IQ PROCEEDINGS

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"DIVE SAFETY THROUGH EDUCATION"

Proceedings from the International Conference on Underwater Education
ICUE 2017, Long Beach, California – May 6 & 7
"Dive Safety Through Education"

IQ 2017 Proceedings

Small Scale Artisanal Fishermen Divers

Background

The Supply Chain of Marine Resources

How does the fish or fish product you eat get to your table? What is the distance that it has to travel in order to get into your sushi roll? Most of us consume these marine resources with very little insight into the supply chain. The end consumer is usually only interested in a high quality product.

A high-value species, for this reason, is one that a consumer is willing to pay higher amounts of money per gram of product. Lobster, octopus, and especially sea cucumber have all become highly profitable species (Figure 1). Sea cucumbers, in particular, have become a sought after food commodity in China over the past 1,000 years; since the 1980s, there has been a growth of harvesting activity in order to meet Asian market demand (Purcell *et al.* 2012).

Figure 1. Pictured above is a dried sea cucumber. Its sluggish pace makes it an easy target for fishermen in more than 70 countries (Purcell *et al.* 2012).

Over the past 50 years, the annual per capita fish consumption has steadily increased. Unfortunately, 30% of fish have now become biologically unsustainable, further driving their demand and value. In fact, the quantity of world trade in fish for human consumption has multiplied by 515% from 1976. This equates to $80 billion of fishery exports from developing countries, with a net revenue of $42 billion (The State of World Fisheries and Aquaculture 2016).

Capture Techniques

Capture fisheries produce over 90 million tons of fish per year (The State of World Fisheries and Aquaculture 2016). Much of what is captured in the ocean is harvested by two types of fishermen: those that work in large-scale fleets and those that work in small-scale fisheries. Small-scale fishermen are defined by the Food and Agricultural Organization (FAO) as fishermen who utilize minimal technology to capture fish, undertaking daily fishing trips in relatively small vessels (Figure 2).

Figure 2. Small-scale vessels, like the one shown above, make up about 85% of the motorized fishing vessels around the world (The State of World Fisheries and Aquaculture 2016). What is considered small-scale fleet for one country is not necessarily for another (Hazin).

Small-scale fisheries employ 90% of the people working in capture fisheries (The State of World Fisheries and Aquaculture 2016). When compared to their large-scale counterparts, small-scale fisheries are considered to be more ecologically friendly because capture techniques in the latter can be targeted to specific species, accomplishing a huge reduction in unintentional collection of the wrong types of fish (i.e. bycatch). Their capture techniques vary by region, from net casting to breath-hold diving.

In the coastal communities of the Yucatán Peninsula of Mexico, small-scale fishermen have introduced compressed air diving as a method of harvest (Figure 3). It is estimated that about 1,000 fishermen in this region currently utilize this method (Chin *et al.* 2016). These fishermen use a setup known as the hookah dive system (HDS), which enables them to dive for long periods of time at greater depths (Figure 4). Fishermen travel up and down the water column in search of their target species, diving for hours under dangerous conditions. In an effort to capture fish and produce an income, fishermen in regions like the Yucatán take on high-risk diving behavior by diving deep and long, sometimes exceeding 100 feet of seawater (Huchim *et al.* 2017).

Figure 3. About 250 fishermen comprise the two fishing cooperatives of San Felipe and Rio Lagartos on the northeastern coast of the Yucatán Peninsula of Mexico. Between 2003 and 2012, the hyperbaric center of the Mexican Institute of Social Security in Tizimín City treated 209 cases of diving-related illness each year from this population of fishermen (Huchim-Lara *et al.* 2015).

Figure 4. The hookah dive system is commonly used among small-scale fishermen across Central and South America. The setup is simple and cost-effective (Huchim *et al.* 2016). A gas-powered engine fuels a pump that compresses ambient air into a 1-2 cubic feet volume tank (blue in the photo).

Impact of Diving

Decompression illness (DCI) is a condition defined as the formation of inert gas bubbles, mainly nitrogen, in the blood or tissues. In a diving setting, DCI occurs when a diver does not adequately relieve the buildup of pressure from harvesting at depth. A diver can do so by stopping for a certain length of time at a certain depth on his or her way back up to the surface; otherwise, a rapid reduction in environmental pressure would cause the excess nitrogen to escape the bloodstream as gas bubbles (i.e. bubbling). The ensuing obstruction of blood flow or tissue damage by the bubbles may induce a range of symptoms from joint pain, nausea, vertigo to ecchymosis, paralysis, or death.

For the most part, inert gas onloading is a function of dive depth and duration. In its simplest explanation, every exposure to pressure leads to an increased gas loading in theoretical tissue compartments. These tissue compartments are said to be perfusion limited, meaning that gases will enter these tissues through blood flow (Historical Evolution of U.S. Navy Air Decompression Procedures and Decompression Concepts). Now most predictive models of DCI are ascribed to the theory that decompression will lead to DCI that either causes bubbling or does not cause bubbling. This type of binary deterministic modeling has worked well for last several decades (Thalmann 1983). Some more sophisticated models assign a level of risk to each dive. This probabilistic modeling has the potential to allow the diver to choose a level of risk he or she takes with each dive (Van Liew and Flynn 2005). Regardless of the decompression model used, all have a level or error in predicting the outcome of DCI.

Because most of the decompression modeling is being developed for recreational and commercial military divers, fishermen are left to learn by trial and error. Fishermen have had access to limited decompression algorithms that would allow them to ascend safely from their dives. This gap in science is partially due to the fact that much of the behavior that explains gas loading is associated with the type of species being hunted, yet data on fishermen's harvest and diving behavior is lacking in many regions of the world. The algorithms that are needed for these fishermen would dictate - based on analysis of such data - the length and depth of the stops they should undertake to safely decompress on their ascent to the surface.

On the northeastern coast of the Yucatán, more than 75% of the fishermen experience DCI at least once in their lifetime (Mendez 2017). The majority suffer repeated hits throughout their fishing career, with the likelihood of developing severe symptoms increasing with the number of hits and the probability of suffering 5 or more DCI events becoming almost certain after 55 years of fishing (Chin *et al.* 2015).

The primary treatment for DCI is recompression therapy in a hyperbaric chamber. Unfortunately, fishermen in the Yucatán generally do not have robust knowledge on how to recognize or address the symptoms of DCI. They tend to manage mild pain by taking pain relief drugs or drinking alcohol (Huchim *et al.* 2015). Only when symptoms become intolerable or life-threatening do they travel about 40 miles to the chamber in Tizimín City. On arrival, wait times may span hours to days, depending on resource availability (Huchim *et al.* 2016). Such barriers to treatment access, on top of losing income, are economic disincentives to seeking treatment.

Inadequate decompression during diving does not cause just DCI. It causes other injuries as well, such as dysbaric osteonecrosis (DON), or bone death. Compared to the general population or divers in the U.S. Navy, fishermen suffer DON at a much higher frequency (Denoble 2012). Accurate diagnosis in each fishing community, however, requires radiographic imaging, a service small-scale fishermen as in the Yucatán usually do not seek or receive. As such, identifying the predisposing risk factors of diving accidents early on and implementing targeted measures to reduce such risks requires preventive health screenings.

In the Yucatán, the underdiagnosis and underreporting of diving-related injuries are due in part to such socioeconomic factors. As exemplified by the situation in this region, neither the high incidence of DCI nor the factors driving it and other diving-related injuries among fishermen divers have been well established in the current literature. These unknowns are objects of a complex investigation involving not only the physiological and environmental conditions of the local fishing communities but also the bigger market forces at play that in turn affect fishery governance and fishermen's risk-taking behavior at the community level. An in-depth understanding of this mechanism would help design targeted strategies for risk mitigation. The goal of this effort is to grow small-scale fishing communities' capacity to support themselves and the global economy.

Methods of Investigation

Diving Behavior

Since 2012 we have been recording dive profiles of artisanal fishermen divers from the Yucatán Peninsula, Mexico. Since its inception, this international collaboration has collected over 1,800 open sea diving days from 16 fishermen divers, the largest collection of open sea dives among fishermen to date. ReefNet Sensus Ultra dive recorders have been used to collect detailed dive data, including depth, duration, and temperature (Figure 5).

Figure 5. Each consenting fisherman wears a Sensus Ultra dive recorder on his dive belt throughout each dive. The dive recorder is set to collect pressure every 10 seconds, with an accuracy of +/- 1 foot of sea water. This input coupled with a user written algorithm has allowed us to clarify the level of decompression stress these fishermen divers expose themselves to.

A subroutine created utilizing R-Studio has allowed for data from the recorders to be elegantly analyzed for patterns in diving. Fishermen divers display two specific dive patterns, yo-yo and square (Figures 6 and 7). Much of what we know thus far with regards to what they hunt can now be predicted by their dive patterns. Because different dive patterns lead to different nitrogen loads, understanding their dive profiles allows us to create targeted interventions based on target species.

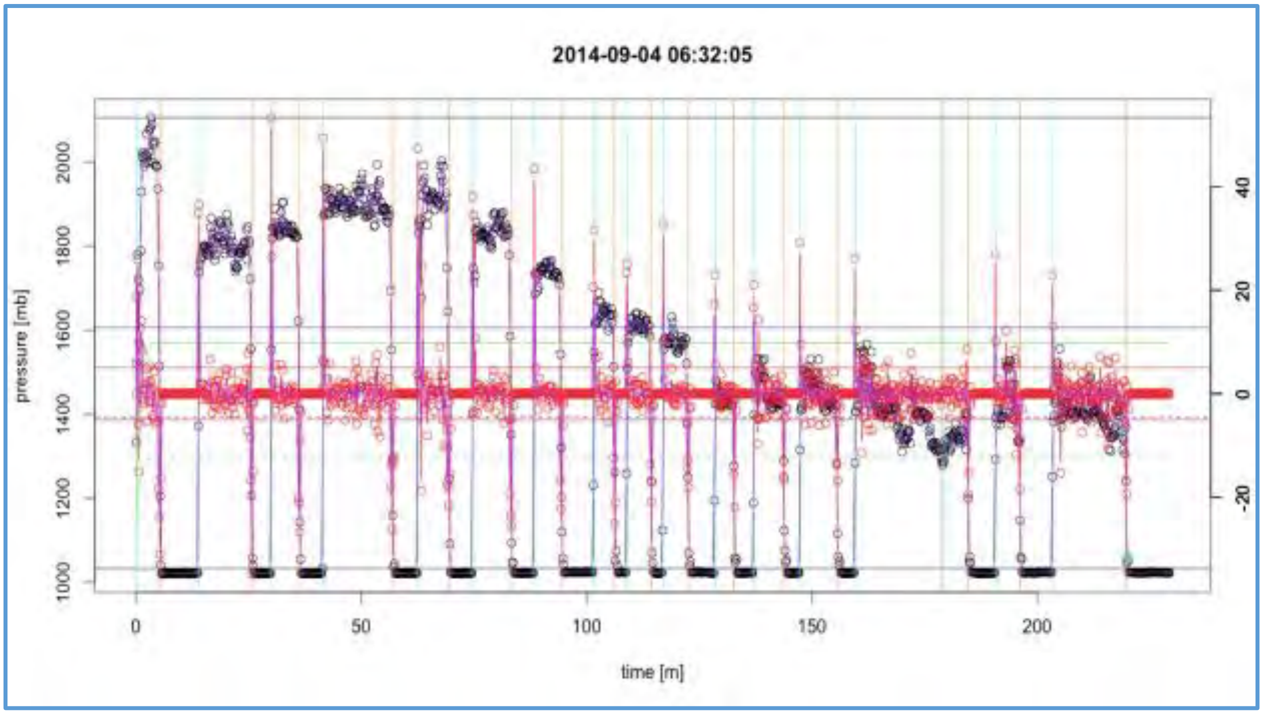

Figure 6. A yo-yo dive profile is typically exhibited by fishermen when they harvest lobster. Lobsters are agile, and the fishermen can only catch a handful per dive, so they must make frequent trips between depth (data plotted above at high pressure) and surface to unload their catch.

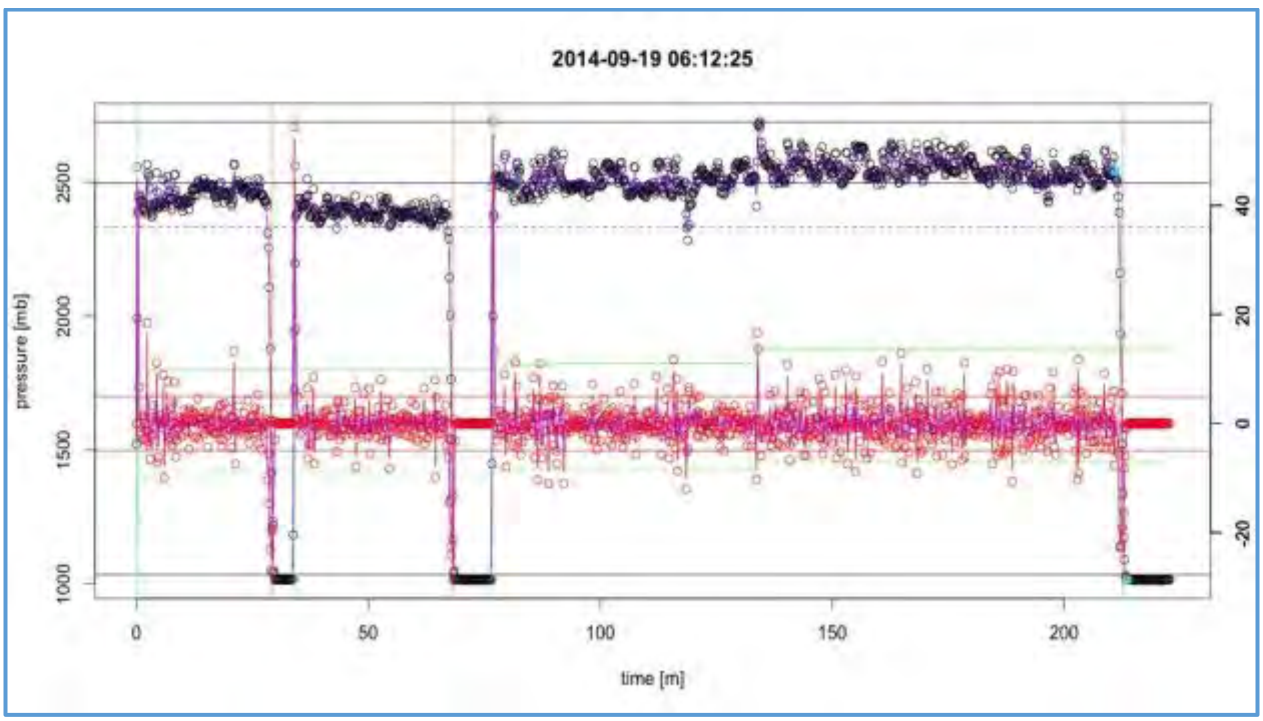

Figure 7. Compared to lobsters, sea cucumbers are non-mobile, and fishermen typically harvest up to 60 kg per dive. This means that they stay at depth longer each time they submerge themselves.

