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A Comparison of the Actual and Recommended Diving Profiles of Dominican Republic Diver Fishermen

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A Comparison of the Actual and Recommended Diving Profiles of Dominican Republic Diver Fishermen

By

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Accepted in Partial Completion
of the Requirements for the Degree
Master of Science

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Master's Thesis

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A Comparison of the Actual and Recommended Diving Profiles of Dominican Republic Diver Fishermen

A Thesis
Presented to
The Faculty of
Western Washington University

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Abstract

Decompression stops upon ascent of a dive help to decrease the likelihood of developing decompression sickness in divers. The purpose of this study was to compare the actual versus the recommended dive profiles of compressor fishermen in the Dominican Republic to explore the occupational risk associated with decompression sickness that these fishermen endure. For this study, 10 male diver fishermen from Monte Cristi, Dominican Republic self-reported their diving profiles including the dive depth, the time spent at that specific depth, the duration of ascent, and the surface interval between repeat dives, for each dive conducted in a single workday. The depth and duration of each dive was then entered into V-Planner dive decompression planning software to calculate the decompression needed for safe diving profiles. Each dive was graphed using depth and time, and the area under the curve for the actual and recommended diving profiles was calculated. The total dive time (294.3 ± 101.9 min actual and 524.7 ± 170.57 min recommended), total decompression time (10.4 ± 3.75 min actual and 244.4 ± 153.36 min recommended), and the area under the curve (16204.7 ± 5609.6 depth*time actual and 21368.1 ± 9030.8 depth*time recommended) between the actual and recommended diving profiles were significantly different (p=0.001). Analysis of the effect size for these differences showed a large effect size for the diving time (d=1.556) and for the decompression time (d=2.046), and medium effect size for area under the curve (d=0.676). The results of this study indicate that there is a significant reduction in decompression time in the actual diving profiles of fishermen compared to a safe diving profile, putting the divers at a risk of developing decompression sickness.

Acknowledgments

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Table of Contents

Abstract.....iv

Acknowledgements.....v

List of Tables and Figures.....viii

Introduction.....1

Methods.....4

    Participants.....4

    Experimental Procedure.....5

    Statistical Analysis.....6

Results.....6

Discussion.....8

References.....19

Review of Pertinent Literature.....24

    Introduction.....24

    Diving Methods.....26

    Injuries.....29

    Decompression Illness.....32

    Socio-economic and Environmental Pressures.....35

    Risk Factors.....37

    Prevention.....39

    Treatment.....41

    Rationale for Return to work.....44

    Summary.....44

References 46

Appendices..51

List of Tables and Figures

Table 1. Participant demographics……………………………………………...……………...6

Figure 1. Total dive time for actual and recommended diving profiles……………………..……8

Table 2. Average depth, bottom time, decompression, surface interval, and number of dives…..8

Figure 2. Total decompression time for actual and recommended diving profiles...………..……9

Figure 3. Case dive one actual diving profile………..……………………………….………10

Figure 4. Case dive one recommended diving profile………..…………………………………10

Figure 5. Case dive two actual diving profile………..……………………….…………………10

Figure 6. Case dive two recommended diving profile………………………………..………11

Introduction

Diver fishermen in the Dominican Republic are at an increasing risk for diving related injuries because of the changing environments in which they work. For example, fishermen used to find fish easily in the shallows of Monte Cristi, a small fishing town located in the Northwest region of the Dominican Republic. As fish populations have migrated into deeper waters in the Caribbean, diver fishermen were forced to adopt more dangerous forms of fishing. The transition from freediving to compressor fishing has allowed fishermen to spend more time at greater ocean depths, significantly increasing their risk of decompression sickness (Mallon Andrews, 2020). Exposure to the high pressures under the surface of the ocean can have negative effects on body physiology, and depending on diving conditions, this exposure may result in injuries from high pressure and inert gas supersaturation (Bove, 2014).

The most dangerous aspect and greatest threat to the health of diver fishermen is the development of decompression sickness. Decompression sickness, also known as the bends, is caused by intravascular and extravascular bubbles that form when a diver moves between the high- and low-pressure environments. At thirty feet under the surface of water, the pressure put on a body doubles and nitrogen, a gas at sea level, becomes water soluble, dissolving into the body’s blood and tissues (Wilmshurst, 1998). As the body moves to a lower atmospheric pressure, dissolved nitrogen will return to its gaseous form within the body tissues, expanding into air bubbles. These free nitrogen bubbles can form in different organs and tissues in the body, negatively affecting joint, nerve, ear, and other bodily physiological functions. Negative outcomes caused by these nitrogen bubbles is widespread and it may manifest as a skin rash, joint pain, permanent nerve damage, and even death (Vann et al., 2011).

The occupational risk of decompression sickness to diver fisherman is higher in small fishing communities because of their limited access to expensive diving equipment and technology (Winkler, 2016). Diver fishermen in developing countries are exposed to over thirty times higher risk of decompression sickness when compared to recreational divers in developed countries (Westin et al., 2005). Unlike recreational diving with SCUBA tanks, these divers use surfaced supply systems where air compressors on a boat pump air to a diver through a rubber tube. As shown in several survey studies of artisanal fishermen, 82 – 100% of occupational diver fishermen report experiencing at least one incident of the decompression sickness (Cha et al., 2019; Mallon Andrews, 2020; Winkler, 2016).

Diving depth and duration are important factors that can increase the risk of decompression sickness in diver fishermen. The transition from breath-hold fishing to compressor fishing has allowed fishermen to spend more time at greater ocean depths, however, this has significantly increased their risk of decompression sickness (Mallon Andrews, 2020). The deeper a diver descends into ocean depths, the increased exposure they have to greater partial pressures of gases. This exposure leads to an increase in bubble formation in the diver’s tissues and the longer that a diver remains at depth, the more bubbles that will accumulate in their tissues. The ability of these bubbles to become resorbed depends on the number of bubbles that accumulated, making time and depth important factors during a dive (Hall, 2014). Decompression stops are performed during deep or long dives to allow the gas to be released through respiration to avoid formation of bubbles in vulnerable tissues (Wilmshurst, 1998).

The frequent exposure to such extreme environments that diver fishermen endure has both chronic and acute adverse effects on the body. Common acute symptoms that these fishermen experience after a dive include muscle and joint pain, rashes, headaches, and stomach pain (Gold et al., 2000b; Kusnanto et al., 2020; Westin et al., 2005). Although research is limited on long-term effects of frequent exposure to these environments, lifelong diver fishermen report chronic symptoms of excessive tiredness, hearing loss, persistent headaches, and chronic joint pain (Westin et al., 2005). Mortality rates are significantly higher in commercial divers compared to recreational divers. Recreational divers have a mortality rate of less than one death per 100,000 dives whereas commercial divers have a mortality rate of 300 deaths per 100,000 dives (Buzzacott et al., 2015; Gold et al., 2000b). Despite the high risks and dangers that their occupation comprises, diver fishermen in the Dominican Republic continue to enter deep waters because there are few job opportunities outside of fishing.

Fisherman divers in developing countries are at much greater risk of adverse health outcomes and mortality than recreational divers from developed countries (Buzzacott et al., 2015; Gold et al., 2000b). Furthermore, it is evident that much of these adverse outcomes are associated with decompression sickness. Modern software are used to help divers better plan their dives to reduce the risk of decompression sickness. These software use a decompression algorithm to quantify the manner in which inert gases leave and enter body with changes in ambient pressure with respect to different depth and duration of the dive. This algorithm can help provide insights into the risk of developing decompression sickness based on differences in diving profile, helping plan safer dives. However, it is unknown to what extent diver fishermen comply with these recommendations. A contrast of the recommended versus their actual diving profile may provide valuable data regarding the compliance to recommendations and it may also help elucidate health risks associated with decompression sickness in this population. A decompression algorithm can be used to quantify the manner in which inert gases leave and enter body with changes in ambient pressure. This algorithm can help provide insights into the risk of developing decompression sickness based on differences in diving profiles. This project explores the level of occupational risk taken by diver fishermen in the Dominican Republic, based on their reported diving profiles.

The purpose of this study is to compare the actual versus the recommended dive profiles of compressor fishermen in the Dominican Republic to explore the occupational risk associated with decompression sickness that these fishermen endure. By comparing the diving profiles of Dominican fishermen to the recommended profile for the duration, decompression, and depth of each dive, this study was aimed toward a better understanding of the circumstances and practices that lead to chronic cases of decompression sickness. This information is crucial for understanding the broader health implications of diving with a compressor in the Dominican Republic and in other fisheries of the global south.

Materials and Methods

Participants

Ten male diver fishermen from the Dominican Republic were recruited for this study. Data collection was approved by the University of California Irvine Institutional Review Board and the Western Washington University Institutional Review Board accepted their review for use of the coded data from this study. Informed consent was obtained from all participants prior to testing. All participants were occupational fishermen from the Dominican Republic and over the age of 18 years. Study participants were contacted through social networks established within Monte Cristi and the northern border region from previous research projects (Mallon Andrews, 2020). The participants that the lead researcher has worked with on previous studies and consented to be contacted for future research were recruited through calls and e-mails of previously obtained contacts for participants.

