive company and not shared with the diving or medical communities. The potential decrease in the incidence of DCS relates to the diminished number of excursions needed by the CAWs; to and from depth. Saturation hyperbaric interventions only require the CAWs to compress and decompress once; at the beginning and end of the project as compared to compressing and decompressing on a daily schedule. CAWs remain at the working depth for a maximum 28-day period. Despite requiring a lengthy decompression period, the decompression period is irrespective of the increased time spent at depth (bottom time) and more dependent on the actual saturation depth (pressure). As a general and simplified rule only, every 100 FSW (3.06 Bar) requires approximately 24 hours of decompression. Saturation hyperbaric interventions and diving are reserved for those jobs that move beyond the depths considered safe or accessible by bounce diving. It is difficult at times to employ saturation techniques as some companies cannot see past the increased operational expense to appreciate the potential decreased expense risk of DCS and work productivity. Dismissing saturation diving in favor of bounce diving at extreme depths are the avoidance of operational uncertainties resulting in worker catastrophes resulting in financially draining lawsuits to the company.

Saturation dives can be accomplished using compressed air but are most commonly performed using mixed gases; helium being the most common additive to air or gas mixture. All the components of the air we breathe become toxic at depths greater than 60 FSW and over prolonged periods of time. The potential for oxygen toxicity increases with the risk of nitrogen narcosis. The addition of helium to the mix decreases the amounts of oxygen and nitrogen rendering the breathing mixture less-toxic to the CAW. The goal is to maintain an oxygen partial pressure of 0.3 to 0.4 atm at depth (slightly higher than sea level at 0.21). These levels seem to mitigate the risks of oxygen toxicity and hypoxia. Lowering nitrogen levels mitigates the risk of nitrogen narcosis and improved CAW mentation. CAWs performing hyperbaric interventions need not be concerned with an excursion deeper than or more shallow than the working depth. Any minimal changes in depth between the habitat, excursion shuttle, and man-lock are managed by the dive team life support technologists and hyperbaric physician. This is not the same for wet divers who may be required to ascend and descend in the water once they leave the diving bell or transfer capsule to reach a work area. Here, excursion decompression tables are used to mitigate the risk of DCS.

Complications

There are currently no studies specific to the epidemiology, incidence, and prevalence of the adverse effects potentially experience by CAWs. Despite this, adverse effects associated with compressed air work can be categorical and multifactorial. There are adverse effects related to both the actual construction work and the atmospheric environment in which they work. The environmental concerns pertain to the air, its potential contaminants, and those associated with breathing compressed air and mixed gases. Construction injuries get classified according to etiology. They range from minor injuries requiring first aid as simple cuts or abrasions or can be major, including traumatic amputations, burns, ergonomic injuries, and multiple trauma from falls.[9][10] The air CAWs breathe may be contaminated with methane and/or other gases and various forms of dust resulting in acute and chronic respiratory pathologies.[11][12] We will concentrate on the adverse effects associated with the compressed air environment and breathing compressed air. Adverse effects can be further broken down into mechanical, physiological, and pharmacologic categories, and categorized as occurring during compression (descent) or decompression (ascent) of the hyperbaric chamber.

Common Mechanical Adverse Effects of Compression and Decompression

The mechanical effects relate to Boyle's law that states pressure and volume are inversely proportional to one another. As pressure increases, volume decreases, and vice versa. This change in volume of air or gas will effect CAWs in the air containing spaces of the body only; the eustachian tube (ET), middle ear space (MES), sinuses, respiratory tree, lungs, and gastrointestinal tract. Hyperbaric pressure will have no direct mechanical effect on body tissues, plasma, blood, or other matter. Hyperbaric pressure may also effect iatrogenically created air spaces such as air pockets surrounding dental work and air created by a tooth abscess. Also included is air introduced into the globe of the eye following common surgical procedures such as cataract extraction, or intraocular injections.