Results

Over the last five years we have collected over 2,900 dives over more than 1,800 diving days. Some of these dives have resulted in minor DCI while others in severe hits.

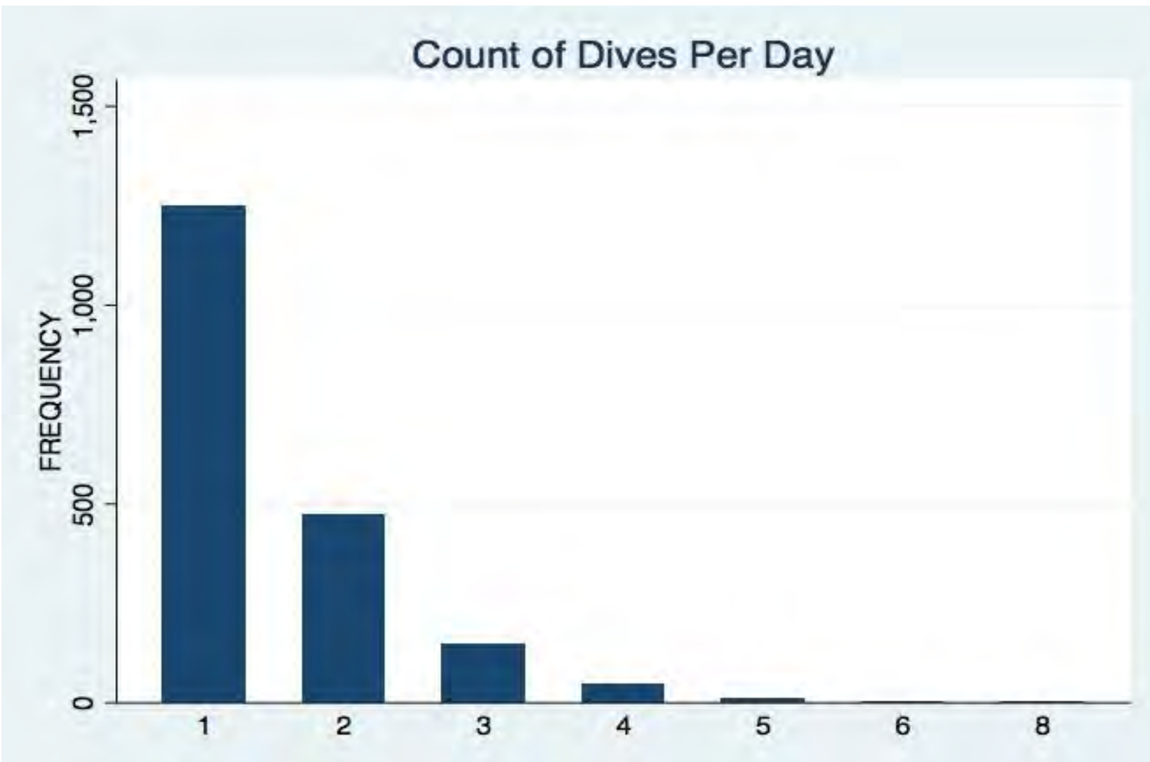

Figure 8. A breakdown of the diving data shows that the fishermen completed 1 dive per day 64% of the time, 2 dives 25% of time, and 3 to 6 dives 10% of the time.

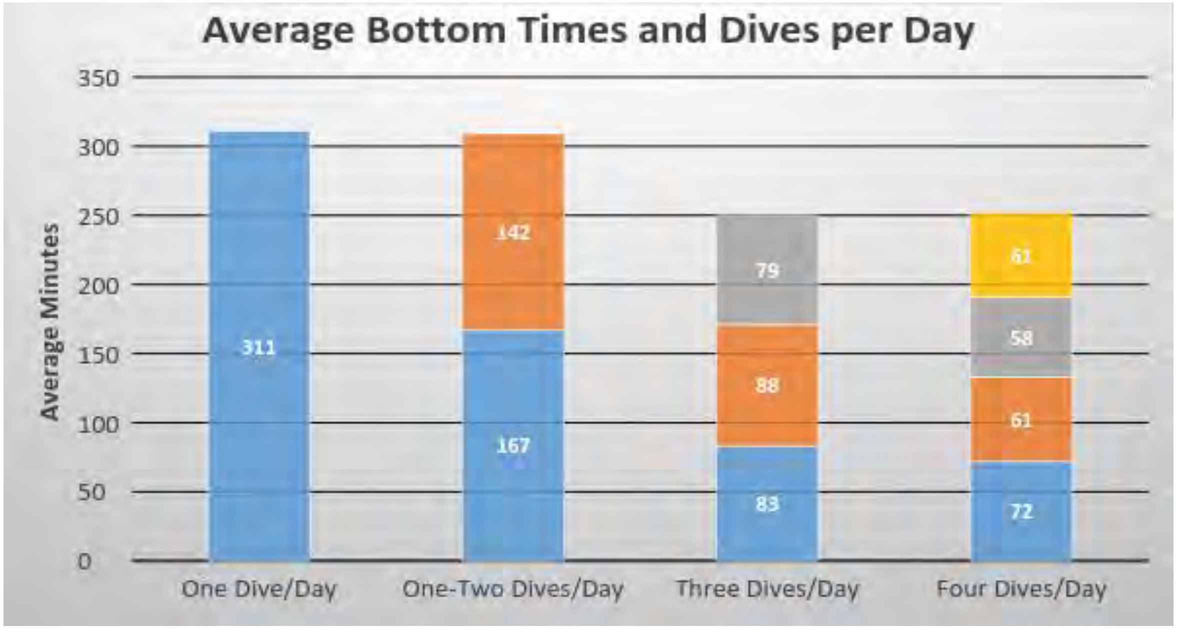

Figure 9. Fishermen spend, on average, a total of 300 to 250 minutes submerged. When they conducted more than one dive per day, the total bottom times were slightly lower, possibly meaning that as they caught more fish they would move on to a new dive site.

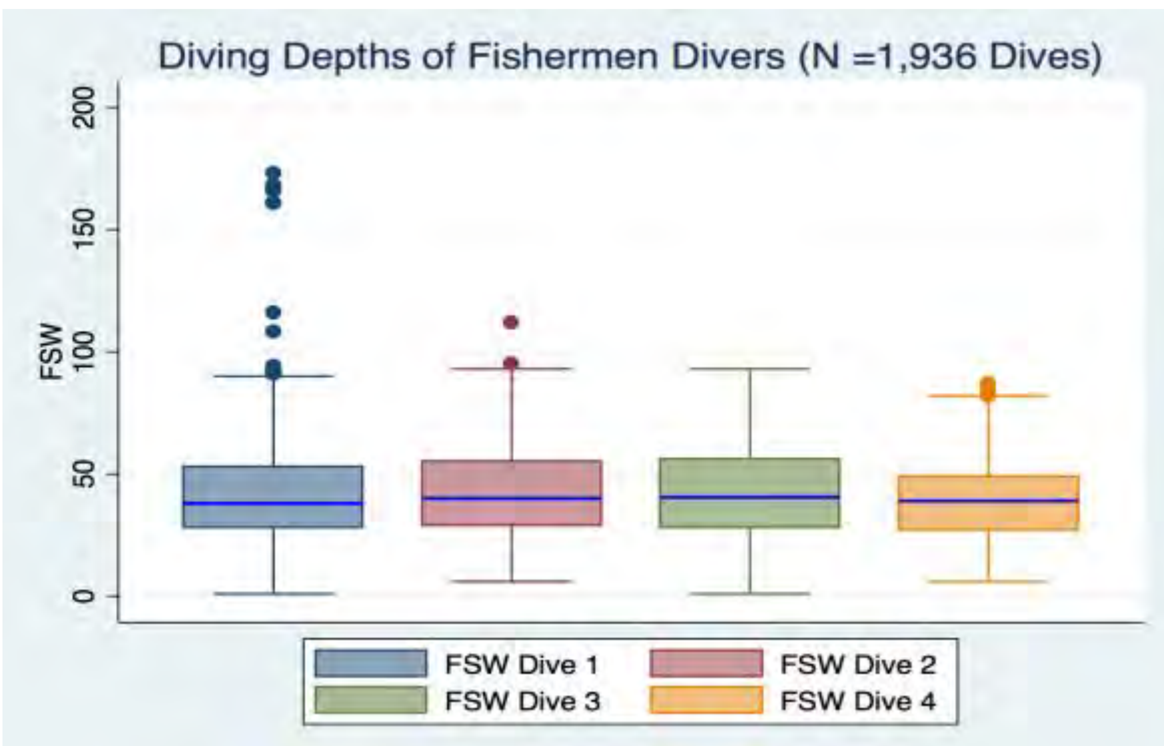

Figure 10. This boxplot shows a median depth of 44 FSW for most of the dives conducted by the fishermen in Yucatán.

Discussion and Next Steps

The data collected thus far has allowed us to predict nitrogen loading in a sample of fishermen in the Yucatán. Based on this data, we have identified where in the water column a fisherman would need to decompress in order to make a safe ascent: a stop at 20 feet would allow 90% of the loaded tissue to be decompressed. This would decrease the incidence of DCI among these fishermen. In an effort to test the efficacy of this intervention, we plan to model a simple decompression line with this stop and conduct a pilot study among one small group of fishermen in this region. If the intervention proves to be successful, we will disseminate the learning to the rest of the fishing communities in the Yucatán with similar diving behaviors.

While DCI has become an extremely rare injury in the United States, this condition affects thousands in developing nations. The marine resource that they help bring to our table comes as a cause. Fishermen risk their lives in order to provide subsistence for themselves and at the same time we gain a cheaper product we can buy. We have a moral obligation to help the fishermen divers who do not have the resources to tackle these injuries. These fishermen present a unique opportunity to advance our understanding of decompression stress and how that evolves into DCI. Through simple interventions and informed decision making for not only the local fishermen and treating medical team but also the local investigating team who can apply these learnings in other regions, we have gained a deeper understanding of the nature of collaborative work. We hope to continue this important work in Yucatán Peninsula and use what we have learned as a model for other fisheries around the world.

About the Authors

For over five years two researchers have been collaborating with five fishing villages in the Yucatán Peninsula of Mexico. Walter Chin is an investigator of University of California, Los Angeles who has worked in the field of medical diving for over 14 years. Oswaldo Huchim is an investigator from Marista University in Merida. He has dedicated over 6 years to establishing the foundation of this research. Together, Dr. Huchim and Walter have established collaborative partnerships that have grown over the last five years to include multidisciplinary team members in the fields of epidemiology, anthropology, and medicine from universities and fisheries across both Mexico and the United States.

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Lead The Culture
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By Tec Clark

Why NAUI? Is it that they have the best materials in the industry? The best books, the best materials? Is it that they have the best marketing in the industry? Is it that they have the worldwide domination of certifications? Or, is it that NAUI has "safety through education", and that NAUI has "academic freedom"?

You see, the certification agency 48 miles away has sexier books and materials than NAUI does. That same agency has marketing budgets that will blow NAUI out of the water. That same agency has the worldwide domination in certifications. Again I ask you, why NAUI?

It's because the values that you have and you hold that are part of your culture resonate because of the values that are in the culture of NAUI. That culture, that assimilation, that bonding, that pairing is what we're going to talk about today.

Before we get started we need to hear a story. Back in the early 2000s Vail Ski and Snowboard School, which is a legendary skiing and snowboarding school, they went through a challenge. The challenge was that they were seeing decreases in everything that went along with their downhill sports: snowboarding, skiing, downhill skiing, anything. What happened was that this was an industry trend where they lessened the prices of lessons and contact hours with an instructor had diminished.

Because they had reduced down the time and the contact hours, and then the cost, advanced skiing, excursions, backcountry skiing, heli-skiing, and equipment sales, were suppressed.

Carol Levine who was the director of the Ski and Snowboard School, got her team together and said we need to make a change here. The change was they had to look internal into the culture that was going on. What were their own instructors doing? What was their team doing that was leading to these other suppressions? Could it only be the classes themselves?