Experimental Procedure

Prior to data collection, participants were asked if they would be willing to record their dive schedules for a day’s work. Divers who agreed were asked to record their diving profiles which included the depth of their dive, the time that they spent at that specific depth, the duration of their ascent, and the surface interval between repeat dives, for each dive they conducted during a single workday (Buzzacott, 2012; Cha et al., 2019; Gold et al., 2000b, 2000a; Huchim-Lara et al., 2015; Wahab et al., 2008). The divers self-reported their height, weight, age, and years of fishing experience. After the divers returned from the sea, each fisherman was contacted via Whatsapp call to verbally report their diving profiles. The diving profiles were record in writing and coded to not include the names of study participants. Study participants were asked to self-report their dive schedules up to three times on different workdays. Each self-report interview took no more than 10 minutes and were audio recorded with the participant’s permission. Short follow-up interviews occurred when clarification was needed.

The identity of each participant was not reported in the analysis as identification codes were used to identify each diving profile. The individual diving profiles were entered into V-Planner (V-Planner 3.100.5), a dive decompression planning software. Dive depth, time, and surface interval, the measures that were self-reported from each diver fisherman, were entered into V-planner. Using the Varying Permeability Model (VPM-B) for decompression profiles, V-planner produced the recommendations for safe decompression for each individual dive (Gutvik et al., 2011). The recommended decompression times for each dive from V-Planner were compared to the actual diving profiles that the diver fishermen self-reported. The longer that a diver remains at depth, the more nitrogen that will accumulate in their tissues, turning to gas as they surface. One way to capture the cumulative effects of the depth of dive and duration a diver stays at that depth is by examining the area under the curve of the diving depth versus time graph. To calculate the accumulative effects of the depth and duration of a dive, the data for each dive schedule was graphed using depth (m) over time (min) and the area under the curve was calculated for both the actual and V-Planner dives via a custom-written Matlab program (MATLAB R2020, The MathWorks, Inc., Natick, Massachusetts, USA). Dive depth, decompression time, and total dive time were self-reported by the fishermen in this study.

Statistical Analysis

All data analyses were completed using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). This study involved a two-tailed t-test to assess the difference between two independent means. The area under the curve, decompression time, and the total dive time from the reported dive profiles were compared to the area under the curve, decompression time, and total dive time from the V-Planner recommended dives. Values are presented in mean ± standard deviation. Statistical significance was accepted if *p*-value was <0.05. Effect size was calculated as Cohen’s d and interpreted from the values stated in Cohen (1988), none being <0.2, small as ≥0.2 – 0.49, medium as ≥0.5 – 0.79, and large as ≥0.8.

Results

Ten male diver fishermen from the Dominican Republic participated in this study. All participants were occupation fishermen over the age of 18 years. The average age of the fishermen was 30.8 years with an average experience of 11.83 years (Table 1). The fishermen had an average height of 1.53 m and average weight of 57.82 kg (Table 1).

Table 1. Participant demographics including age (yrs), height (m), weight (kg), and fishing experience (yrs).

Age (yr)	Height (m)	Weight (kg)	Experience (yr)
30.80 ± 5.88	1.53 ± 0.52	57.82 ± 21.35	11.83 ± 9.17

Note. Data presented as Mean ± Standard deviation.

Each self-reported case dive was graphed and compared with the V-Planner recommended dives. On average the diver fishermen dove to depths of 20.08 meters, stayed at that depth for 67.88 minutes, spent 3.06 minutes on decompression, waited 21.88 minutes before diving again, and completed 3.4 dives a day (Table 2). There was a significant difference between the total dive times of the actual and recommended diving profiles (p=0.001) with the recommended total time being much longer, and there was a large effect size of the mean difference between the total time of the actual and recommended dive profiles (d=1.556). A significant difference in the decompression time of the actual and recommended diving profiles (p=0.001) with the recommended decompression time being much longer, and a large effect size between the means of the two variables (d=2.046) was observed. There was also a significant difference in the area under the curve of the actual and recommended diving profiles (p=0.001) with the area under the curve of the recommended diving profiles being much greater, and a medium effect size between the means of the two variables (d=0.676) was observed.

Only one out of 10 of the reported diving profiles completed the decompression time recommended by V-Planner (Figure 1). Case dive three, which met the recommended decompression, was a profile of seven consecutive dives of short durations and shallow depths, requiring little time spent on decompression. The greatest depth reported for this profile was the first dive of 12.19 meters, but the following dives were much shallower, ranging from 4.57

meters to 6.10 meters. Because of the lack of depth, V-Planner required no decompression for the dives in this profile.

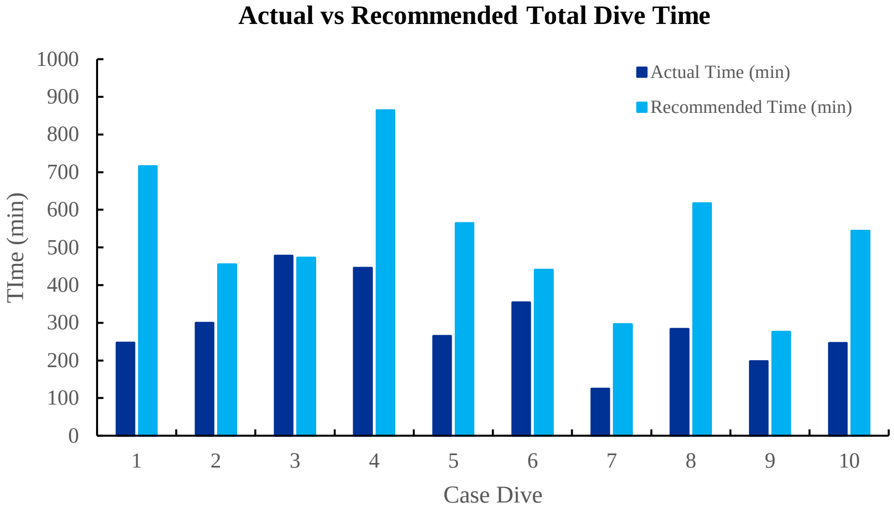

Figure 1. The actual and V-Planner recommended total dive time for each case dive.

In the reported dives, decompression time ranged from 0 to 5 minutes, with an average of 3.06 minutes (Table 2). Calculated by V-planner, the longest decompression time should have been 248 minutes according to the depth and duration of the dive. The average total decompression time from the actual diving profiles was 10.4 minutes while the average total decompression time from the V-Planner diving profiles was 244.4 minutes. The recommended decompression time exceeded the actual decompression time reported from the fishermen for all but one case dive (Figure 2). Because case dive three included seven dives that were short in duration and shallow in depth, zero decompression was required but the fishermen reported performing several one-minute decompression stops.

Table 2. The average depth (m), bottom time (min), decompression (min), surface interval between dives (min), and number of dives in each case dive for the reported diving profiles.

Depth (m)	20.08 ± 8.59
Bottom Time (min)	67.88 ± 40.17

Decompression (min)	3.06 ± 1.76
Time Interval (min)	21.88 ± 12.87
Number of dives	3.4 ± 1.56

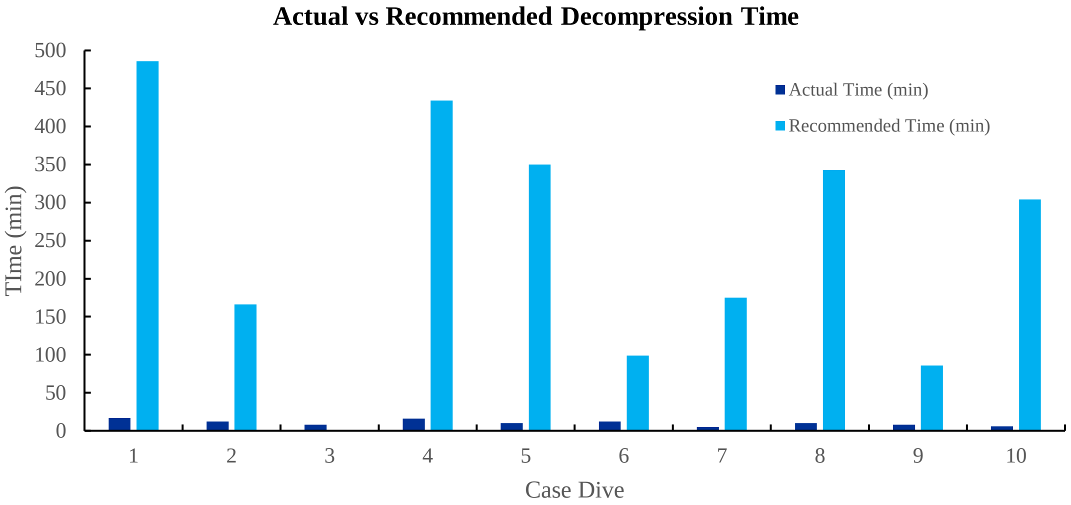

Figure 2. The actual and V-Planner recommended total decompression time for each case dive.