During descent or compression of the hyperbaric chamber, the most common adverse effect is eustachian tube dysfunction (ETD) and middle ear barotrauma (MEB).[13][14] Increasing pressure in the external ear canal creates a negative pressure in the middle ear space when the eustachian tube cannot ventilate the space. The occurrence of eustachian tube dysfunction and middle ear barotrauma are unpredictable. They may be preventable at times by using medications under specific circumstances, changing compression rates, or the slopes of compression. During dry hyperbaric compression in tunnel work and clinical hyperbaric chambers, a modified Politzer device providing high-pressure air easily delivered into the nares while swallowing has been demonstrated to decrease the incidence of eustachian tube dysfunction and are safe in a multiplace Class-A chamber environment. Ear pain is the most common symptom that may be relieved by halting compression and allowing the CAW the opportunity to equalize. Ascending a few feet in the chamber may also facilitate clearing. Sinus barotrauma is less common but can occur in less than 1% of divers. It may present as sinus discomfort, facial pain, and nasal bleeding.[15][16][17] Sinus barotrauma does not appear to be significant in the compressed air industry and does not appear in the tunneling literature. Air spaces left after dental work are also subject to gas compression and expansion and can also be the cause of significant tooth or mouth discomfort. Pulmonary barotrauma may occur from breath holding or physiologic and anatomical trapped gas that expands during ascent or decompression.[18] Anatomical disruptions in the pulmonary and vascular components caused by barotrauma may potentially lead to an air gas embolism or AGE.[19]

Physiologic Adverse Effects

Nitrogen narcosis usually occurs at depths greater than 4.0 atm. Symptoms are similar to alcohol intoxication as it impairs judgment and slows responses that will impede the CAWs performance.[20] If using mixed gases during saturation tunnel work, cautions are taken depending on the gas mixtures used. Helium is associated with high-pressure nervous syndrome or HPNS.[21][22] It is most commonly reported in wet saturation diving at depths deeper than standard tunneling (usually greater than 600 fsw). Nonetheless, saturation diving has been utilized and will become more prominent and accepted as a reasonable (and possibly better) alternative to bounce diving as tunnels become deeper.[5][4] When saturation diving is routinely employed, the potential adverse events will have to be proactively considered and managed by the compressed air medical teams and life support technologists. Inert gas counter-diffusion occurs when changing gas mixtures on decompression. This can cause DCS despite no significant excursion depth from storage depth or change in ambient pressure. DCS is treated as per usual routines.

Decompression with oxygen has significantly mitigated the risk of DCS and decreases the total time necessary for decompression.[6][23] This factor has significantly improved work productivity from a safety and time perspective. When oxygen is used at increased atmospheric pressure it has the risk of causing adverse events including oxygen toxicity. The risk of oxygen toxicity is usually greatest during mixed gas diving and at more extreme depths (pressure)[24][25]

Dust inhalation during all types of construction work that includes dust exposures during hyperbaric tunneling interventions may lead to minor and major clinical pathological problems.[26][27] Chronic dust inhalation may lead to exacerbation of asthma or reactive asthma-like syndrome, pulmonary fibrosis, and a decline in pulmonary function.[26]

Enhancing Healthcare Team Outcomes

The healthcare of CAWs is not overly streamlined or consistent. CAW health evaluations are routinely performed by either occupational or Undersea & Hyperbaric Medicine physicians and those practicing primary care. OSHA states that physicians caring for CAWs need only have "experience" in working with those subjected to the extremes of atmospheric pressure. The OSHA policies regarding CAWs are clearly outdated, non-specific, and in need of significant revision.[6] Medical teams having the responsibility of caring for CAWs need to have the appropriate training, qualifications, and experience expected, as in any other field of medicine. Undersea & Hyperbaric Medicine physicians undergo rigorous training during a one-year fellowship program to eventually become board certified to adequately care for CAWs at a level expected of any medical specialty. Occupational medicine physicians are not specifically trained to care for CAWs. Some may have significant experience, however, especially when located in demographic areas known for commercial diving activities. Adequate maintenance of health records is imperative. CAWs tend to move around in geographic areas. Allowing access to the records by those members of the hyperbaric health team responsible for continued care is imperative; this is to assure reasonable and responsible care on a year-to-year basis during periodic health evaluations and to maintain a responsible follow-up to organ systems that may potentially affect the CAWs career, especially the hearing and cardiopulmonary systems. The days of prudent monitoring of various health-related problems such as myopia, decompression sickness, and silica exposure in "caisson workers" has passed.[28][29][30]

Although needed, there are no significant new clinical trials ongoing to evaluate the risks to CAWs. Studies in saturation divers are few and have relied on brief communications about diver self-reporting.[31] Significant changes to current policy are in order, especially regarding the immediate health and ongoing long-term healthcare of the CAW.

Review Questions

- Access free multiple choice questions on this topic.
- Comment on this article.

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