They analyzed it and they saw that there was patterns of behavior that were taking place that were diminishing the contact hours with her instructors. The ski instructors would go up the ski lifts together, eat lunch together, etc. Here's what Carol Levine and company did. They said we're going to change this. We're going to change our culture, and we're going to change it, because what we want, the most critical thing that we can do is develop skiers. We want people to call themselves skiers when they're done with our programs.

So, they purposefully changed their lessons to improve the contact hours with the students. This cultural change, by focusing on the value of creating skiers, led to increases in all areas of operations.

What is culture? Simply put, an invisible force that influences the behavior of a group. This invisible force is what makes a crowd act different at a symphony than at a rock concert. But, what we're talking about is what's called organizational culture. Organizational culture, or workplace culture is studied in business schools all over. This is a vital part of what makes a business succeed, any business, any size, is it's culture, and it has to come from within, and it's personality driven and people based.

The definition of organizational culture is the values, behaviors, beliefs, and assumptions that contribute to the unique social and psychological environment of an organization. Think of this, social and psychological environment of an organization. Have you ever gone into a business and that business felt weird? You got a vibe the second you walked in. That feeling is just a byproduct of a bad culture. Remember the culture is the social and psychological environment. That comes from people and personalities.

People lead a culture just as people lead an organization. People can lead culture at any level that you are. You could be CEO. You could be manager. You could be founder. You could be just a good guy. But the deal is that when you are putting your values, attributes, beliefs, behaviors into your culture, now your fingerprints are all over your organization, your company.

We always think that the leader has to be the founder, this top dog executive. If we take a look at Steve Jobs with Apple, he co-founded it, and grew it, and he's a visionary, and he's a disciplinarian, but everything's about the vision. What a great guy to lead the culture.

Well guess what ? It doesn't need to be that the CEO is the influencer. The person that influences is the one that is dynamic and has a bold personality and has great vision. That person could be a team player. Take a look at Tim Tebow. Tim Tebow comes off of an abysmal failure of a game, and then says to the world I'm going to be the strongest, hardest working quarterback you've ever seen. What happens? National championship.

Wait a minute. He's not the coach, but that stand that he took shaped the culture of the Florida Gator team. Not Urban Meyer, Tim Tebow. People got behind him, and people recognized the brand, and people recognized the culture that was forming because of his influence. That is the power of an influencer. Don't ever be in a position where you think you don't matter, or it won't make a difference. You can be an influencer too.

Now that we know who shapes the culture, how do we do it? It's pretty simple. We actually look at two areas. That's going to be values and norms. With values we are looking at the things that stand out the most to you. The things that would be on the wall on a vision statement or a mission statement. These are the things that are so powerful, they are part of you. They have to be part of you. They're part of your DNA. In the last frame we had the Tim Tebow and the football reference. Well winning is a great value for a sports team, but if we look at Apple then innovation might be it. What do they do? They come up with slogans. "Think differently" is what Apple uses. Why? They wanted it creative. They wanted to show that they are innovative, and so they use a slogan that matches that innovation style that they've got.

Then you've got research. You could look at pharmaceutical companies, Pfizer Pharmaceuticals. Tons of value goes into research. Then as we take a look at different values that go here you could look at quality. Toyota, Ford Motor Companies, Ford Motor Company used the "Quality is Job One" slogan.

Then, this all translates into the norms. The values go to norms, the norms are the actual physical manifestation, or tangible manifestation of the values. The norms can be formal or informal. Informal norms would be something just fun like dress-down Fridays. It could be informal like doughnuts are being brought to the dive site on open water dives. It can also go to the formal stuff that says we are going to have a particular way that we inventory our gear. We are going to have a particular way of how we keep our dive locker clean. We're going to have a particular way, and those are set in standards, procedures, policies, etc, but they're the physical representation of the values.

When we look at the values and norms and we kind of put them together how do they get there? How do we get values that are in your heart, and how do we get them on paper and then get them actually translated into your dive center? It's quite a simple process actually. It's three steps. First is a values assessment, second is mind mapping it, and then third is putting those in place in implementation.

First, a values assessment. You can look up values all over the place. You can find them, look at corporate values, on and on and on. Really it's not about that. It's about what is in your heart, what is important to you. Here's the way I tell everybody about values. What do you want to be known for? What do you want to be known for? Because if this works right everybody will know you for your values, and that's what you want, because it's that important. So, when we take a look at these things here: service, fun, change, creative exploration, environmental, pick something. Pick two, pick three, whatever resonates with you but that you are going to get behind and you're going to own it, and people will know you for it.

Again, it doesn't do any good if you want to be known for fun, but you are a grumpy old man. You will not pull it off. Your values won't work. It will never get to norms because you will crush the norms because it's not part of your DNA. You have to own the values, number one. Step one is the values assessment.

Step two is mind mapping. With that, you've got a very simple way to take something that is important to you and flesh it out, and break down all of the elements of it into the areas of operation. Let's do something simple. Let's say that in the middle here I've got vacation. I want to go on a vacation. What I would do is look at all of the externals to the vacation. What's that going to be? Well it's going to be how are we going to get to where we want to go on our vacation? So transportation would be right here. Then were are we going to stay? Lodging would be right here. What are we going to do? That's going to go right here. It goes on and on.

Those are your areas that you're brainstorming, and they just kind of flow, and you put them in these bubbles, but you attach these lines to them, and on the lines you put all the options. So you see this mind mapping can get really big, but what's great about it is it fleshes out everything that you need to get to what it is that you want to create.

In this case you put your value here. You put your central value that is your core value, put it right in place, and then you branch off from there in every area of operations that you have. It doesn't matter if you're a dive center. Maybe you have retail. But you could be an independent instructor. Do your students still need to get retail at some point? Yeah, so what can you do? We can put classroom, pool, retail, training. We can put anything around our value, and what it means is that that value that you owned here is going to go into every area of your operation, and you will find a place to put it. Then, we go to step three, which is the implementation.

Where do we put it and how do we put it there? It's easy. Once you've done your mind map and put all those areas into play, now you put them in your policies and procedures manual. They become part of that culture. You put them in your mission statement, on the wall, so that you and your staff, and everybody is seeing what you're about and you're being reminded of it daily as you walk by a mission statement. Staff training, at meetings. Put it in your environment. Whatever value you owned and you've got in your environment, it needs to be present. It needs to be felt. It needs to be palpable so that everybody sees it, embraces it, feels it, know it is part of you. .

Some places that are doing it right, first of all Southwest Airlines. What did they want to be known for? Great customer service. They took that energy that came from boards, and presidents, and pushed it forward into their norms. Now their norms are that it's okay if flight attendants sing. It's okay if flight attendants do sketches to give their safety briefings. It's okay if captains get on and joke about the bumpy landing. It's okay because they want people walking on the plane laughing, and they want people walking off the plane laughing.

Then you've got Chick-fil-A. Chick-fil-A founded by Truett Cathy. This guy is a strong Christian believer. What he believed in was servant leadership. Servant leadership was such a part of him and his value system that he put it in the Chick-fil-A brand. Now every employee that goes through Chick-fil-A training is trained to be a servant first. What do you need? What can I get you? What can I get you? What can I get you? What do they say at the end of every interaction? It's my pleasure. When you say thank you, it's my pleasure. They wanted to be known for that, and that value rings out.

Then Disney. I've talked about Disney as being the happiest place on earth, but if I were to say, hey guys picture Walk Disney World or picture Disneyland. What's one of the first things that comes to mind about those two places? Clean is actually the number one response from all focus groups. Why would cleanliness be such a thing if they want to be the happiest place on earth? Well you see it was one of Walt Disney's actual other big values. He was so fanatical about cleanliness that he wanted it such that people would be embarrassed to drop trash or garbage in the park.

So what did he do? He literally studied the behavior of people and watched them. Peered from hidden areas, as he moved trash cans around for weeks, and weeks, and studied it, and he came up with his own theory that individuals if they have to walk more than 30 feet to a trash can they will drop stuff, but if trash cans are placed 30 feet they'll use them. So guess what? That became a norm. His value was cleanliness. The norm was we're going to put trash cans every 30 feet. Do you see how this works? That's when it gets right, and that's what's special.

Let me break it down to you for what we did as an academic dive program at Nova Southeastern University. When we came to life we said, all right we've got some values. As the founder of that dive program at NSU what was going to be the values that I put in place? First, I came from an academic diving program, so the University of Florida Academic Dive Program 1988 is when I became a NAUI instructor, and so that is an important part of who I am, the academic freedom, the academic integrity, and the ability to teach great courses. That is important, and we put values into place for that.

But another value that we put into place was safety. You see as a former national training agency director and a forensic dive accident investigator I'm intimately familiar with dive safety. It's very important to me. What we did, and for an example is we build the value of safety into everything we do operationally. In Rescue and Divermaster we teach more proactive skills than reactive skills. In staff meetings we look at case histories of dive accidents and quiz how to prevent and/or handle. We have safety signs, safety agreements with the students, safety statement in our syllabi. And we conduct regular in-service trainings. These trainings are as real to life as possible. We do these trainings everywhere we frequent locally with our dive program.

What this does is creates what we wanted to be known for. You see every operator actually see our NSU Academic Diving Program in action handling mock emergencies with mighty skill. It's impressive. That gives us a reputation of that we take safety extremely seriously and we are good at it. The other by product is our staff. They have tremendous appreciation for their talents in safety because when it is put to the test in front of strangers and operators, they shine. That builds confidence. That confidence is infectious and it shows to others, and others are drawn to that confidence and that level of talent. Again, securing who we are and what we want to be known for.

This is how implementing your core value or values into every area of your diving business will bless you, your staff and your customers tremendously. And you can do it for whatever your vision and values are.

Gas diffusion among bubbles and the DCS risk

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We present some experimental and simulation results that reproduces the Ostwald ripening (gas diffusion among bubbles) for air bubbles in a liquid fluid. Concerning the experiment, there it is measured the time evolution of bubbles mean radius, number of bubbles and radius size distribution. One of the main results shows that, while the number of bubbles decreases in time the bubbles mean radius increases, hence, it follows that the smaller bubbles disappear whereas the – potentially dangerous for the diver – larger bubbles grow up. Consequently, this effect suggests a possible contribution of the Ostwald ripening to the decompression sickness, and if so, it should be pursued its implementation to the Reduced Gradient Bubble Model (RGBM) so as to build up dive tables and computer programs for further diving tests.

In memory of Randy Shaw and Sergio Viegas

I. INTRODUCTION

The formation of gas bubbles [1] – due to nucleation (homogeneous or heterogeneous) and tribonucleation, and their evolution (expansion or contraction), owing to decompression or compression, diffusion, counterdiffusion, coalescence and Ostwald ripening – in the blood and tissues of the human body can give rise to the decompression sickness (DCS). The Ostwald ripening mechanism consists in gas transfer from smaller bubbles to larger bubbles by diffusion in the liquid medium, consequently, the radii of larger bubbles increase at the expenses of decreasing radii of the smaller ones. It shall be presented the results of experiment and simulation which the Ostwald ripening is investigated for the case of gas (air) bubbles in a liquid fluid with some rheological parameters of the human blood. There, it has been measured and analyzed the time evolution of the bubbles mean radius, the number of bubbles and the radius size (frequency) distribution. At a fixed ambient pressure, namely, at the same "depth", one of the main experimental results has been undoubtedly shown that, while the number of bubbles decreases in time the bubbles mean radius increases, meaning that the smaller bubbles disappear whereas the larger (potentially dangerous) bubbles grow up. This phenomenon may reveal a contribution of the Ostwald ripening effect to the decompression sickness risk during and after diving, suggesting, therefore, a deeper theoretical and experimental investigation. Beyond that, if the Ostwald ripening shows up as an important physiological effect, its implementation to the RGBM (Reduced Gradient Bubble Model) [1–3] for further diving tests should be pursued.

The outline of this presentation is as follows. In Section II and Section III, there are introduced the macroscopic and microscopic processes of bubble formation, respectively. The processes of bubble evolution are presented in Section IV, and the physiological consequences of bubble formation and evolution – the decompression sickness – are introduced in Section V. Section VI introduces and discusses theoretical aspects of the Ostwald ripening phenomenon for gas bubbles in a liquid. The experiment, its apparatus and the result analysis are presented in Section VII. In Section VIII, some preliminary results of the finite element simulation for one bubble, three, five and fifty bubbles are introduced. The conclusions and perspectives are left to Section IX.

II. MACROSCOPIC MECHANISMS OF BUBBLE FORMATION

A. Cavitation

Cavitation is the process of rupturing a liquid by decreasing the pressure at roughly constant temperature – quasi-isothermal process (FIG.1).

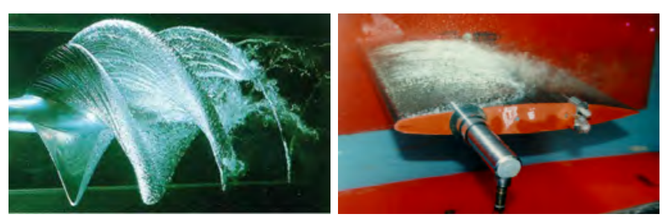

FIG. 1. Cavitation [4].

B. Boiling

Boiling is the process of rupturing a liquid by increasing the temperature at roughly constant pressure – quasi-isobaric process (FIG.2).

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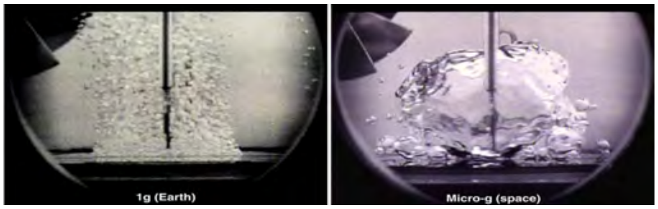


FIG. 2. Boiling [5].