The average ascent rate from the self-reported dives was 8.18 m/min while the average ascent rate from the safe diving profile calculated in V-Planner was 2.83 m/min. Most fishermen from the current study completely omitted any length of decompression, increasing the risk of developing decompression sickness. The shorter total dive time as compared to the total recommended dive time from V-Planner is demonstrated for all case dives in Figure 1.

Examples of the diving profiles that were self-reported by the fishermen are shown below in a graph of depth over time. Case dive one and two demonstrate a typical dive day for fishermen in Monte Cristi. The multiple immersions, rapid ascents, and short surface intervals are common characteristics of fishermen who fish with a compressor. Case dive one shows a diver that increased the time and depth of their dive as the day continued (Figure 3). The V-Planner recommended profile of this dive demonstrates a safe profile based on the reported dive depth and time, with accumulating decompression time for each dive (Figure 4).

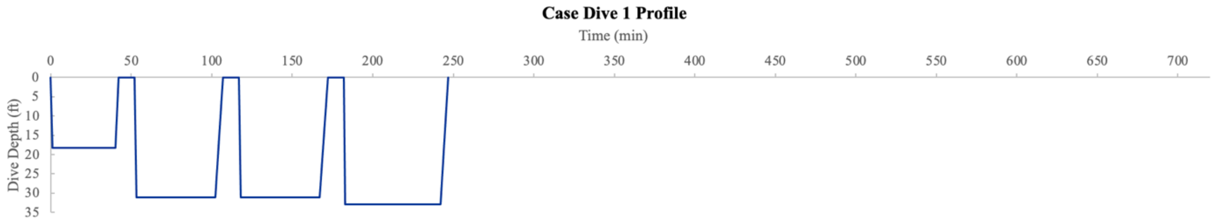

Figure 3. The actual diving profile of Case Dive 1 with the depth (m), duration (min), decompression, and surface interval of each dive in one fishing session.

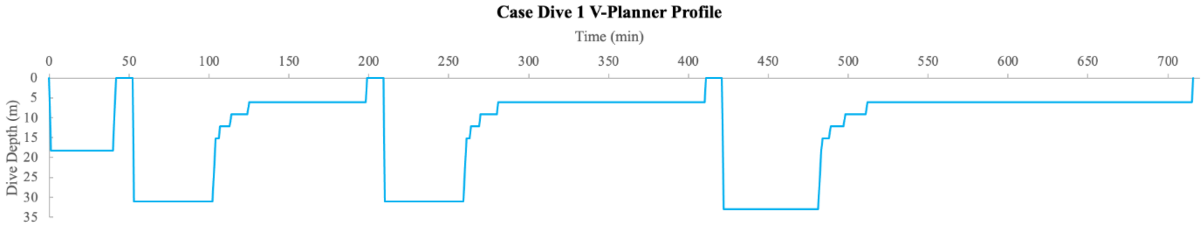

Figure 4. The V-Planner recommended diving profile for Case Dive 1 with the depth (m), duration (min), decompression, and surface interval of each dive in one fishing session.

Case dive two shows a diver that completed short and long dives throughout their diving day (Figure 5). The V-Planner recommended profile of this dive demonstrates a safe profile based on the reported dive depth and time, with accumulating decompression time for each dive and no decompression for the short dives (Figure 6).

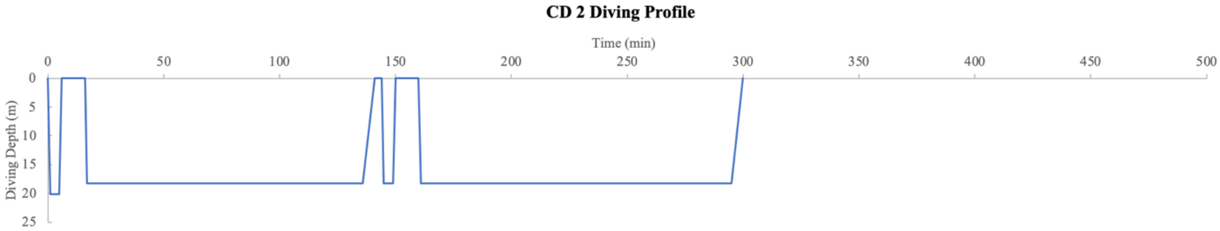

Figure 5. The actual diving profile of Case Dive 1 with the depth (m), duration (min), decompression, and surface interval of each dive in one fishing session.

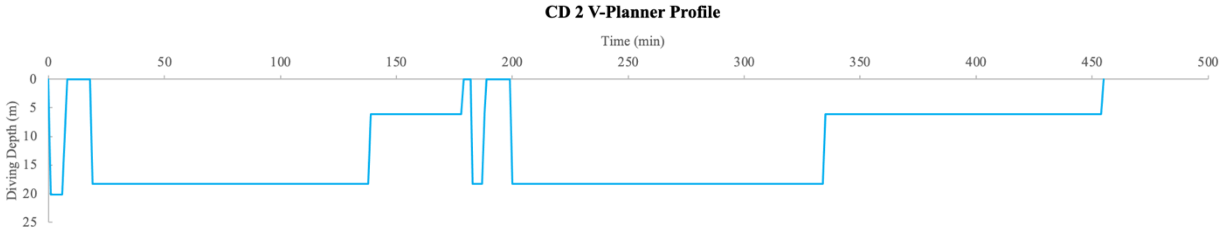

Figure 6. The V-Planner recommended diving profile for Case Dive 2 with the depth (m), duration (min), decompression, and surface interval of each dive in one fishing session.

Discussion

The primary purpose of this study was to compare the actual versus the recommended dive profiles of the fishermen in the Dominican Republic. The total dive time and area under the curve of graphed diving profiles were used to compare the actual and recommended diving profiles. The results of the present study indicate a significant difference between the actual reported diving profiles and recommended diving profile for total time of dive and area under the curve. The effect size was large for total dive time and medium for the area under the curve indicating that the difference between the actual and recommended dive profiles is meaningful.

Dangers of Diving with a Compressor

The introduction of the compressor allowed for an increase in productivity for diver fishermen but increased the risk of decompression sickness. As more fishermen report that finding fish close to shore has become increasingly difficult, the use of compressors among small coastal communities has become more common (Huchim-Lara et al., 2016; Mallon Andrews, 2020). The transition from freediving to compressor diving has allowed sustenance divers to become more successful as they utilize their access to deeper waters. In a study analyzing fishing techniques in Caribbean coral reefs, the compressor divers who participated in the study encountered more fish and obtained higher catch rates than the freedivers (Barbosa-Filho et al., 2020; Pavlowich and Kapuscinski, 2017). With the ability to fish continuously without going to the surface for air, the compressor fishermen captured 69% of the fish that they targeted, which was 28% more than the freedivers (Pavlowich and Kapuscinski, 2017). Compared to freediving techniques, compressor diving has allowed fishermen to maximize their time and range underwater, encountering more fish in deeper waters, but this efficiency has come at a cost.

The deeper a diver descends into ocean depths, the greater the exposure to higher partial pressures of gases. This exposure leads to an increase in bubble formation in the diver's tissues as they surface. The longer that a diver remains at depth, the more nitrogen that will accumulate in their tissues, turning to gas as they surface. The ability of these bubbles to become resorbed into solution depends on the number of bubbles that accumulated, making duration and depth important factors during a dive (Hall, 2014). Decompression stops are essential to allow gas to be released through respiration, avoiding the formation of bubbles in vulnerable tissues (Wilmshurst, 1998).

In the current study, larger total dive time recommended by V-Planner was primarily the result of the lack of decompression made among the diver fishermen. Figure 3 shows the diving profile from one case dive in the current study. In this dive the participant completed four dives in 247 minutes. Their decompression varied between the dives, starting at two minutes for the first and shallowest and shortest dive (18.29 meters of depth and 40 minutes in duration) and progressing to five minutes of decompression for the three subsequent dives. The last dive in this profile was the deepest and longest (32.92 meters of depth and 60 minutes in duration) but only 5 minutes of decompression was reported. Figure 4 shows the same diving profile as Figure 3 but with the recommended decompression for the depth and duration of the dives. According to V-planner, only two minutes of decompression was needed after the first dive, 97 minutes after the second dive, 152 minutes after the third, and 235 minutes after the fourth dive. The total time of the recommended dive with safe diving decompression was 716 minutes, almost three times longer than what was reported by the participant.

Decompression

A lack of decompression is common among the fishermen in the Global South. Out of 196 fishermen from South Korean fisheries, only 12.2% performed underwater decompression in accordance with their decompression tables and 93.9% of the divers experienced a rapid ascent (Cha et al., 2019). In a study on diver fishermen in Thailand, during dives lasting 30 minutes or longer and at depths deeper than 40.54 meters, only 53.8% of divers made at least one decompression stop and the rest do not make a stop at all (Gold et al., 2000a). In fishermen from the Galapagos with extremely long average bottom times of 175 minutes, no decompression stops were made upon ascent (Westin et al., 2005). Fishermen understand the risks that they take by diving deep and rapidly ascending to the surface of the water. Although some will decrease their ascent rate and complete their stops closer to the surface rather than halfway up, as recommended by the U.S. Navy Standard Air Decompression Tables, decompression stop protocol remains inconsistent and often inadequate among small fisheries (Blatteau et al., 2015).