III. MICROSCOPIC MECHANISMS OF BUBBLE FORMATION

A. Nucleation

Nucleation is a process of stochastic nature (microscopic fluctuations) that initiates the formation of new phase or structure.

1. *Homogeneous*

Bubbles nucleate inside the bulk phase of a gas, liquid or solid (FIG.3).

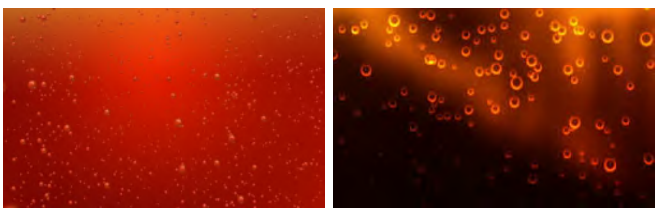


FIG. 3. Homogeneous nucleation [6].

2. *Heterogeneous*

Bubbles nucleate upon liquid-solid, gas-liquid or gas-solid, interfaces (FIG.4).

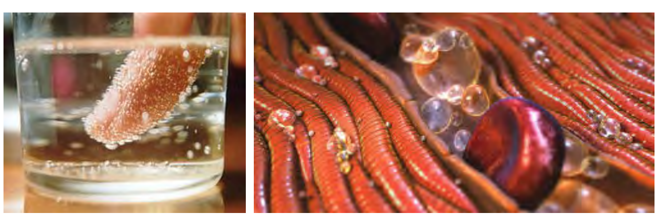


FIG. 4. Heterogeneous nucleation [7].

B. Tribonucleation

Tribonucleation is a gas microbubble formation process due to the relative movement among the liquid, containing dissolved gas, and a solid surface (FIG.5).

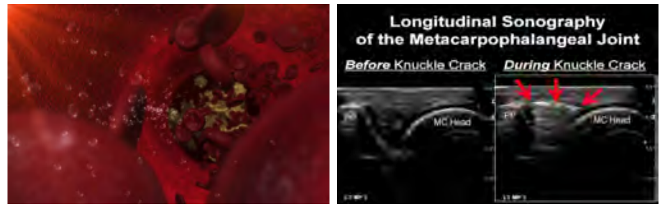


FIG. 5. Tribonucleation [8].

Bubble Formation

$$\begin{cases} \text{nucleation} \rightarrow \begin{cases} \text{homogeneous} \\ \text{heterogeneous} \end{cases} \\ \\ \text{tribonucleation} \end{cases}$$

IV. MECHANISMS OF BUBBLE EVOLUTION

A. Decompression or compression

Decompression (compression) is the process of decreasing (increasing) of the ambient pressure (FIG.6).

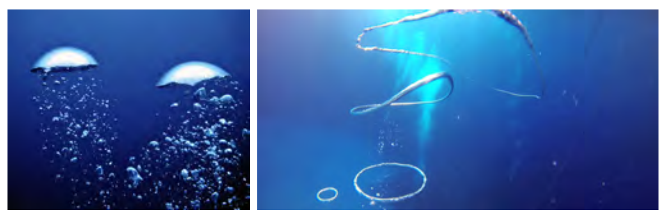


FIG. 6. Bubbles decompression [9].

B. Coalescence

Coalescence is the fusion process of two or more bubbles. (FIG.7).

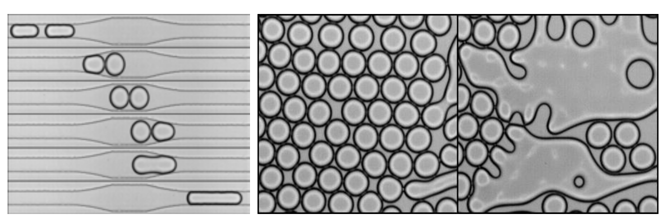


FIG. 7. Bubbles coalescence [10].

C. Diffusion

Diffusion is the flow of substance (atoms or molecules) from regions of higher concentration to regions of lower concentration (FIG.8).

FIG. 8. Diffusion [11].

D. Isobaric counterdiffusion

Isobaric counterdiffusion is the diffusion of different gases into and out of tissues while under a constant ambient pressure [12, 13]. When in diving, with multiple inert gases, and performing an isobaric gas mix switch, the inert components of the initial mix breathed by the diver begin to off-gas the tissues, whereas the inert components of the second mix begin to in-gas the tissues. “There is no change in pressure and the gases are moving in opposite directions, this is called *isobaric counterdiffusion*” [14].

E. Ostwald ripening

In 1896, Wilhelm Ostwald has verified a phenomenon that small crystals (sol particles) dissolve and redeposit onto larger crystals (sol particles) [15], which is called Ostwald ripening (FIG.9). Later on, it has been already observed the Ostwald ripening among gas bubbles in liquid fluids, namely, gas transfer from smaller bubbles to larger bubbles (FIG.10).

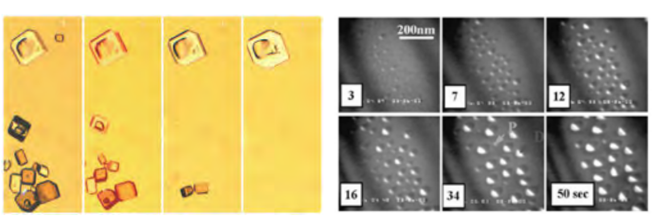


FIG. 9. Ostwald ripening: crystals and sol particles [16].

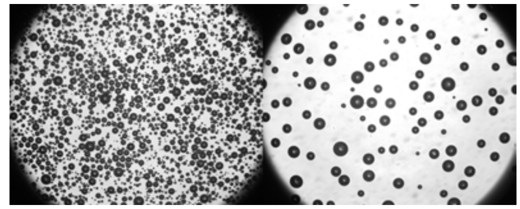


FIG. 10. Ostwald ripening: gas bubbles in a liquid fluid.

<u>*Bubble Evolution*</u>

$$\begin{cases} \text{present on } \textit{deco} \text{ models} \rightarrow \begin{cases} \text{decompression/compression} \\ \text{diffusion} \\ \text{isobaric counterdiffusion} \end{cases} \\ \\ \text{absent on } \textit{deco} \text{ models} \rightarrow \begin{cases} \text{coalescence} \\ \textit{Ostwald ripening} \end{cases} \end{cases}$$

V. DECOMPRESSION SICKNESS

One of the hazards that divers, astronauts, aviators and compressed air workers, are subjected while under hyperbaric (or hypobaric) conditions, submitted to compression and decompression, is the decompression sickness (DCS) [17]. These gas bubbles injuries, that trigger the decompression sickness, are due to the formation and evolution of intravascular and extravascular gas (N_2, He, O_2, CO_2, H_2O vapour) bubbles (FIG.11). The collective insult of the gas bubbles to the body shall produce primary effects to the tissues which are directly insulted, further, the secondary effects can jeopardize the function of a wide range of tissues, therefore, compromising body’s health, may even lead to its death. Decompression sickness is recognized by means of the signs and the symptoms exhibited by the body, just as its classification: Type 1 and Type 2. Type 1 DCS are usually characterized by mild cutaneous or skin symptoms, and musculoskeletal pain. Type 2 DCS symptoms are more severe, and they are typically split in three categories: cardiopulmonary, inner ear and neurological.

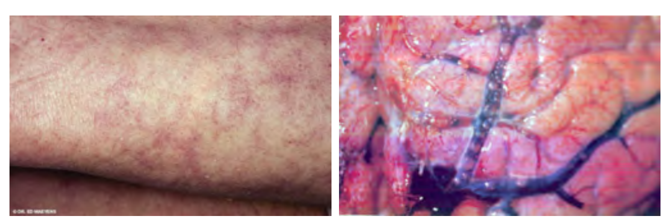


FIG. 11. Gas bubbles injuries: decompression sickness [18].

VI. OSTWALD RIPENING: GAS BUBBLES IN A LIQUID FLUID

Smaller bubbles might *feed* larger bubbles – the phenomenon of Ostwald ripening is ought to gas transfer from smaller bubbles to larger bubbles by diffusion in the liquid medium, provoking the radii increasing of larger bubbles at the expenses of decreasing radii of the smaller ones. (FIG.12).

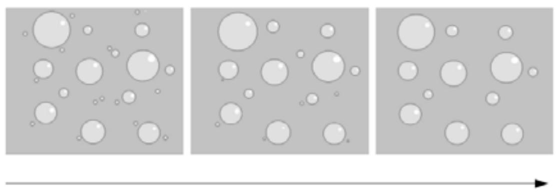


FIG. 12. Time evolution of gas bubbles in a liquid fluid.

The behaviour – of a single spherical gas bubble at rest in a liquid fluid – can be partially described by the Young-Laplace equation [19]:

$$\Delta P = P_{\text{in}} - P_{\text{out}} = \frac{2\gamma}{r} \ , \tag{1}$$

where r is the bubble radius, γ the surface tension and, P_{in} and P_{out} are the pressure inside (gas) and outside (liquid) the bubble, respectively. It shall be stressed that, from the Young-Laplace equation (1), the gas bubble inner pressure (P_{in}) is always greater than the outer pressure (P_{out}), moreover, the smaller the bubble radius (r) the greater the pressure inside (P_{in}) the bubble for a fixed ambient (outside) pressure (P_{out}).

Now, what could happen if there were two gas bubbles, with different radii, into the liquid (FIG.13)?

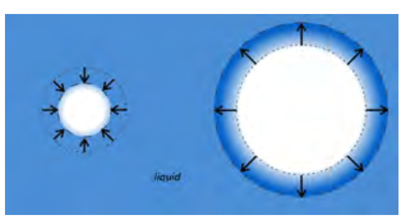


FIG. 13. Two gas bubbles with different radii in a liquid fluid.

Young and Laplace get the answer! Bearing in mind the Young-Laplace equation (1) for the two bubbles, it follows that:

$$P_r = P_{\text{amb}} + \frac{2\gamma}{r} \quad \text{and} \quad P_R = P_{\text{amb}} + \frac{2\gamma}{R} \ , \tag{2}$$

where r and R are de radii of the smaller and greater bubbles ($r < R$), respectively, the ambient (liquid) pressure is P_{amb}, whereas P_r is the inner pressure of the smaller bubble, and P_R the inner pressure of the greater one. Therefore, it can be concluded from (2) that, since $r < R$, then $P_r > P_R$, consequently, owing to the gradient pressure between the two bubbles, and by assuming a fixed ambient pressure (diver at a fixed depth – $P_{\text{amb}} = constant$), it stems – gas flow from the smaller to the larger bubble – the Ostwald ripening.

Dispersed throughout the body (inside tissues and blood) of a diver, astronaut, aviator or compressed air worker, there is a huge amount of gas (N_2, He, O_2, CO_2, H_2O vapour) bubbles whose radii vary from $10^{-1}\mu$m to $10^{2}\mu$m. The evolution of these gas bubbles is quite complicated since it involves altogether, compression/decompression, diffusion, isobaric counterdiffusion, coalescence, Ostwald ripening and besides other more complex phenomena, therefore, experimental, theoretical and computational attempts to investigate, understand and describe such kind of complex system are herculean tasks.

VII. OSTWALD RIPENING: THE EXPERIMENT

One of the main purpose of this work is to investigate and describe experimentally[1] the Ostwald ripening for gas bubbles [20] – the phenomenon of gas diffusion among bubbles – in a liquid with some rheological parameters (density, surface tension and viscosity) as close as to the human blood [3]:

$$\begin{aligned} \text{density} &\longrightarrow 1,00 \leq \rho_{\text{blood}} \leq 1,15 \ (\text{g cm}^{-3}) \ , \\ \text{surface tension} &\longrightarrow 15 \leq \gamma_{\text{blood}} \leq 80 \ (\text{mN m}^{-1}) \ , \\ \text{viscosity} &\longrightarrow 1,00 \leq \eta_{\text{blood}} \leq 4,00 \ (\text{mPa s}) \ . \end{aligned} \tag{3}$$

The physical quantities adopted, in order to describe the time evolution of the whole system consisting of air bubbles in a liquid solution (v/v) – 75% glycerol + 25% H_2O (deionized) – confined in a (bubbles) chamber (FIG.14), are: mean bubble radius ($\overline{R}(t)$), number of bubbles ($N(t)$), radii (frequency) distribution ($f(R,t)$) and radii normalized (probability) distribution ($p(R,t)$).

FIG. 14. Air bubbles confined in a chamber.

The experiment apparatus includes an optical microscope (10x lense), a B&W camera coupled to the microscope and connected to a computer, a bubbles chamber

[1] The experiments were held at the Laboratory of Microfluidics and Complex Fluids of the Department of Physics.

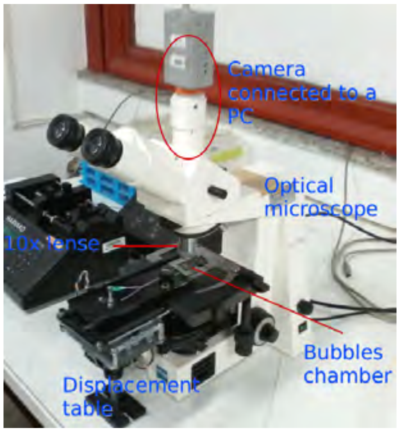


FIG. 15. Experimental apparatus.

attached to a displacement table controlled by the computer (FIG.15), also, there is a mixer used to produce (by cavitation) the air bubbles in the liquid solution, prior to injection into the bubbles chamber (FIG.14).

The liquid solution (v/v) used in the experiment contains 75% of glycerol and 25% of deionized water, which exhibits the following measured rheological parameters:

$$\begin{aligned} \text{density} &\longrightarrow \rho_{\text{exp}} = (1,17 \pm 0,01)\ \mathrm{g\,cm^{-3}}\ , \\ \text{surface tension} &\longrightarrow \gamma_{\text{exp}} = (65,3 \pm 0,01)\ \mathrm{mN\,m^{-1}}\ , \\ \text{viscosity} &\longrightarrow \eta_{\text{exp}} = (34,530 \pm 0,002)\ \mathrm{mPa\,s}\ , \end{aligned} \tag{4}$$

at 25°C room temperature. It shall be noticed that, in order to set apart (experimentally) the Ostwald ripening from other effects, namely, by reducing potential coalescence among air bubbles and also by avoiding their dislocations (FIG.16), the liquid solution viscosity, η_{exp} (4), had to be fixed one order of magnitude greater than the mean blood viscosity, η_{blood} (3).

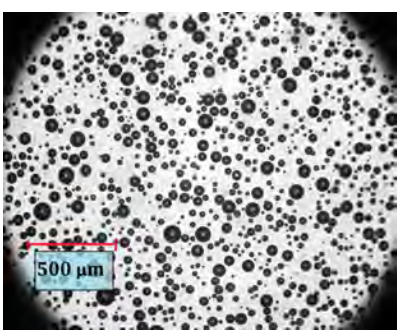
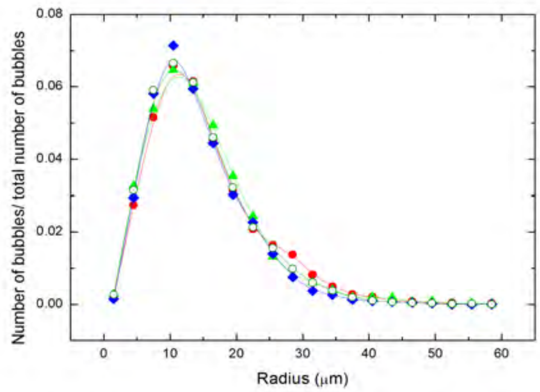
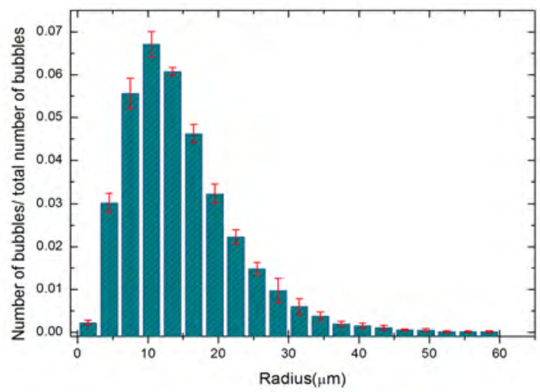


FIG. 16. Air bubbles: microscope focus.

The experiment runs for four samples of air bubbles in the liquid solution, 75% of glycerol and 25% of deionized water (v/v). The initial radii normalized distribution ($p(R,0)$) – defined by the ratio among the number of bubbles with radius R (the radii distribution $f(R,0)$) and the total number of bubbles ($N(0) \sim 10^4$) at instant zero (0h) – of the four samples analyzed, validates the reproducibility of the experiment (FIG.17).



(a)



(b)

FIG. 17. Reproducibility: (a) the initial radii normalized distribution ($p(R,0)$) for the four samples; (b) the respective histogram with error bars.

The radii (frequency) distribution as a function of time ($f(R,t)$) is acquired analyzing[2] the images taken by the B&W camera (coupled to the microscope) at different zones of the bubbles chamber – which are reached through the displacement table controlled by the computer. When the acquisition of the images by the B&W camera and the subsequent bubbles radii measurement, the radii (frequency) distribution ($f(R,t)$) and the radii normalized (probability) distribution ($p(R,t)$) were obtained at the time instants: 0h, 1h, 5h and 14h (FIG.18 and FIG.19). In what concerns the bubbles time evolution, it can be deduced, from FIG.18 and FIG.19, that the number of bubbles ($N(t)$) decreases whereas mean bubble radius ($\overline{R}(t)$) increases, which shall be proved below.

[2] The software used to treat the pictures, so as to measure the radii of the bubbles, was the open source image processing **ImageJ** [21].

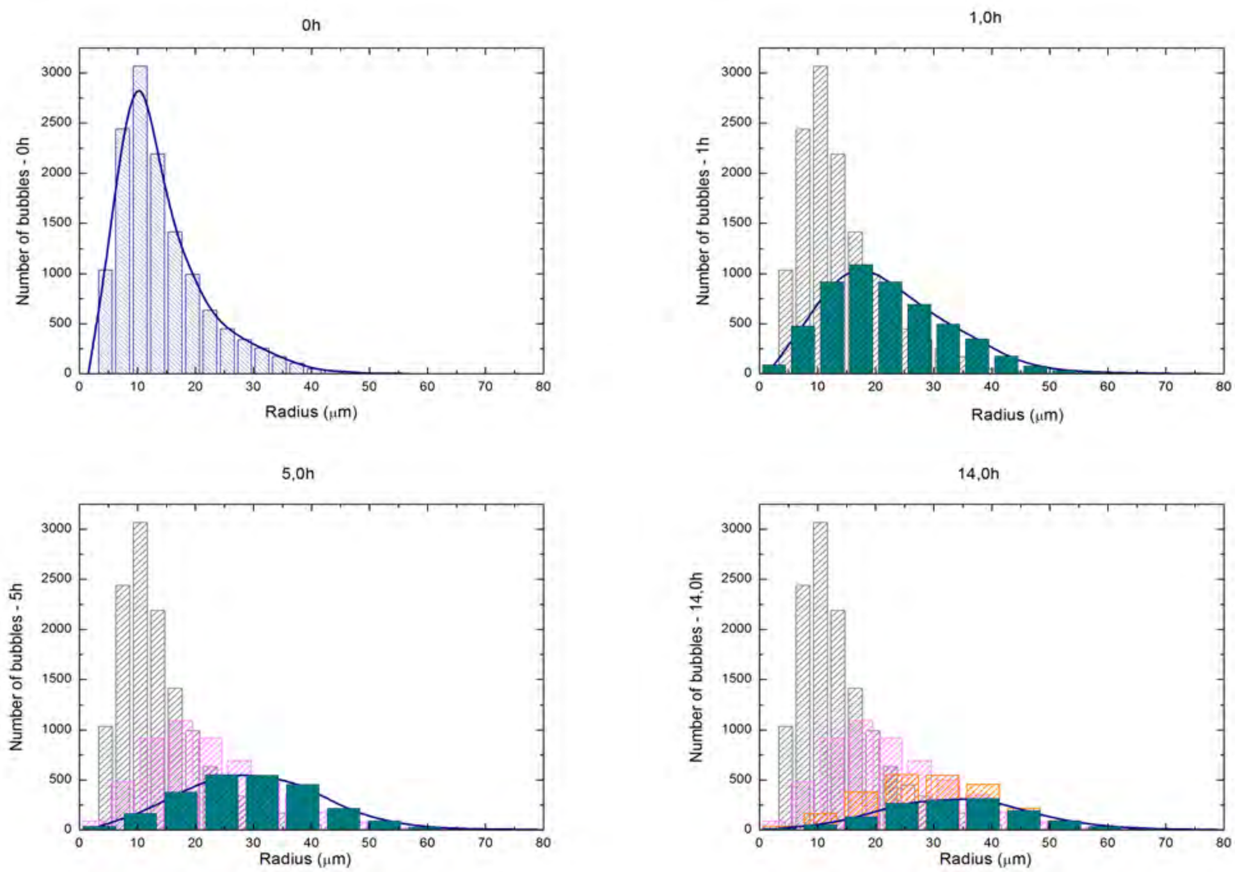


FIG. 18. The radii (frequency) distribution ($f(R,t)$) at $t = 0$h, $t = 1$h, $t = 5$h and $t = 14$h.

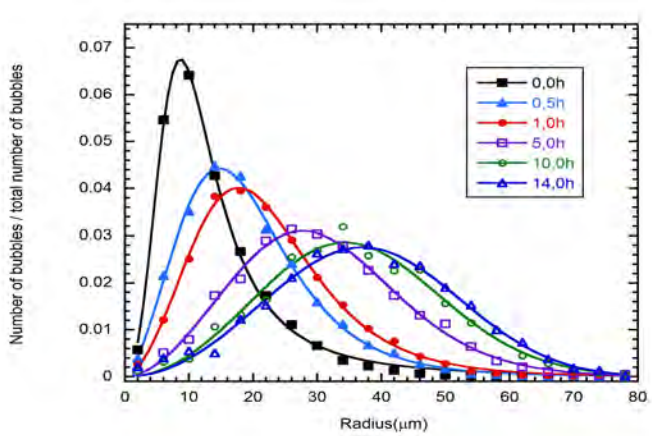


FIG. 19. The radii normalized (probalility) distribution ($p(R,t)$) at $t = 0$h, $t = 1$h, $t = 5$h and $t = 14$h.

The experimental results for the mean bubble radius ($\overline{R}(t)$) show that it increases monotonically in time, which can be straightforwardly concluded from FIG.20, wherein, together with the experimental curve fit, it is also sketched a curve for the mean bubble radius ($\overline{R}_{\mathrm{LSW}}(t)$) if the bubbles dynamics was dictated by the LSW (Lifshitz-Slyozov-Wagner) theory [22]. The mean bubble radius ($\overline{R}_{\mathrm{LSW}}(t)$) in LSW theory is given by:

$$\overline{R}_{\mathrm{LSW}}(t) = \left[\overline{R}^3(0) + Kt\right]^{\frac{1}{3}} \;\;,\;\; \overline{R}(0) = 18,42\mu\mathrm{m}$$
$$\text{and} \quad K = 6,1 \times 10^3 \mathrm{m}^3\mathrm{s}^{-1} \;,$$

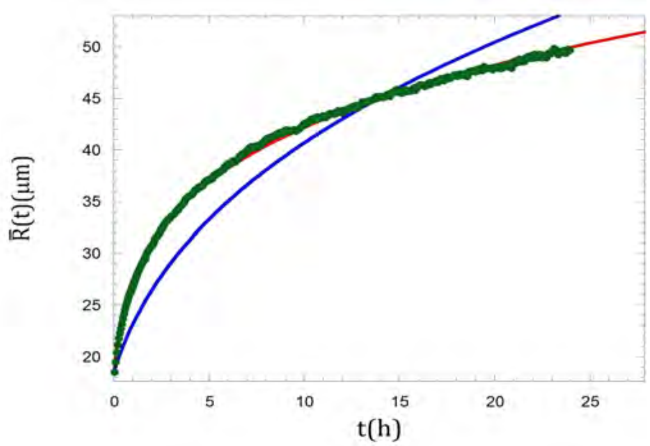


FIG. 20. The mean bubble radius: the experimental data fit ($\overline{R}(t)$ – red line) and the LSW theory prediction ($\overline{R}_{\rm LSW}(t)$ – blue line) assuming the same experimental initial condition, the initial mean bubble radius $\overline{R}(0) = 18,42\mu$m.

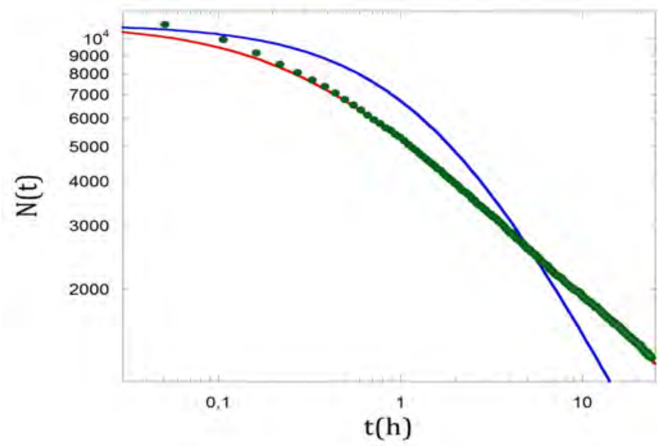


FIG. 21. The number of bubbles: the experimental data fit ($N(t)$ – red line) and the LSW theory prediction ($N_{\rm LSW}(t)$ – blue line) assuming the same experimental initial condition, the mean bubble radius, $\overline{R}(0) = 18,42\mu$m, and the number of bubbles, $N(0) = 1,8 \times 10^4$.

where K depends on the temperature, surface tension, diffusion coefficient, gas solubility and gas molar volume. Therefore, it can be verified from FIG.20 (blue line) that the LSW theory does not properly describe such a system of gas bubbles in a liquid, which should be expected since the system analyzed does not satisfy the primary premises assumed by the LSW theory. Nevertheless, bearing in mind the experimental data acquired and modelling the mean bubble radius ($\overline{R}(t)$) as below:

$$\overline{R}(t) = \left[\overline{R}^{\frac{1}{\chi}}(0) + Kt\right]^{\chi} \ , \tag{5}$$

$$\overline{R}(0) = 18,42\mu\text{m} \ , \quad K = 2,0 \times 10^7 \text{m}^{\frac{1}{\chi}}\text{s}^{-1}$$
$$\text{and} \quad \chi = 0,1956 \ ,$$

from FIG.20 (red line) it follows that the empirical model (5) proposed perfectly fits the experimental data.