Omitting decompression saves the fishermen time, allowing them to perform more dives in a day and catch more fish. In the current study, the average total time of a reported diving session was 294.3 minutes while the average recommended time from V-Planner was 524.7 minutes (Table 2). Safe diving protocols can cost fishermen financially because of extra time that they must spend on the water. The cost of fuel is a major constraint for small fishing communities and is subtracted from the daily earnings of each fishermen (Huchim-Lara et al., 2016; Winkler, 2016). The longer that the fishermen stay on the water, the more fuel that they must use for the boat and the compressor. By omitting decompression, fishermen can spend more time looking for fish and less time doing unproductive decompression stops. Aware of the dangers of this kind of diving, fishermen consider the risks worth the reward (Winkler, 2016).

The considerable risk of decompression sickness that these diver fishermen face by omitting staged decompression is not always seen in their daily dives. In the current study, no participants experienced any symptoms of the bends during their reported dives but 20 out of the 34 dives performed exceeded the no-stop limit in U.S. Navy dive tables (Navy Department, 2016). The no-stop limit refers to the maximal amount of bottom time that should be allowed for any single dive. With an average depth of 20.08 ± 8.59 meters, the no stop limit from U.S. Navy Dive tables is 48 minutes but the average bottom time of the fishermen was 67.88 ± 40.17 minutes (Table 2). Similarly in a study of Galapagos diver fishermen, the observed rate of DCS was 3.3% over the 150 dives recorded but 82% of all immersions had ascent rates that were faster than what was recommended according to the depth and duration of each dive (Westin et al., 2005).

Although no participants in the study experienced the bends during the recorded dives, 100% have experienced DCS symptoms at least once in their diving careers (Mallon Andrews, 2020). Several studies indicate a higher rate of injury for lifelong fishermen. In a study that recorded similar diving profiles for South Korean fisheries (average diving depth of 23.59 meters and average bottom time of 74.7 minutes), 84.7% of the participants experienced DCS symptoms in the last year and in a diving study on the Yucatan Peninsula, 100% of fishermen reported experiencing the bends at least once during their fishing careers (Cha et al., 2019; Huchim-Lara et al., 2015).

Occupational fishermen accumulate a substantial number of dives through their daily work. During a nine day observational period of 12 diver fishermen in the Galapagos, 380 immersions were recorded (Westin et al., 2005). Depending on the time and year and weather, fishermen from the current study spend four to six days a week on the water, completing multiple dives a day (Mallon Andrews, 2020). The constant exposure to the extreme environments under the surface has caused many fishermen to accumulate chronic DCS symptoms. Lifelong fishermen in the Dominican Republic report experiencing consistent joint pain, trouble walking, chronic headaches, and extremity numbness of which they attribute to their frequent diving.

Socio-economic and Environmental Pressures

Socio-economic and environmental pressures have increased the risk of diving for small scale fisheries. The changes to the Caribbean marine ecosystems have been affecting fishing communities for decades. Fishermen in Grenada report changes in water quality, climate, and coastal development of which they believe are the reasons for the decreasing fish populations that they observe underwater (Winkler, 2016). In Monte Cristi, fishermen state that they transitioned from freediving to compressor diving to start fishing in deeper, riskier water because they were no longer finding fish close to shore (Mallon Andrews, 2020).

Increasing ocean surface temperatures have already resulted in widespread coral bleaching and mortality as many reef-building corals live close to their upper thermal tolerances. Because the organisms that have the highest heat-tolerance are often the ones that live closest to their thermal tolerances, marine life in the Caribbean, and other low-latitude climates, are especially at risk with warming ocean temperatures (Harley et al., 2006). These changes in ocean ecosystems will continue to affect the livelihood of those who depend on the sea for their food and income.

The fishing market plays an important role in fishing activity and changes in marine ecosystems. Prices of fish are defined by the buyer according to demand, and Asian markets have increased the demand and payment for specific species (Bassett, 2019; Huchim-Lara et al., 2016). The high price of lobster, sea cucumber, and red grouper, from these Asian markets, creates the incentive for fishermen to target these species (Huchim-Lara et al., 2016). Tourism and export industries in the Dominican Republic have also increased the demand for seafood, requiring targeted fishing for lobster, octopus, conch, and other fish species which are sent exclusively to the hotels and restaurants that feed American and European visitors. An increase in seafood demands has put diver fishermen at physical risk as they continue to fish in dangerously deep waters (Mallon Andrews, 2020).

Fisheries in the Dominican Republic, and other parts of the Caribbean, are being targeted by many conservation campaigns led by American and European biologists and fisheries scientists. In Monte Cristi, these scientists started leading educational interventions about reef and ocean health and pressuring the government to create laws banning the sustenance fishermen from targeting certain species. In 2017, catching parrotfish was made illegal, criminalizing a catch that had previously provided 50% of the fishermen’s daily income and limited the use of a fish that the fishermen regularly brought home to feed families (Mallon Andrews, 2020). Fishery conservation and management regulations inadvertently push small scale fishermen into more dangerous waters. Fishermen in Yucatan, Mexico report that they were forced to dive further from the coast to catch bigger fish and lobster to comply with management regulations (Huchim-Lara et al., 2016). These interventions place blame on fishermen who use compressors for the depletion of marine resources, ignoring tourism, export industries, and chemical runoff of industrial agriculture (Mallon Andrews, 2020).

A lack of employment opportunities outside of fishing in small coastal communities, force artisanal fishermen to continue entering the ocean, despite knowledge of the inherent dangers of diving (Barratt and Van Meter, 2004). It has become economically impossible for fishermen to dive safely in the waters of Monte Cristi. Financially, fishermen must adapt to the changing underwater environments. Compressor fishing is now widely used across Central and South America because of its cost effectiveness. In Monte Cristi, a freediver fisherman might make 1,000–2,000 pesos (US $20–$40) a day in calm seas, but a fisherman using a compressor can make 2,000–5,000 pesos (US $40–$100) in a day (Mallon Andrews, 2020). The risk of DCS is often worth the reward of fish for these financially constrained fisheries (Winkler, 2016). The physiological consequences that these divers face are severe. Despite the risks of injury and high rate of mortality among these diver fishermen, they continue to enter dangerously deep waters.

Resilience to Decompression Sickness

The dangerous diving profiles of the diver fishermen from the current study indicate that they are resilient against DCS. These fishermen spend upwards of six hours a day at sea and underwater, using an air compressor to reach depths ranging from 9.14 to 45.72 meters, and conduct an average of three to six dives per day (Mallon Andrews, 2020). The physical demand of this kind of diving is extreme and the physical fitness required by these occupational fishermen may be one of the factors that decrease the frequency that they get the bends. Physical fitness and percent body fat can affect the probability of a diver getting the bends. Because nitrogen is five times more soluble in fat than in water and five times more soluble than oxygen in fat, more time is required for the elimination of the excess inert gases while ascending from ocean depths for those with more body fat (Mahon and Regis, 2014; Navy Department, 2016). Similarly, U.S. Navy divers with higher skin fold measurements were five to six times more at risk of DCS then the general U.S. Navy diver population (Mahon and Regis, 2014). Physical fitness, measured by VO_{2max}, is considered a protective measure against DCS. Regular exercise may impact the risk of DCS as it is involved in the generation of micronuclei, nitric acid generation, and nitrogen uptake and elimination (Mahon and Regis, 2014).

Diver fishermen must be constantly aware of their environmental surroundings. Without access to expensive diving equipment, diver fishermen use their experience and their crew mates to dive as safely as possible. In the current study, the diver fishermen reported their time and depth without instrumentation. The measurement of depth was reported by the fishermen in “brazas” which is 2 meters and considered an arm’s span distance. The fishermen also indicate the measurement of their catch in relation to their own arms, pointing to a spot from their fingertips to their proximal arm that match the size of their catch. The use of their bodies in measurement and within their environments show a bodily intelligence that these divers might be using for safe diving.

Summary

Results from this study indicate that there is a significant difference between the actual diving profiles, decompression time, and the recommended diving profiles for dive time and area under the curve of the graphed case dives. The main difference between the actual and recommended diving profiles was the amount of decompression conducted by the diver fishermen. The lack of decompression from the diver fishermen in the current study has been observed among many small diver fishermen communities around the world (Cha et al., 2019;

Gold et al., 2000a; Huchim-Lara et al., 2016; Westin et al., 2005; Winkler, 2016). Safe diving protocols can cost fishermen financially because of extra time that they must spend on the water. The cost of fuel is a major constraint for small fishing communities because it is subtracted from the daily earnings of each fishermen (Huchim-Lara et al., 2016; Winkler, 2016). The longer that the fishermen stay on the water, the more fuel that they must use for the boat and the compressor. By omitting decompression, fishermen can spend more time looking for fish and less time waiting underwater completing their recommended decompression stops.