On the other way around, the experiment shows that, while the mean bubble radius ($\overline{R}(t)$) increases in time, the number of bubbles ($N(t)$) decreases monotonically as displayed in FIG.21, where it can also be seen that the number of bubbles ($N_{\rm LSW}(t)$) proposed by the LSW theory:

$$N_{\rm LSW}(t) = N(0)\frac{\overline{R}^3(0)}{\overline{R}^3(0) + Kt} \ , \quad \overline{R}(0) = 18,42\mu\text{m} \ ,$$
$$N(0) = 1,8 \times 10^4 \quad \text{and} \quad K = 6,1 \times 10^3 \text{m}^3\text{s}^{-1} \ ,$$

does not fit (blue line) the experimental data. However, by considering the experimental data, and modelling the number of bubbles ($N(t)$) as follows:

$$N(t) = N(0)\frac{\overline{R}^{\frac{\lambda}{\chi}}(0)}{\left[\overline{R}^{\frac{1}{\chi}}(0) + Kt\right]^{\lambda}} \ , \tag{6}$$

$$\overline{R}(0) = 18,42\mu\text{m} \ , \quad K = 2,0 \times 10^7 \text{m}^{\frac{1}{\chi}}\text{s}^{-1} \ ,$$
$$\chi = 0,1956 \quad \text{and} \quad \lambda = 0,48 \ ,$$

it can be verified that the empirical model (6) fits the experimental data, FIG.21 (red line).

In summary, the experiment realized – upon a system of air bubbles in a liquid fluid with some rheological parameters close to the human blood – shows that the mean bubble radius ($\overline{R}(t)$) increases (FIG.20) in time whereas the number of bubbles ($N(t)$) decreases (FIG.21). Moreover, it is verified straightforwardly that the smaller bubbles disappear whereas the larger bubbles, the ones potentially dangerous for the diver which cause the decompression sickness, grow up.

Based on the experimental analysis of the Ostwald ripening phenomenon, it has been proposed an empirical model so as to describe the time evolution of the mean bubble radius (5) and the number of bubbles (6), where it properly describes the time evolution of the system.

Taking into consideration the Ostwald ripening empirical model proposed here, it should be interesting to probe its implementation to the Reduced Gradient Bubble Model (RGBM) in such a manner to compute decompression sickness risks and develop dive tables for further diving tests.

In addition to the experimental results and the empirical model introduced here, simulation of gas bubbles evolution has been performed and some preliminary results are presented in the next Section.

VIII. OSTWALD RIPENING: THE SIMULATION

Another purpose of this work is, by adopting the finite element method, the computational modelling and simulation[3] of gas diffusion among bubbles in a liquid and their time evolution. By working out the Ostwald ripening computational simulation together with the experimental results it stems a more profound knowledge about the details of the Ostwald ripening phenomenon, which are crucial to its further implementation to the RGBM so as to realize diving field tests.

At this preliminary stage, the simulations are performed by assuming nitrogen (N_2) gas bubbles into water, where its initial N_2 gas concentration is equivalent to critical radius given by $R_c = 10\mu$m, which means that a single N_2 bubble with a radius equal to the critical radius would remain in equilibrium, namely, it would neither decreases nor increases.

The first case considered deals with one single N_2 bubble (FIG.22), in a $500\mu\text{m} \times 500\mu\text{m}$ lattice, with its initial radius given by $R(0) = 3\mu$m. Therefore, as expected, it decreases in time, since its radius is smaller than the critical one, $R_c = 10\mu$m.

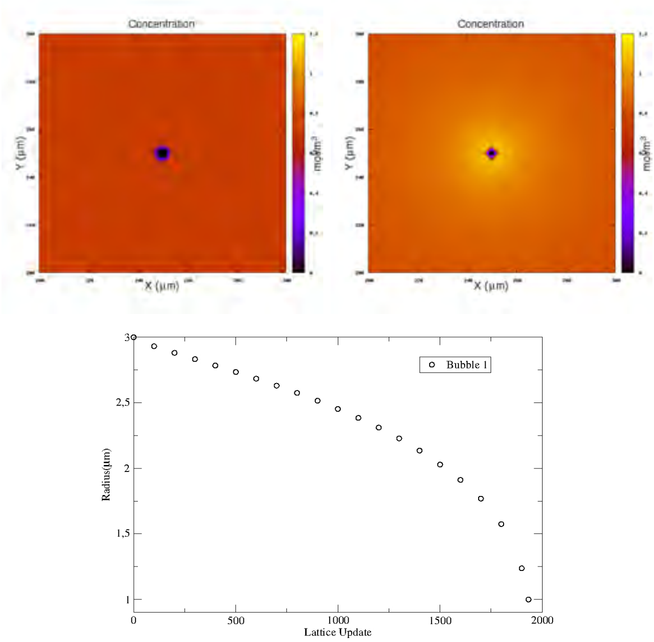


FIG. 22. Simulation of one bubble ($R_c = 10\mu$m).

A configuration of three bubbles aligned are the second case studied, where they have the same initial radius $R(0) = 3\mu$m but are spaced such that (FIG.23) the left bubble (bubble 2 – red dots) are closer to the central bubble (bubble 1 – black dots) than the right bubble (bubble 3 – blue dots), with the lattice size equal to $500\mu\text{m} \times 500\mu\text{m}$. There, it is verified that the closer bubble (bubble 2 – red dots) to the central, decreases faster than the farther bubble (bubble 3 – blue dots), however, while they decrease the central bubble increases until they disappear, thereafter the central bubble starts decreasing. It shall be stressed that unlike the LSW theory – where all three bubbles would decrease simultaneously, namely with the same time rate, independently on how they are spaced – the behaviour of the three bubbles are strongly dictated by the distance among them, becoming evident that the inter-bubbles gas pressure gradient should be taken into consideration in a future extension of the Reduced Gradient Bubble Model (RGBM).

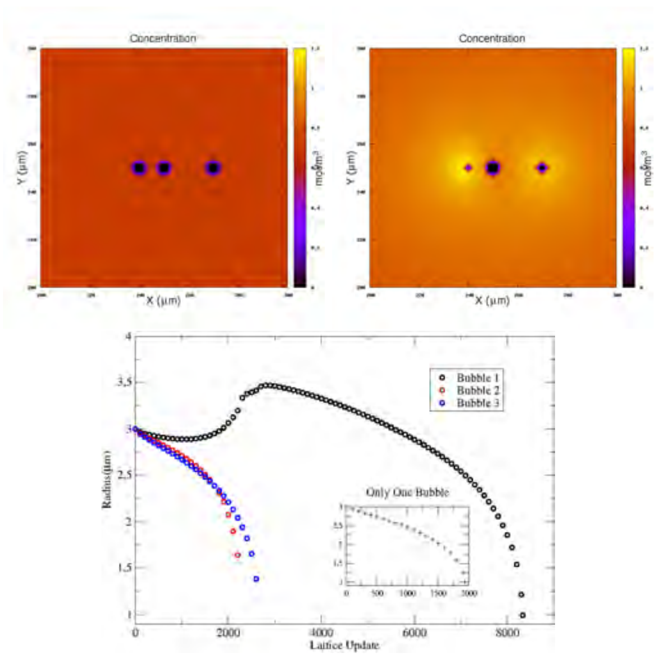


FIG. 23. Simulation of three bubbles ($R_c = 10\mu$m).

The third case analyzed is a system of five bubbles, in a $500\mu\text{m} \times 500\mu\text{m}$ lattice, all with the same initial radius $R(0) = 3\mu$m, arranged so that four of the five bubbles are located at the vertices of a square whereas the fifth bubble stays at its centroid (FIG.24). It is observed that the four bubbles located at the vertices decrease simultaneously while, fed by them, the fifth bubble at the center increases until the four disappear, right after it begins decreasing. It shall be called into attention again to the fact that, unlike the LSW theory, the way how the bubbles are settled takes place also in their evolution.

The last and more complex configuration tackled consists of fifty N_2 gas bubbles into water – with initial N_2 concentration equivalent to a critical radius given by $R_c = 10\mu$m – randomly spread throughout a $1000\mu\text{m} \times 1000\mu\text{m}$ lattice, with their initial radii ($R(0)$) aleatory picked up from 5μm to 25μm (FIG.25). It can be verified from the graph of the bubbles radii time evolution (FIG.25) that even bubbles with initial radii greater than the critical radius ($R_c = 10\mu$m) may decrease by feeding other bubbles, unlike to what would be expected from the LSW theory – where the bubbles with radii smaller than 10μm decrease while those with radii greater than

[3] The computational simulations were held at the Complex Systems Investigation Laboratory of the Department of Physics.

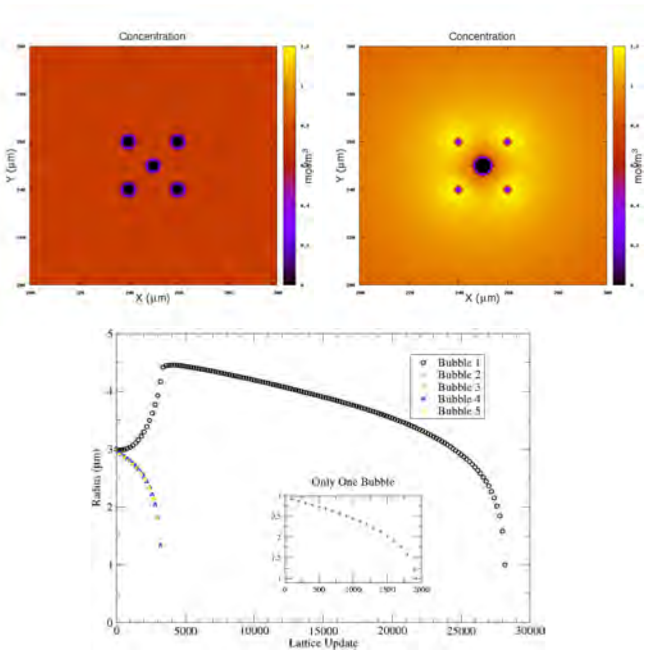


FIG. 24. Simulation of five bubbles ($R_c = 10\mu$m).

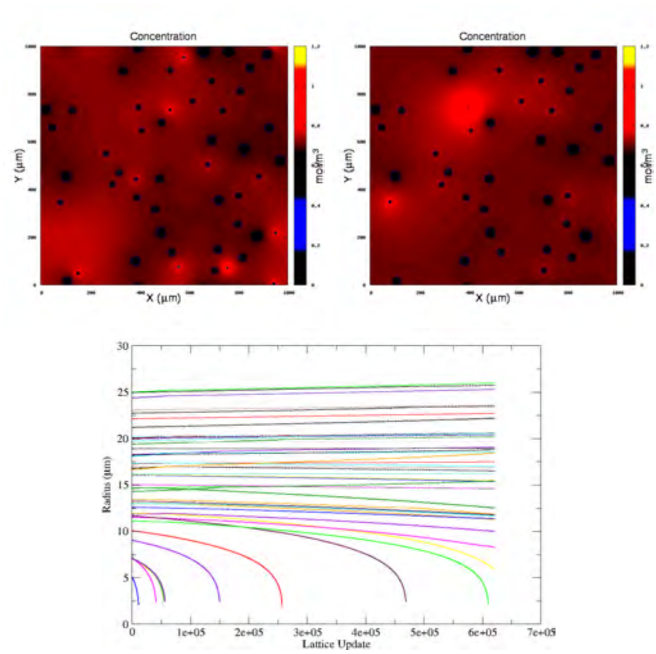


FIG. 25. Simulation of fifty bubbles ($R_c = 10\mu$m).

10μm increase. LSW theory assumes an infinity volume of the liquid phase, as well as that the distances between bubbles are much greater than their radii, and that the concentration of dissolved gas in the liquid phase remains homogeneous despite its time dependence. Due to all of these assumptions being far from such a system of gas bubbles in a liquid which is the issue in decompression sickness, for that reason it seems to be important to study more deeply the Ostwald ripening phenomenon so as to investigate its contribution to the decompression sickness risks.

IX. CONCLUSIONS AND PERSPECTIVES

The Ostwald ripening, the phenomenon of gas diffusion among bubbles, which results that larger bubbles are fed by the smaller, are reproduced and described experimentally and by computational simulation. The experiment consisted of air bubbles into a chamber filled by a liquid solution with some human blood-like rheological parameters, density and surface tension.

The experiment which ran at 25°C under normobaric pressure showed that the number of bubbles ($N(t)$) – the initial number of bubbles was of order 10^4 – decreases in time while the mean bubble radius ($\overline{R}(t)$) increases. It is proposed, analyzing the experimental results, an empirical model for the Ostwald ripening by describing the time evolution of the number of bubbles (6) and the mean bubble radius (5). It should be stressed that one of the main results shown, even at a constant ambient pressure (at the same diver "depth"), a decreasing number of bubbles in time while the bubbles mean radius increases, consequently, the smaller bubbles disappear whereas the larger (potentially dangerous to the divers, by causing DCS) bubbles grow up, hence this might reveal a contribution of the Ostwald ripening to the decompression sickness risk during and after diving.

The finite element computational simulation, even though at an embryonic stage, has allowed a perception about how critical is the correlation among the distance between bubbles and their time evolution. By way of example, from the case presented above of the three bubbles aligned (FIG.23), it can be conjectured that the closer a smaller bubble is to a larger bubble the faster it will disappear. Finally, the simulation of fifty bubbles (FIG.25) with radii varying from 5μm to 25μm, within a $1000\mu\text{m} \times 1000\mu\text{m}$ lattice, made evident the complexity of a liquid-gas bubbles system when the Ostwald ripening is taken into consideration. Meantime, it became more clear the relevance of the distances between bubbles and their influence to the behaviour of a liquid-gas bubbles system.

There are many perspectives and challenges to be pursued. From the experimental point of view, and for further computational simulation, it is important to search for mechanisms to suppress or to promote the Ostwald ripening. Besides, the experiment shall be performed at typical human body temperatures, around 36,5-37,5°C, for nitrogen bubbles into human plasma, also by adding to the plasma polystyrene microdisks, with diameters about 6-8μm, simulating the red blood cells. The Ostwald ripening empirical model – for the number of bubbles (6) and the mean bubble radius (5) in time – might be implemented to the Reduced Gradient Bubble Model (RGBM) [1–3], first to recreational air diving protocols, in order to obtain the "new" risk estimates for various NDLs (no-decompression time limits) and compare them to those of RGBM, as well as to those from other models, namely, ZHL (Bühlmann), USN (U.S. Navy) and VPM (Varying Permeability Model).

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O.M.D.C. dedicates this work to the memory of Randy Shaw (NAUI Worldwide) and Sergio Viegas (DAN Brasil), both friends passed away on July 2017. He also dedicates it to his father (Oswaldo Del Cima, *in memoriam*), mother (Victoria M. Del Cima, *in memoriam*), daughter (Vittoria) and son (Enzo).

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Lionfish Venom: Cardiovascular, Neuromuscular, Cytotoxic, and Immunologic Effects

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Objectives

On completion of this presentation, the participant will be able to:
1. Analyze a complex case of lionfish envenomation, with apparent neurologic complications
2. Discuss how lionfish venom components have multiple potential consequences
3. Formulate a first-aid response to a severe lionfish envenomation

Abstract

Lionfish are not normally aggressive towards divers, so stings with envenomation should be rare. Introduced to the Western Atlantic Ocean in about 1985, these invasive species have no natural predators here, they feed ravenously, and they reproduce prolifically, making them a danger to reef ecosystems. Culling programs have focused on killing them at depth, trying to teach other animals to feed on them (illegal in certain regions), and bringing them to the surface to be used as food. Hunting lionfish is becoming a popular sport. As a result, envenomation is becoming more prevalent as the spines are being handled. Most patients report extremely severe and long-lasting pain, local swelling and redness, and numbness. Systemic symptoms include rapid heart rate, high (or low) blood pressure, abdominal pain, generalized swelling, rashes, generalized weakness, and fainting. Envenomations can be complicated by infection. This presentation will feature an analysis of a complex case of lionfish envenomation, discuss the known components of lionfish venom (and that of related fish), and review first-aid measures for mild and severe envenomations.

Target audience

1. Advanced recreational divers
2. Dive professionals

Biosketch

Dr. Bill Dolen is Professor of Pediatrics and Internal Medicine at the Medical College of Georgia at Augusta University. He is Residency Program Director for allergy-immunology, and Director of the Allergy-Immunology Laboratory. He is a past president of the Allergy, Asthma and Immunology Society of Georgia, the Southeastern Allergy, Asthma and Immunology Society, and the American College of Allergy, Asthma and Immunology. A NAUI Master Scuba Diver, his favorite place to dive is the West Palm Beach area, but he also enjoys diving the local river and lake, as well as México, Roatán, and Bali.

Case presentation
This case, shared by Jim Chimiak, MD, DAN medical director, has been lightly edited for clarity. As you read it, think about what information is missing.

On 11 June 2016, a commercial diver was participating in a lionfish derby. He was stung by lionfish twice, first on the third digit of the right hand, and the second on the left wrist. Within an hour, he began having intense pain, redness and swelling of the arm. He was not treated with an antibiotic.

Two days after the event, he was diving with EAN36 to a maximum depth of 124 feet, with the majority of his dive reported at around 90 feet. Details of the length of his dive or the time spent at the safety stop are not available, although he reported not going into deco. Shortly after surfacing, the diver reportedly had generalized weakness and his left grip strength was markedly decreased. He took aspirin 81mg, was placed on 100% O2 and taken to a local hospital where he received hyperbaric oxygen therapy for 6 hours at 65 feet with improvement of his weakness and paresthesias.

On the following day, his symptoms began to return. He was taken to 65 feet for 6 hours, and then 2 hours at 45 feet. When seen by a neurologist several days later, he still had numbness, tingling, and mild pain in his hands and feet.

Introduction
The lionfishes are natives of the Indo-Pacific seas. They have various common names, including turkeyfish, zebrafish, firefish, and butterfly cod. The genus Pterois (from Greek, πτερον, *pteron*, wing) has 12 species, including the red lionfish *Pterois volitans* (from Latin *volitans*, flying) and the common lionfish *Pterois miles* (from Latin *miles*, soldier). The latter two species are visually similar, and require genetic studies for differentiation. The lionfishes are members of the Scorpaenidae family, which contains three subfamilies, several dozen genera, and 201 species. This venomous family includes the scorpionfish and stonefish.

Lionfishes came to the West as ornamental animals for saltwater aquarium-keepers. The invasion began in the 1980s, probably after a few aquarists released their pets into the western Atlantic Ocean. Although hurricane Andrew damaged a large seaside aquarium in August of 1992, allowing release of six adults into Biscayne Bay, this event is not the original source of the invasion. Nonetheless, hurricanes have played a major role in the dispersion of lionfish eggs and larvae [1]. They are now found on the Atlantic coasts of North and South America, in the Caribbean, and the Gulf of Mexico. Genetic studies indicate that the red lionfish accounts for 93% of specimens found in the Atlantic, with the common lionfish accounting for the rest [2]. The invasion can be traced to a founder population of as many as 12 individuals, including at least 3 red lionfish females and 1 common lionfish female [2].

Highly efficient predators [3], their ravenous appetite has made them a significant threat to natural and artificial reefs, affecting ecosystem functioning and integrity, and producing a loss of biodiversity, displacing native animals, particularly juvenile reef fish and crustaceans, by eating them. They proliferate rapidly and have no natural predators in the west. A single female can produce eggs every few days, and as many as 2 million eggs in a year. Thus, their population has increased dramatically.

Eradication appears to be impossible. Well-intentioned attempts to encourage western predators, such as eels, sharks, and groupers, to feed on lionfish have not met with much success. Some sharks, eels, and other animals have simply come to expect that divers will catch lionfish for them, and feed them. A few recent YouTube videos have shown native fish pursuing and eating lionfish apparently without human intervention, and scientists are attempting to develop lionfish-specific traps. Otherwise, the only means of controlling them is lionfish hunting, an increasingly popular sport that has caused a rise in the number of human envenomations.

For humans, lionfish are a tasty treat, and lionfish derbies and hunting tournaments, which can collect hundreds or thousands of animals, have encouraged restaurants in the Caribbean and southern United States to offer them on their menus. This practice has also resulted in fishmongers and restaurant workers being stung. Although they are potential sources for ciguatera fish poisoning, and ciguatera toxin has been detected in some lionfish samples [4], the assays used may have detected lionfish venom components similar to ciguatoxin [5]. Some symptoms of ciguatera poisoning are similar to symptoms of lionfish envenomation.

Lionfish envenomation

Although lionfish are docile and not aggressive to divers, they pose a significant health risk to humans because envenomation can cause severe symptoms. The attractive fins contain needle-like spines, all of which are venomous, except for the pectoral fins. The red lionfish has 18 venomous spines (13 dorsal, 3 anal, 2 pelvic), each of which is associated with 2 elongated venom glands on the inner side of the spine. The spines are modified scales that can regenerate when broken off. Envenomation occurs when an individual comes in contact with a venomous spine, producing a puncture wound. As the spine enters the skin, a loose sheath surrounding the spine compresses the venom glands, allowing 5-10 mg of venom to travel through paired grooves in the spine, and into the victim.

Aquarium keepers learned early on that stings are exceptionally painful and long-lasting, far out of proportion to the size of the puncture wound. Fortunately, lionfish venom is less toxic than that of other Scorpaenidae family members; while systemic manifestations of envenomation can occur, deaths are rare. The prevalence of lionfish envenomations is not known, since not all injured persons seek medical attention, and there is no requirement for medical treatment facilities to report envenomations.

Clinical features of envenomation

Local pain, which can radiate up the affected extremity, is the universal feature of a significant envenomation. Onset is immediate, and without intervention, it will peak at 60-90 minutes following the sting, and last for several days, as can local numbness. Local swelling (edema) is nearly universal.

At first, the puncture wound is pale with surrounding redness. Skin manifestations of lionfish stings can be described by a grading system. A Grade I wound site will have pallor (skin blanching), intense redness (erythema), bruising (ecchymosis), hard swelling (induration), or swelling (edema). A Grade II wound site will have vesicles (blisters) or bullae (large blisters), and a Grade III wound site will have necrosis (tissue death) that can produce long-term limited joint mobility.

Frequently reported systemic symptoms include nausea, vomiting, heartburn, and diarrhea. Others include headache, fever, sweating, shortness of breath, dizziness, numbness or paresthesia (pins and needles), and convulsions. Less commonly observed and rare systemic symptoms include heart failure, temporary limb paralysis. Deaths are very rare.

A recent report of 117 cases from Martinique indicated that the majority of cases seen involved divers (47%) and fishermen (32%) [6]. Envenomation also occurred in swimmers (21%) and cooks (3%). All patients reported severe pain (described as intense and throbbing), 98% reported edema, 90% reported sensory changes such as tingling (paresthesia) and numbness (hypoesthesia). Muscle aches (myalgia) and muscle cramps occurred in 62%, with muscle weakness or paralysis in 24%. Skin rash occurred in 32%. Systemic symptoms occurred in 66% of patients. These included cardiovascular manifestations of a fast heart rate (tachycardia) in 34%, a slow heart rate (bradycardia) in 3%, high blood pressure (hypertension) in 21%, and low blood pressure (hypotension) in 18%. Gastrointestinal symptoms were found in 28%. Fainting and dizziness were found in 27%. Some patients required hospitalization.

First aid management

A diver who suspects that he has been stung should attempt to remain calm and make a controlled safe ascent. Immediate first aid consists of rinsing the wound with clean fresh water, removing visible spines, and immersing the affected body part in very hot but non-scalding water (up to 45°C or 113°F if possible) for 30-90 minutes, which often reduces both the intensity and duration of pain. Since pain and numbness from the envenomation might affect the victim's perception of heat, the first aid provider should test the water. If possible, the victim's unaffected limb should be placed in the same hot water to limit scalding. The victim should be advised to seek medical attention on return to shore since a wound that appears innocuous at first may progress in severity. Contacting DAN is advisable. Over-the-counter analgesics (pain-killers) may be offered, but the response is variable because the pain is apparently due to stimulation of bradykinin receptors, not always responding to pain-relieving medications, including narcotics.

In the Martinique report, patients initially treated with hot water had a pain duration of 2.8±3.8 days, whereas patients not treated had a duration of 8.9±12 days). The mechanism by which heat reduces severity and duration of pain is not clear. Some reports suggest that heat denatures some of the toxin components.

At the hospital

At a medical facility, standard wound management includes cleansing and irrigation with warm saline solution, with identification and removal of foreign bodies (such as spine fragments) [7]. When hot water immersion is ineffective for pain control [8], a local or regional nerve block with a local anesthetic may be beneficial. The pain response to narcotics is variable. The utility of bradykinin receptor antagonists, such as icatibant, in management of inflammation and severe pain warrants study.

Some experts recommend drainage of the blisters of a Grade II envenomation to release toxin. The development of tissue necrosis will require specialty management.

Tetanus prophylaxis is advisable, and some authorities recommend antibiotic prophylaxis for severe envenomations [7]. In the event of actual infection, the microbiology laboratory should be notified to culture specimens for unusual marine organisms [7].

A lionfish-specific antivenom is not available. An Australian stonefish antivenom, made in horses, has been studied in scorpionfish envenomations [9], but not in lionfish. Risks include anaphylaxis and serum sickness.

Clinical effects of venom components

The clinical manifestations of lionfish envenomation are due to various venom components (Table 1), which have a rather broad pharmacology, causing pain, inflammation, cell damage or death, cardiovascular, and neuromuscular effects. Some venom components can produce destruction of proteins (proteolysis), destruction of red blood cells (hemolysis), and blood coagulation. Investigators have studied lionfish venom in the hope of finding human therapeutic uses for some of the venom components [10, 11]. A peptide from the red lionfish causes certain types of cancer cells to die without affecting normal cells [12].

Pain is at least in part due to local synthesis of bradykinin, a 9 amino acid peptide formed in the course of acute inflammation. It is the most potent endogenous inducer of pain known [13], acting via the B2 receptor to cause pain by direct activation of sensory nerve endings, and also causing local swelling (edema).

In the cardiovascular system, both hypertension and hypotension have been observed. Hypotension may be due to endothelium-dependent smooth muscle relaxation [11], an effect that appears to be dependent on stimulation of muscarinic receptors [14], with relaxation related to nitric oxide release [11, 15]. The potential additive effect of the phosphoesterase-5 inhibitor drugs used to treat male impotence has not been examined. Tachycardia appears to be due to an effect of a protein venom component on β1-adrenergic receptors [14], but bradycardia has also been reported.

Neuromuscular effects of muscle twitching and weakness/paralysis are due to the release of endogenous acetylcholine from presynaptic nerve terminals [16], in part caused by intracellular increases in calcium ion levels [17], which results in increased release of neurotransmitters. While complete paralysis is rare, a 24-year-old male developed complete upper and lower paralysis within three hours of a lionfish envenomation in the middle finger of his right hand; this resolved in 8 hours [18].