The fishing industry is one of the most dangerous occupations in the primary sector (Huchim-Lara et al., 2018). Small coastal fisheries around the world face the highest occupational risk because of their limited access to expensive diving equipment and technology (Winkler, 2016). Diver fishermen continue to work in increasingly risky environments because marine ecosystems are rapidly changing as a result of river runoff, tourism, coastal pollution, and overfishing from targeted export markets. As a result of their working conditions and the environmental factors that have driven fish populations into deeper water, occupational divers in the Dominican Republic who engage in compressor fishing are at risk of acute and chronic decompression sickness.

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Review of Pertinent Literature

Introduction

Fishermen in the Global South, the low-income regions of Latin America, Asia, Africa, and Oceania, that are politically and culturally marginalized, have long relied on the ocean for their survival. These small coastal communities of artisanal fishermen utilize two distinct forms of fishing which include freediving and compressor fishing. Freedivers use only a mask, fins, snorkel, speargun, and a single breath to dive for fish (Pavlowich and Kapuscinski, 2017). Although some fishermen can dive to depths up to 30.48 meters, this form of fishing is usually used in the shallows and coral reefs, close to shore (Ilardo et al., 2018). Compressor fishing is a far more dangerous method of fishing that uses air compressors on a small fiberglass boat that pump unfiltered surface air to the underwater diver along a small-bore tube, extending up to 91.44 meters long (Huchim-Lara et al., 2015; Winkler, 2016). Because the use of a compressor eliminates the need to surface between breaths and allows fishermen to explore deeper waters, fishermen have more successful and effective dives while compressor fishing (Pavlowich and Kapuscinski, 2017). As more fishermen report that finding fish close to shore has become increasingly difficult, a widespread use of compressors among small coastal communities has emerged (Huchim-Lara et al., 2016; Mallon Andrews, 2020). The transition from freediving to compressor fishing has allowed fishermen to spend more time at greater ocean depths, significantly increasing their risk of decompression sickness (Mallon Andrews, 2020). Exposure to the immense pressures under the surface of the ocean can have extreme effects on human physiology, and depending on diving conditions, this exposure may result in injuries from pressure and inert gas supersaturation (Bove, 2014).

The most dangerous aspect and greatest threat to the health of diver fishermen is the development of decompression sickness. Decompression sickness, also known as the bends, is caused by intravascular and extravascular bubbles that form when a diver moves between the high- and low-pressure environments. At thirty feet under the surface of water, the pressure put on a body doubles and nitrogen, a gas at sea level, becomes water soluble, dissolving into the body's blood and tissues (Wilmshurst, 1998). As the body moves to a lower pressure, dissolved nitrogen will return to its gaseous form within the body tissues, expanding into air bubbles. These free nitrogen bubbles can form in different organs and tissues in the body, negatively affecting joints, nerves, ears, and other bodily functions. Negative outcomes caused by these nitrogen bubbles is widespread and it may manifest as a skin rash, joint pain, permanent nerve damage, and even death (Vann et al., 2011).

The frequent exposure to the extreme environments that diver fishermen endure has both acute and chronic effects on the body. Common acute symptoms that these fishermen experience after a dive include muscle and joint pain, rashes, headaches, and stomach pain (Gold et al., 2000b; Kusnanto et al., 2020; Westin et al., 2005). Although research is limited on long-term effects of frequent exposure to these environments, lifelong diver fishermen report chronic symptoms of excessive tiredness, hearing loss, persistent headaches, and chronic joint pain (Westin et al., 2005).

Occupational risk is higher in these small fishing communities because of their limited access to expensive diving equipment and technology (Winkler, 2016). Diver fishermen in developing countries are exposed to over thirty times higher risk of decompression sickness when compared to recreational dives (Westin et al., 2005). As shown in several survey studies of artisanal fishermen, 82 – 100% of occupational diver fishermen report experiencing at least one incident of the bends (Cha et al., 2019; Mallon Andrews, 2020; Winkler, 2016). Mortality rates are significantly higher in commercial divers compared to recreational divers as well. Recreational divers have a mortality rate of less than one death per 100,000 dives but commercial divers have a mortality rate of 300 deaths per 100,000 dives (Buzzacott et al., 2015; Gold et al., 2000b).

Despite the high risk and danger that their occupation comprises, diver fishermen in the Dominican Republic continue to enter deep waters because there are few job opportunities outside of fishing. This project explores the level of occupational risk taken by diver fishermen in the Dominican Republic, based on their reported diving profiles. By comparing the fishermen's diving profile to the recommended profile for safe decompression, this study will expose the great risk that fishermen endure everyday as they labor in underwater environments for extended periods of time. This study will also highlight the effect of climate change and social-economic factors and on small fishing communities and the behavior of diver fishermen. The depletion of marine resources from tourism, targeted markets, export industries, global warming, and overfishing, have forced fishermen to seek fish in deeper and more dangerous water. The transition from freediving to compressor diving has significantly increased the occupational risk among small fishing communities, putting them at a greater risk of developing decompression sickness.

Diving Methods

There are two distinct types of fishing utilized by occupational fishermen from small coastal communities. These techniques are freediving and compressor diving. Freediving, also known as breath-hold diving or apnea diving, is a form of diving that requires fishmen to use a single breath of air to hunt in ocean depths. In Southeast Asia, a population of fishermen known as the Sea Nomads, exclusively use breath-hold diving to fish and hunt for their food. This requires them to dive to depths of over 30.48 meters for periods of several minutes at a time (Ilardo et al., 2018). Sustenance diving populations like the Bajau in South-East Asia and the Ama from Japan, spend 50 to 60% of their daily working time underwater (Lodin-Sundström, 2015). In the Caribbean, diver fishermen wear lycra to protect their skin from the sun during long days on the water. Freedivers use only a mask, fins, snorkel, and speargun during their dives (Pavlowich and Kapuscinski, 2017). Spearfishing is the most common form in artisanal fisheries and both freedivers and compressor divers use the same types of spearguns. This method allows the fishermen to individually select the fish that they want to capture in a second-by-second decision making act (Pavlowich and Kapuscinski, 2017).

Unlike recreational diving, which more often utilizes Self Contained Underwater Breather Apparatuses (SCUBA), occupational divers in the Global South use surfaced supply systems. Surfaced supplied systems, also known as compressor or hookah diving, use air compressors on a small fiberglass boat that pump unfiltered surface air to an underwater diver along a small-bore tube, extending up to 91.44 meters long (Huchim-Lara et al., 2015; Winkler, 2016). A 5 to 6-horsepower gas-powered engine powers the pump that compresses 100-120 pounds per square inch gauge of ambient air into a 1 to 2-cubic-foot volume tank. This air is delivered through a plastic hose, to the fishermen beneath the surface (Huchim-Lara et al., 2015). These fishermen use only a mask, fins, speargun, and a regulator supplied with the compressed air from the boat (Pavlowich and Kapuscinski, 2017). Hookah systems are more cost-effective compared to SCUBA dive systems because they have an unlimited supply of air, making them the most commonly utilized diving system in commercial fisheries of the Global South (Huchim-Lara et al., 2015).

As more fishermen report that finding fish close to shore has become increasingly difficult, a widespread use of compressors among small coastal communities has emerged (Huchim-Lara et al., 2016; Mallon Andrews, 2020). The transition from freediving to compressor diving has allowed sustenance divers to become more successful due to the ability to effectively dive in deeper waters. In a study analyzing fishing techniques in Caribbean coral reefs, the compressor divers that participated in the study encountered more fish and obtained higher catch rates than the freedivers (Barbosa-Filho et al., 2020; Pavlowich and Kapuscinski, 2017). The compressor fishermen also captured 69% of the fish that they targeted, which was 28% more than the freedivers. Because the compressor fishermen were able to fish continuously without going to the surface for air, they were far more successful and effective in deeper waters (Pavlowich and Kapuscinski, 2017). Compared to freediving techniques, compressor diving has allowed fishermen to maximize their time and range underwater and encounter more fish beneath the surface.

Although compressor fishing has increased the fishermen’s success, risk is incredibly high for this type of diving. Diver fishermen, practicing compressor fishing, perform dives at a thirty times higher risk of decompression sickness when compared to recreational divers and are at an increased risk compared to fishermen utilizing SCUBA dive systems (Huchim-Lara et al., 2015; Westin et al., 2005). Other dangers that divers face using surface-supplied compressed air can occur if their air supply is disconnected, the compressor fails or runs out of fuel, or if the air supply is contaminated with engine exhaust (Bassett, 2019; Winkler, 2016). Occupational risk is made higher in small fishing communities because of their limited access to expensive diving equipment and technology, like pressure gauges and oxygen tanks (Winkler, 2016).

Injuries

There are many life-threatening injuries that come from exposure to pressures underwater. To understand the injuries that occur to freedivers and compressor divers, the physical properties of gases need to be understood. According to Boyle's Law, the volume of gas varies inversely with pressure, while the density of gas varies directly with pressure. This gas law is written as $PV = k$. In this equation the "P" represents pressure, the "V" represents volume, and the "k" represents a constant. Gas volume is inversely related to pressure so when pressure increases, gas volume will decrease. This equation only remains true when temperatures remain constant. At sea level, atmospheric pressure is 100 kPa or one bar absolute. As a diver descends under the surface of water, the pressure on a diver increases by 100 kPa for every 10 meters of decent. Because gas volume is inversely related to pressure, as pressure increases from 100 kPa at sea level to 200 kPa, at 10 meters below the water's surface, gas volume is halved (Wilmshurst, 1998).

Barotraumas are injuries directly related to Boyle's law. They occur due to the forces generated from pressure differences between body cavities and ambient pressure. These types of injuries can occur during both freediving and compressor diving. With increased pressure under the surface of the water, the gas volume in air-containing body cavities, like the lungs, middle ear, paranasal sinuses, and gastrointestinal tract, is diminished and if the pressure in these spaces does not equalize with the ambient pressure, tissue damage may occur (Bove, 2014). The most common type of barotrauma experienced by diver fishermen is of the middle ear, but they can occur in the air spaces of the mask, sinuses, eyes, teeth, and gastrointestinal tract. The most serious form is a pulmonary barotrauma (Bove, 2014; Winkler, 2016).

Another important gas law in diving is Dalton's law of partial pressures. This law is written as $P_{Total} = P_{p1} + P_{p2} + P_{pn}$ where "P_{Total}" represents the total pressure of the gases, "P_{p1}" represents the partial pressure of one gas component, "P_{p2}" represents the partial pressure of the second gas component, and "P_{pn}" represents the partial pressure of the other gas components. According to Dalton's Law, partial pressures of each gas will increase proportionally to the total absolute pressure. Dry air is a composition of gases at sea level that is 78% nitrogen and 21% oxygen, and 1% carbon dioxide, argon, helium, hydrogen, and many other gases. Dalton's law states that if dry air is made up of 21% oxygen, the partial pressure of oxygen at any depth will remain 21% of the total pressure of the gases. This law is important to understand when discussing oxygen and nitrogen toxicity (Wilmshurst, 1998).

At sea level, humans have several liters of nitrogen dissolved in their bodies. When a diver breaths air at 10 meters under the water's surface, the partial pressure of Nitrogen doubles as the absolute pressure changes from 100 kPa to 200 kPa. When breathing for a long enough time that the body reaches equilibrium at these higher pressure, twice as many Nitrogen molecules are dissolved in the human body at 10 meters, compared to at sea level (Wilmshurst, 1998). Nitrogen narcosis is a potentially dangerous side effect in compression diving that is caused by high concentrations of nitrogen in the bloodstream. At depths over 30 meters, some divers experience neurological dysfunction along with impaired motor coordination, cognitive skills, and an altered emotional state that can cause poor decision making and dangerous dive behavior (Bassett, 2019; Bove, 2014). The deeper the depths and longer the durations that a diver fisherman is exposed to underwater, the greater the risk of injury.

Another gas law for understanding dive related injuries is Henry's law which states that the partial pressure of a gas is directly proportional to the concentration of a gas dissolved in a liquid (Bove, 2014). This law is written as P = KC where “P” represents the partial pressure of the gas solute, “C” represents the concentration of the gas, and “K” is the Law’s constant. According to Henry’s law, dissolved gases in the blood will increase proportionally with increasing hydrostatic pressure. During an apneic dive, a diver may experience an excess of oxygen as they descend. As the pressure increases underwater, oxygen will diffuse from a high concentration in the lungs to a lower concentration in the blood. During the ascent, pressure decreases in the lungs and oxygen diffuses from a high concentration in the blood, back to the lungs (Lodin-Sundström, 2015). As the concentration of oxygen in the lungs decreases and the partial pressure of oxygen decreases, a diver may lose consciousness as they can no longer utilize the low levels of oxygen.

All three gas laws are important for understanding the most common injuries in freediving and compressor diving. In freediving, when a diver holds their breath underwater, Boyle’s law describes the way that air filled cavities in the body will change inversely with changes of pressure. During the descent, the increased pressure causes the airspaces in the body to compress. The partial pressures of oxygen and nitrogen increase according to the total pressure put on the body, as described in Dalton’s law, producing an increase in arterial and tissue gas partial pressures (Wilmshurst, 1998). When a diver starts their ascent, the hydrostatic pressure is reduced with a corresponding decrease in oxygen partial pressures in alveolar gas, arterial blood, and other body tissues. According to Henry’s law, the gasses that were dissolved in the body tissues under high pressure, will decrease in concentration upon descent (Lodin-Sundström, 2015). A rapid fall of cerebral oxygen pressure caused by this change of pressure can become dangerous, causing the diver to lose consciousness underwater (Wilmshurst, 1998).

Drowning during breath-hold diving is normally a result of a loss of consciousness when a diver ascends too quickly. Most frequently experienced in breath-hold diving, shallow water blackouts are caused by the reduction in the arterial partial pressure of oxygen, a result of the consumption of oxygen and a decreasing ambient pressure during ascent (Bove, 2014). During a breath-hold dive, the oxygen in the tissues decreases as it is metabolized by the body. When the carbon dioxide levels increase within the body, receptors in the medulla react to the increasing levels, sending electrical impulses to the frontal cortex, creating an overpowering urge for a breath-hold diver to surface for oxygen. This mechanism protects the body, signaling that oxygen is needed before the falling oxygen levels cause unconsciousness (Pearn et al., 2015; Wilmshurst, 1998). A breath-hold can be extended with hyperventilation immediately before a dive. Hyperventilation does not affect the rate of oxygen consumption, but it lowers the arterial partial pressure of carbon dioxide, delaying the natural stimulus to breathe. This puts a diver in danger because they do not feel the need to breath before their oxygen levels are too low, putting them at risk for going unconscious underwater (Bove, 2014; Eichhorn and Leyk, 2015). Deep water blackouts typically occur upon ascent and in last few meters below the surface of a breath-hold dive. In the ascent phase of deep-water dives, the partial pressure and of oxygen is lowered by the decreasing ambient pressure. As lung volume increases and the concentration of oxygen in the lungs decreases, a diver is susceptible for a loss of consciousness from lack of oxygen (Eichhorn and Leyk, 2015).

Decompression Illness

The greatest risk that fishermen face in underwater environments is decompression illness. Decompression illness is caused by intravascular and extravascular bubbles that form in the blood and body tissue as a result of exposure to a reduction in environmental pressure.

Decompression illness includes two different pathophysiological syndromes, atrial gas embolism (AGE) and the more common decompression sickness (DCS) (Bove, 2014; Vann et al., 2011). Both barotraumas and DCS can result in an atrial gas embolism. AGE occurs when expanding gas stretches and ruptures alveolar capillaries, allowing gas bubbles to escape to the arteries and block blood passage (Bassett, 2019). This syndrome can affect a diver in ascent from a depth as shallow as 1.5 meters if their starting lung volume was close to capacity. It may also be caused by gas becoming trapped as a result of airway obstructions in diseases like asthma or abnormalities like pulmonary blebs or cysts (Vann et al., 2011).

DCS is commonly known as the bends, a term that originated from the contorted posture of caisson workers after they emerged from underwater depths, that resembled the stooped posture of a dance move called the “Grecian Bend” (Neuman, 2002). The occurrence of DCS in diving is a result of the physical properties of gases. Nitrogen is highly soluble and dissolves in great concentrations in the body tissues at ocean depths. According to Dalton’s law, the partial pressures of gases increase proportionally to the total absolute pressure and dry air is made up of 78% nitrogen. As a compressor diver descends into the ocean, the partial pressure of nitrogen increases and so does the concentration of nitrogen in the body tissues (Wilmshurst, 1998). During ascent, the nitrogen molecules that dissolved in the tissues at depth, need to be liberated. If the rate of decompression is too rapid for the nitrogen to escape through respiration, dissolved nitrogen molecules can transform into free gas, forming bubbles in supersaturated tissues throughout the body (Bove, 2014; Wilmshurst, 1998). Decompression stops are performed during deep or long dives to allow the gas to be released through respiration to avoid formation of bubbles in vulnerable tissues (Wilmshurst, 1998).

Depending on the severity of symptoms, DCS can be classified as Type I or Type II. Type I DCS affects the musculoskeletal system and can include symptoms like joint pain, pain in the upper and lower limbs, itchy skin, or cutaneous rash. Type II DCS usually involves the neurologic system but it can include symptoms like generalized weakness, paralysis or numbness, chest or respiratory pain, dizziness or vomiting, auditory disturbance, and urinary disturbances (Bove, 2014; Cha et al., 2019). Common clinical manifestations of the bends include the musculoskeletal system, skin, inner ear, brain, and spinal cord (Bove, 2014). Musculoskeletal symptoms are the most common manifestation of DSC, causing joint pain throughout the body. Osteonecrosis may occur with lifelong exposure to deep and prolonged diving and is especially common in those that report chronic musculoskeletal symptoms of the bends. Cutaneous DCS is associated with skin rashes that usually resolves within 24 hours. Acute neurologic hearing loss or vestibular disfunction are less common but they can occur after prolonged underwater exposure and high pressure. These injuries are classified as type II DCS as they can lead to permanent deafness. Pulmonary vascular obstruction occurs when large amounts of free gas appear in the venous system and it can result in chest pain, dyspnea, or a cough. Spinal cord injuries normally occur in the lumbar spine, causing paresthesia, weakness, partial paralysis of the lower extremities, and bowl or bladder incontinence (Bove, 2014).

The frequent exposure to extreme environments that diver fishermen endure has both acute and chronic effects on the body. Common acute symptoms that these fishermen experience after a dive include muscle and joint pain, rashes, headaches, and stomach pain (Gold et al., 2000a; Kusnanto et al., 2020; Westin et al., 2005). Although the long-term effects of frequent exposure to these environments is less researched, lifelong diver fishermen report chronic symptoms of excessive tiredness, hearing loss, persistent headaches, and chronic joint pain (Westin et al., 2005).

Socio-economic and Environmental Pressures

Compressor diving is a dangerous method for commercial fishermen but it is still widely used in small-scale fisheries all over the world (Huchim-Lara et al., 2015; Winkler, 2016). The transition from breath-hold diving to compressor diving is a common trend among small scale fisheries. When asked why they started to fish in deeper, riskier water, fishermen from a northwestern region of the Dominican Republic, a small fishing town called Monte Cristi, stated that they were forced to make the switch from freediving to compressor diving because they were no longer finding fish close to shore. Those who started their careers freediving, moved to compressor fishing to reach the fish that could no longer withstand the increasing temperatures in the shallows (Mallon Andrews, 2020).

The fishing market plays an important role in fishing activity and changes in marine ecosystems. Prices of fish are defined by the buyer according to demand, and Asian markets have increased the demand and payment for specific species (Bassett, 2019; Huchim-Lara et al., 2016). The high price of lobster, sea cucumber, and red grouper, from these Asian markets, creates the incentive for fishermen to target these species (Huchim-Lara et al., 2016). Tourism in the Dominican Republic has also increased the demand for seafood, requiring targeted fishing for lobster, octopus, conch, and other fish species which are sent exclusively to the hotels and restaurants that feed American and European visitors. An increase in seafood demands do not just provide more work and income for the local fishermen but it puts them at physical risk as they continue to fish in dangerously deep waters (Mallon Andrews, 2020).

The success of fishermen using compressor fishing techniques in deeper waters has generated the unwanted attention of conservation campaigns in many small coastal fisheries. Fisheries in the Dominican Republic, and other parts of the Caribbean, have been targeted by many conservation campaigns led by American and European biologists and fisheries scientists. These scientists started leading educational interventions about reef and ocean health in 2015 in small communities like Monte Cristi. First recommending that the sustenance fishermen refrain from targeting certain species, laws were soon put into place. By making catching parrotfish illegal in 2017, conservationists criminalized a catch that provided 50% of the fishermen's daily income and limited the use of a fish that the fishermen regularly brought home to feed families (Mallon Andrews, 2020). Fishery conservation and management regulations inadvertently push small scale fishermen into more dangerous waters. Fishermen in Yucatan, Mexico report that they were forced to dive further from the coast to catch bigger fish and lobster to comply with management regulations (Huchim-Lara et al., 2016). These interventions place blame on compressor fishermen for the depletion of marine resources, ignoring tourism, export industries, and chemical runoff of industrial agriculture (Mallon Andrews, 2020).

The changes to the Caribbean marine ecosystems have been affecting fishing communities for decades. Fishermen in Grenada report changes in water quality, climate, and coastal development of which they believe are the reasons for the decreasing fish populations that they observe underwater (Winkler, 2016). Anthropogenic climate change is a major concern for ocean health in coastal communities. The increasing greenhouse gas concentrations have already contributed to the rising temperatures of global air and sea surfaces. The increasing temperatures also cause pressure changes that result in stronger wind fields and more extreme wind events that occur over the ocean (Harley et al., 2006).

Increasing ocean surface temperatures have already resulted in widespread coral bleaching and mortality as many reef-building corals live close to their upper thermal tolerances. Because the organisms that have the highest heat-tolerance are often the ones that live closest to their thermal tolerances, marine life in the Caribbean, and other low-latitude climates, are especially at risk with warming ocean temperatures (Harley et al., 2006). Caribbean corals reefs take over eight years to recover from storm damage and an increasing frequency of ocean storms from climate change will reduce the odds of recovery between wind events (Harley et al., 2006). Increasing ocean temperatures and damage to the Caribbean coral reefs will continue to negatively affect marine ecosystems and may be the force that is causing fish to relocate into deeper and safer waters. This change in ocean ecosystems will continue to affect the livelihood of those who depend on the sea for their food and income.

Risk Factors

The risk of DCS can be affected by many factors related to dive and diver attributes. Dive related factors including dive depth, dive duration, water temperature, and ascent protocol all are important attributes for preventing DCS (Louge and Blatteau, 2012). The deeper a diver descends into ocean depths, the increased exposure to greater partial pressures of gases. This exposure leads to an increase in bubble formation in the diver’s tissues. The longer that a diver remains at depth, the more bubbles that will accumulate in their tissues. The ability of these bubbles to become resorbed into solution depends on the number of bubbles that accumulated, making time and depth important factors during a dive (Hall, 2014). To prevent bubbles from forming in the blood and tissues, decompression stops are performed during ascent, to allow time for off-gassing to occur.

Diver attributes, including increased age, lack of physical fitness, physical injury, dehydration, high body fat percentage, and presence of a patent foramen ovale, may predispose a diver to developing DCS but the extent to which these factors increase the probability of the bends is unknown (Hall, 2014; Louge and Blatteau, 2012). Divers with a persistent patent foramen ovale (PFO) and other right-to-left shunts have an increased risk of decompression sickness with the predicted risks paralleling the size of the PFO (Bove, 2014; Eichhorn and Leyk, 2015). A PFO is a hole between the left and right atria that exists in everyone before birth but it is common abnormality that can persist into adulthood (Cartoni et al., 2004; Neuman, 2002). Persistent PFOs allow the venous bubbles formed during the decompression of a dive to circumvent the lung filter, passing through the right-to-left shunt (Wilmshurst, 2019). If nitrogen gas bubbles are shunted from the peripheral to systemic circulation, they are less likely to be expelled through respiration (Cartoni et al., 2004). Although PFOs persist in around 30% of the population, the low incidence of DCS suggests that not all divers with a PFO are at increased risk of developing the bends but those who are susceptible tend to get more serious neurological symptoms (Cartoni et al., 2004; Neuman, 2002; Sykes and Clark, 2013). Divers with large PFOs can benefit from a PFO closure procedure but safe diving practices is normally the recommendation (Sykes and Clark, 2013). The procedure is more frequently recommended for commercial divers with large PFOs and repeated instances of the bends (Bove, 2014).

Preventative pre-dive and post-dive oral hydration is particularly important, especially when divers are performing repeated dives. In a study involving military divers, pre-dive oral hydration significantly decreased circulatory venous gas emboli present after the dive (Gempp and Blatteau, 2010). It is hypothesized that pre-dive oral hydration dive may prevent decreased cardiac preload at the end of a dive, resulting in an increased elimination of inert gas during decompression (Germonpré and Balestra, 2017).

The physical fitness and percent body fat of each diver can affect the probability of them getting the bends. Nitrogen is five times more soluble in fat than in water and five times more soluble than oxygen in fat (Mahon and Regis, 2014; Navy Department, 2016). Because fatty tissue holds significantly more gas compared to the watery tissues in the body, more time is required for the elimination of the excess inert gases while ascending from ocean depths for those with more body fat (Navy Department, 2016). In early diving research, larger caisson workers were noted to be more predisposed for developing DCS symptoms and U.S. Navy divers with higher skin fold measurements were five to six times more at risk of DCS then the general U.S. Navy diver population (Mahon and Regis, 2014). Physical fitness, measured by VO_{2max}, is considered a protective measure against DCS. Regular exercise may impact the risk of DCS as it is involved in the generation of micronuclei, nitric acid generation, and nitrogen uptake and elimination (Mahon and Regis, 2014). Disorders that lower exercise capacity and cardiopulmonary function can increase dive related injuries, making physical fitness an important variable for safe diving (Bove, 2014). Although there are many different risk factors associated with diving, sufficiently hydrated and physically fit individuals that practice safe diving protocols, usually have the best diving outcomes (Hall, 2014).

Prevention

In the early 1900s, an English physiologist name J. S. Haldane composed a set of diving tables that established a method for decompressing in stages while working with Royal Navy divers (Navy Department, 2016). Haldane’s work helped create methods for preventing the occurrence of DCS based on the speed of ascent and duration of decompression stops, depending on the depth and time of a dive (Blatteau et al., 2015). Though these tables have been improved and restudied, Haldanean decompression models are the widely accepted methods for safe diving (Buzzacott et al., 2015; Navy Department, 2016). Diving computers can also be used for safe diving practices. Modern diving computers have algorithms to estimate nitrogen saturation and desaturation during a dive. The algorisms take into account the depth, time, water temperature, physical exertion, heart rate, and minute ventilation, to create an individualized ascent plan for every dive (Eichhorn and Leyk, 2015). Decompression programs like V-Planner can also be used for calculating decompression profiles. V-Planner uses the Varying Permeability Model (VPM-B), originally developed in 1986, creates a diving plan based on research of the changes in nuclear radius, caused by increases and decreases in ambient pressure. The VPM-B uses its algorithm in a Windows dive decompression program to design individualized safe diving plans (Yount and Baker, 2012). Although diving tables, diving computers, and decompression algorithms increase the safety of a dive, DCI can occur even if a diver follows the depths and time limits prescribed and after a diver has completed hundreds of dives without an incident (Sykes and Clark, 2013).

Decompression practices vary in artisanal fisheries all over the globe. Across six different fisheries on the Caribbean island of Grenada, 76% of the fishermen surveyed consider their occupation to be dangerous or very dangerous and 82% report experiencing DCS one or more times. Although divers on Grenada were very aware of the risks of diving, they continued to dive with unsafe diving profiles (Winkler, 2016). In a study on diver fishermen in Thailand, during dives lasting 30 minutes or longer and at depths deeper than 40 meters, only 53.8% of divers made at least one decompression stop and the rest do not make a stop at all (Gold et al., 2000a). In compressor fishermen in the Galapagos with extremely long average bottom times of 175 minutes, no decompression stops were made upon ascent (Westin et al., 2005). Fishermen understand the risks that they take by diving deep and rapidly ascending to the surface of the water. Although some will decrease their ascent rate and complete their stops closer to the surface rather than halfway up, as recommended by the U.S. Navy Standard Air Decompression Tables, decompression stop protocol remains inconsistent and often inadequate among these small fisheries (Blatteau et al., 2015). Omitting decompression saves the fishermen time, allowing them to perform more dives in a day and catch more fish. Well aware of the dangers of this kind of diving, fishermen consider the risks worth the reward (Winkler, 2016).

Treatment

There are multiple methods for treatment of the bends, some more accessible and affordable than others. The best and most common aid for divers who develop DCS is to immediately administer 100% oxygen for several hours, even if manifestations resolve (Eichhorn and Leyk, 2015; Vann et al., 2011). Pure oxygen establishes the largest possible inert gas gradient from tissue to alveolar gas, resulting in rapid removal of inert gas from tissues to lungs by perfusion and from bubble to tissue by diffusion. Pure oxygen also decreases tissue hypoxia caused by bubble-induced ischemia, mechanical injury, or biochemical damage. Immediately administering oxygen to a bent diver may decrease the number of hyperbaric recompressions that they must endure. During an observational study, divers with DCS who received oxygen immediately after a dive had symptom resolution after fewer hyperbaric recompressions compared to those who did not receive post-dive oxygen (Vann et al., 2011). Although oxygen is a portable option for DCS first aid, access to pure oxygen is limited in small occupational fisheries.

Hydration is essential before and after a dive, especially in warmer climates. Intravenous fluid replacement can be beneficial especially in severe cases of DCS (Bove, 2014; Vann et al., 2011). Oral rehydration can be used for stable and conscious patients, but in severe cases oral rehydration may be unreliable (Vann et al., 2011). An intervention that is less commonly used is the administration of vitamin B complex. In the Dominican Republic, a shot of vitamin B complex is often administered as a first aid ritual for fishermen experiencing symptoms of DCS (Mallon Andrews, 2020). Intravenous drip infusion of vitamin B complex has been used as a conservative therapy for inner ear barotrauma but little research has been conducted for its effectiveness for treating DCS (Kozuka et al., 1992).

The best and most effective treatment for DCS is recompression in a hyperbaric chamber. Hyperbaric chamber treatment is advised even if DCS manifestations resolve after a diver is given oxygen and other first aid because untreated DCS symptoms can recur days after the initial exposure. Mild initial manifestation of the bends can come more serious a few hours after surfacing and sometimes even a few days after the dive. Immediate treatment in a hyperbaric chamber should occur to avoid a late reoccurrence of symptoms or an increased severity that can occur over time (Vann et al., 2011). The most common hyperbaric therapy for DCS cases includes compressing patients to 2·8 bar (60 fsw) for about six hours, equivalent to pressures under 18 meters of sea water depth, while breathing 100% oxygen. If treatment pressures are greater than 2·8 bar, enriched nitrogen-oxygen or helium-oxygen may be used to reduce the risk of oxygen-associated toxic effects (Bove, 2014; Vann et al., 2011). If DCS symptoms do not resolve after the first treatment, recompression should be repeated every day until patient is symptom free or no further improvements are observed. Patients with neurological DCS manifestations usually need two or three recompression treatments but in severe cases, some patients do not see symptom resolution until after 15 to 20 repetitive treatments (Vann et al., 2011). Although hyperbaric treatment is most effective for resolving symptoms of the bends, many artisanal fisheries do not have access to these decompression chambers.

There are very few hyperbaric facilities available in tropical coastal regions, forcing artisanal fishermen to use alternative avenues for treatment (Blatteau et al., 2015). In remote regions where resources are limited, in-water recompression can be used for divers who develop severe DCS symptoms (Hall, 2014). In-water recompression is a technique that reproduces the effect of a hyperbaric chamber by resubmerging a bent diver and slowly bringing them back to the surface (Blatteau et al., 2015). After a saturating dive, the submersion of a diver to six meters for 30 minutes with supplemental oxygen, is proven to be more effective at eliminating bubbles compared to just administering 100% oxygen for 30 minutes at the surface. These findings indicate that in-water recompression could be useful in situations where a diver experiences interrupted, rushed, or omitted decompression (Blatteau and Pontier, 2009). Although this method is most effective when a diver is administered pure oxygen to breathe while recompressing, many compressor divers do not have access to pure oxygen or the equipment to administer it underwater (Blatteau et al., 2015).

In emergency situations, some diver fishermen attempt to do in-water recompression with compressed air but it is usually unsuccessful unless specific recompression guidelines and safety protocols are followed (Barratt and Van Meter, 2004; Westin et al., 2005). Structured in-water recompression protocols have been successful after educational interventions for small fisheries in Vietnam. Trainings to recognize and treat DCS with first aid and in-water recompression, helped to decrease DSC related mortality in these occupational fishermen. After the trainings, in-water recompression treatments with compressed air relieved pain in all cases of DCS in the joints and improved the symptoms in those experiencing neurological DCS (Blatteau et al., 2015). This recompression method can be incredibly risky with dangers including drowning, hypothermia, hyperoxia, and dehydration (Blatteau et al., 2015; Winkler, 2016). In-water decompression can be performed effectively if additional divers accompany the symptomatic diver underwater, environmental sea conditions remain safe for the diver and their crew, the systematic diver is stable and can use their extremities, and enough air and gas is available for the additional time on the water (Hall, 2014).

Rationale for Return to work

A lack of employment opportunities outside of fishing in small coastal communities, force artisanal fishermen to continue entering the ocean, despite knowledge of the inherent dangers of diving (Barratt and Van Meter, 2004). It has become economically impossible for fishermen to dive safely in the waters of Monte Cristi. Financially, fishermen must adapt to the changing underwater environments. Compressor fishing is now widely used across Central and South America because of its cost effectiveness. In Monte Cristi, a freediver fisherman might make 1,000–2,000 pesos (US $20–$40) a day in calm seas, but a compressor fisherman can make 2,000–5,000 pesos (US $40–$100) in a day (Mallon Andrews, 2020). The risk of DCS is often worth the reward of fish for these financially constrained fisheries (Winkler, 2016). The physiological consequences that these divers face are severe. Despite the risks of injury and high rate of mortality among these diver fishermen, they continue to enter dangerously deep waters.

Summary

The fishing industry is one of the most dangerous occupations in the primary sector (Huchim-Lara et al., 2018). Small coastal fisheries around the world face the highest occupational risk because of their limited access to expensive diving equipment and technology

(Winkler, 2016). Diver fishermen continue to work in increasingly risky environments because marine ecosystems are rapidly changing as a result of river runoff, tourism, coastal pollution, and overfishing from targeted export markets. These fishermen spend upwards of six hours a day at sea and underwater, using an air compressor to reach depths ranging from 9.14 to 45.72 meters, conducting an average of three to six dives per day (Mallon Andrews, 2020). As a result of their working conditions and the environmental factors that have driven fish populations into deeper water, occupational divers in the Dominican Republic are at risk of acute and chronic decompression sickness.

This project explores decompression risk as a chronic condition among diver fishermen in the Dominican Republic. By comparing the diving profiles of Dominican fishermen to the recommended profile for the duration and depth of each dive, this study will help to understand the circumstances and practices that lead to chronic cases of decompression sickness. This information is crucial for understanding the broader health implications of compressor diving in the Dominican Republic and in other fisheries of the global south.

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Appendix A: Journal Guidelines to Authors

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