Insect venom hyaluronidases can induce IgE-mediated allergic sensitization in humans, producing systemic allergic reactions (anaphylaxis) upon subsequent stings. Anaphylaxis from lionfish stings has been reported [19], but it is not clear which venom components are functioning as allergens. There are no studies of whether lionfish hyaluronidase can induce IgE sensitization in susceptible individuals, particularly individuals already sensitized to a hyaluronidase from a different animal. Medical personnel caring for patients who have had anaphylaxis following a lionfish envenomation should inquire about a past history of anaphylaxis following other exposures, including insect venoms.

Table 1. Venom components.

Component	Clinical effect	Notes
Toxins stimulating release of bradykinin, stimulating bradykinin receptors	Severe pain, edema	
Proteolytic enzyme 45 kDa [12] Proteolytic enzyme 60 kDa [20]	Destruction of proteins	
Cytolytic protein 160 kDa [21] Pore-forming toxins Proapoptotic peptide 7.6 kDa [12]	Cell destruction	
Hyaluronidase [22]	Enzyme that breaks down hyaluronan, a structural component of tissue, allowing other venom components to diffuse from the puncture site	
Neurotoxins and neuromuscular toxins	Block nerve transmission, delaying depolarization at the neuromuscular junction, causing weakness and muscle paralysis	
Pro-inflammatory toxins	Redness, swelling	
Hemolytic and prothrombotic toxins	Destruction of red blood cells; formation of blood clots	
Acetylcholine [16]	Neurotransmitter; muscle twitching; effects on skeletal and heart muscle	
Adrenergic and muscarinic toxins	Affecting the heart and blood vessels	

Prevention

Obviously, lionfish envenomations can be prevented by not touching the animals. Aquarists, lionfish hunters, and food workers need to take special precautions handling them, avoiding contact with the spines. Because lionfish spines can penetrate many types of ordinary safety gloves, special puncture-resistant "needlestick" gloves should be employed to reduce the likelihood of injury. For hunters, various types of collection equipment are available.

Case discussion

What is known	Questions, comments
Male	How old? Any current medications?
Commercial diver	Dive profile for past week and after; download his computer

Participated in lionfish derby on 11 June 2016	
Stung on 3rd digit R hand, and on left wrist	
Within an hour had: - intense pain - redness - swelling	• Need dive profile for that day. 1st dive, SI, 2nd dive; download computer • Which arm? Left? Right? Both? • How was he treated? • Did skin symptoms progress beyond Grade I?

• 2 days later (presumably 13 June 2016), did 124 fsw max dive on EAN36, majority of dive "around" 90 fsw; no other details known
• **Says** he did not go into deco
• On surfacing had:
  - generalized weakness
  - markedly decreased L grip strength
• Took ASA 81mg, started 100% O2
• HBOT at 65 ft x 6 hrs, improved weakness and paresthesias (not previously mentioned)
• Symptoms returned the following day (presumably 14 June 2016)
• HBOT at 65 ft x 6 hrs, 45 ft x 2 hrs
	Need to download computer. A week before the incident, dives related to the incident, subsequent dives.
	
	124 fsw at EAN36 = ppO2 1.7

• Seen at some point later (prior to 27 June 2016) by a neurologist in West Palm, reporting in hands (presumably both) and feet (presumably both):
  - numbness
  - tingling
  - mild pain	

Working differential diagnosis:
• Lionfish envenomation
  - toxic effect of venom
  - immunologic response to venom
  - maybe more prone to DCI
• Neurologic DCI
• Small fiber demyelination (immunologic?)
• Oxygen toxicity perhaps contributing to immunologic response
• Multifactorial	

The case indicates the absolute need for a complete dive history to assist in analysis of a very complex set of clinical findings. Based on available information, neurologic DCI cannot be excluded, and it was prudent to treat him for that. Lionfish envenomation can also produce the observed neurologic symptoms. Oxygen toxicity does not account for the prolonged course unless activation of the innate immune system in some way influenced the immunologic response to the envenomation and/or decompression illness. Scuba diving produces oxidative stress on vascular endothelium, an effect more pronounced in nitrox divers [23] that may decrease the bioavailability of nitric oxide [24]. How this effect might interact with the effects of lionfish venom components or decompression illness is unknown.

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Last revision: 1 May 2017

“Just Add Water- Engaging College Students and Youth in SCUBA Diving”

By Amie Hufton

The Galveston Campus of Texas A&M University is a premier institution for maritime leadership and ocean and coastal studies on the Gulf Coast and a 21st century institution where research and scholarship are one with student learning and success. This campus operates a recreational and scientific diving program that has been well established since 1998. The university was a founding member of the American Academy of Underwater Sciences, and in 2014, the Minor in Diving Technology and Methods was introduced, making the campus one of the few in the nation to formalize SCUBA education into an academic program.

Between 2012 and 2016, the recreational dive program enrollment increased by over 134%, while the school’s undergraduate enrollment increased by 20%. In order to better understand the value and impact of the SCUBA program, we used enrollment in SCUBA II (Advanced and Nitrox certifications) course to compare the diversity (in gender and ethnicity) of SCUBA students to the University average. This course was chosen for the comparison because this seems to be the point where students start to incorporate scuba into their personal identity. In the spring semester of 2016, SCUBA II enrollment was 50% female while the University enrollment was 37% female. Students from underrepresented ethnic populations made up 34% of SCUBA II enrollment, compared to 24% of the University. We also compared the average GPA and total course load of SCUBA II students to the University average, and found that students in this SCUBA II course were enrolled in 1.4 more credit hours and had .131 higher points in their average GPA. We found these trends to be similar across the previous three semesters. The conclusion is that the courses and culture developed within the TAMUG SCUBA program have resulted in high-impact learning and increased inclusion.

As a leader in our DIVE program at TAMUG, I often consider the importance of evaluating the culture that we are developing. This calls to mind the commencement address of David Foster Wallace and the fish story he told to express that “the most obvious, important realities are often the ones that are hardest to see and talk about.” In his analogy, the water represents the culture that we live in, and sometimes it is difficult to evaluate or change the culture because we are all so accustomed to existing and working in it. A great privilege of teaching in higher education is the opportunity to analyze the learning environment we are creating, and some of the current major topics of discussion involve student success rates, transformational learning, inclusion and appreciation of diversity.

Through a survey of Texas A&M University at Galveston alumni, it was identified that a large percentage of the University’s former students were positively impacted by participation in extracurricular experiences. Specifically, 77% of the respondents stated that they had belonged to a student organization while enrolled. The survey also reported that 82% of respondents would attend Texas A&M University at Galveston if they had to do it all over again. These results indicate that the opportunities for leadership development and involvement outside of the classroom are important for college-aged students' satisfaction.

In 2014, the TAMUG DIVE program created the Scuba Educational Adventures Living Learning Community (S.E.A. LLC), which allowed incoming freshmen to apply to be a part of a small cohort of students that would live together in a specific dorm and share a similar interest in diving. This student organization is now completing its third year and is very active in fundraising, service projects, and diving activities. In 2017, we administered an anonymous survey and asked them what they enjoyed most about the S.E.A. LLC. We then took those words and created a word cloud (in the shape of an Aggie thumbs up!) to have a visual display of the impact of the organization. This has been a very helpful tool for us in marketing the dive program and the S.E.A. LLC, and it has helped the DIVE faculty to easily keep in sight and mind the kind of culture we want to continue to foster.

Several reports, such as the 2017 Physical Activity Report, indicate that Americans are seeking nonconventional exercise outlets that have a clear mental or emotional "takeaway," in addition to health benefits. People of all ages are looking for activities that foster an inclusive community, as well as a fun experience. Participation in activities such as CrossFit and triathlons have increased in the past few years in the United States, and these organizations appear to be successful in creating an atmosphere in which everyone is welcomed and encouraged to try new things. Anecdotally, based on several years of working with college-age students, I think young people are looking for ways to connect their community, hobbies, and health. This is an opportunity for leaders and role models in the SCUBA industry to take some time to consider the water (culture) we are living in, and make sure it's appealing to the young fish that follow us.

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Summary of the 3D Photogrammetry Presentation at ICUE 2017 (06/May/2017)

Applying Principles of 3D Photogrammetry Underwater
About the Presenter/Speaker

- Pasi Lammi (Finland)
- Diving Background: NAUI Rec & Tech Instructor #57705, JJ-CCR Instructor
- Favorite Diving Spots: mines and deep wrecks (sites in Finland and other Nordic countries, Estonia and around Europe)
- 3D Photogrammetry Background: contributor in NAUI 3D photogrammetry course development, member of several research groups documenting wrecks
- Further Information and Projects: wreck diving project with the object of Soviet submarine Sch-324 (https://vimeo.com/156070282), selected links in personal webpage (http://iq.pashi.net/), email (pasi@pashi.net)

About Diving in Finland

- relatively big share of technical divers among recreational divers
- poor visibility and lots of shipwrecks in Baltic Sea
- climate with temperatures between -22F (-30C) and +77F (+25C)
- active diving in more than 10 mines in depths up to 656 feet (200 meters) with average groundwater temperature of +41F (+4C)

When diving one needs a vision to go for. Sometimes the actual visibility in the water is very poor but luckily there are ways to improve the visibility. 3D photogrammetry provides a useful tool for making it happen. There are various definitions given for the tool of photogrammetry, but none of them as such succeed in explaining the very method in a comprehensive and truly useful way. In this presentation some additional points of view are provided for describing the tool further.

For creating a 3D visual by the means of photogrammetry one needs a good selection of photos taken from the object. In an example case of a small church on the island of Utö a 3D model was created by choosing a set of 36 photos. The photos were taken from different angles once walking around the whole church. As a result a quite clear 3D model was generated of the church located on the southern most island with permanent inhabitants year around in Finland.

Why 3D photogrammetry then? It has several benefits. It is a powerful visualization tool in conditions of low visibility. It is also useful for modeling big objects and can be used as a means of measurement. Also, photogrammetry models compare very well with other modeling techniques in providing visibility to texture. And as a 3D modeling technique it is pretty simple to get started with. One only needs a camera such as GoPro, lightning equipment and computer with 3D photogrammetry software.

Some underwater examples of 3D photogrammetry: The 1st example is from the bay of Vanhankaupunginlahti in Helsinki, Finland. 376 photos were taken of a wreck in shallow waters. A model was generated with PhotoScan software by Agisoft and the model provided useful measurements for archeological purposes. An animated video of the object is available at http://pashi.net/museolle/vanhankaupunginlahti.mp4.

The 2nd example is from a mine in Finland. During a 1-hour dive with 4k camera a vast amount of data was collected, but only every 15th of the 90,000 frames was used for the 3D modeling. Still the computing time with a powerful laptop was over 100 hours. As a result a 3D model of the cave system was generated. The model is available at https://sketchfab.com/models/4675ca6ae8a34a52a310f33438f0b15f.

The 3rd example case is from the wreck of Huis te Warmelo. The ship was a Dutch frigate that struck rocks and sank in the Gulf of Finland in Baltic Sea around 300 years ago. Various 3D models have been generated of the wreck, among them a detailed model of a wooden figure that is part of the sunken ship.

To conclude, 3D photogrammetry brings wrecks and other places of difficult access visible for even wider public. It is a method easy to get started with. Once the model is created one can even 3D print the object, which brings the method yet another aspect to explore.

Why 'Human Error' is a poor term if we are to improve diving safety - Gareth Lock
NAUI ICUE Presentation - 6 May 17

The aim of this manuscript is to enable the reader to recognise that often when we read accident and incident reports the cause of outcome is reported as 'human error' and yet this is such a simplistic and reductionist approach which adds very little when it comes to improving diving safety. As a consequence, the article will explain that we need to understand the context and sense-making which is present with any adverse event, and determine why it made sense to those involved to make the decisions they made. Fundamentally, divers or instructors do not aim to injure or kill themselves on a dive. If, using hindsight, the risks are perceived to be so obvious, why didn't those involve see them and prevent the accident from happening?

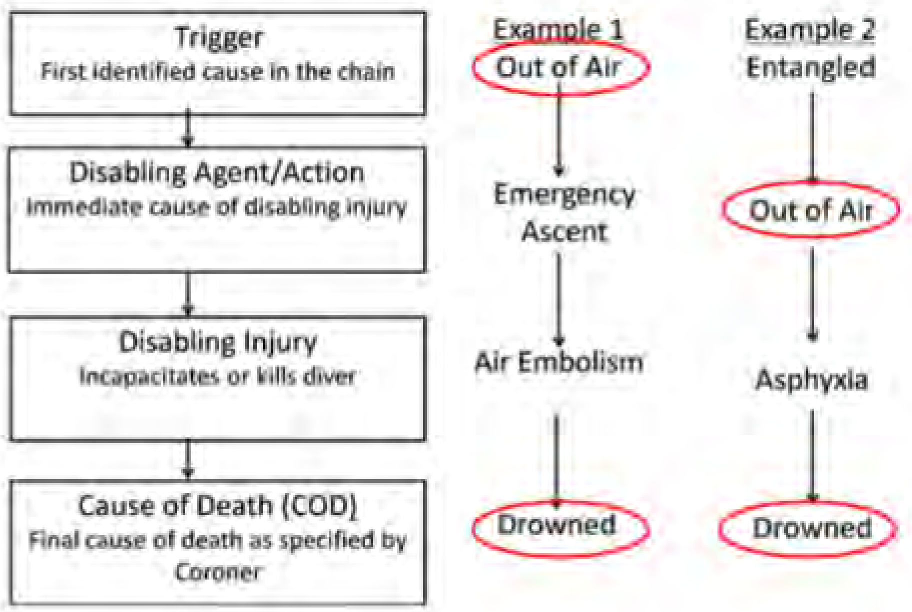
The paper will explain some of the theory behind human error and in the process describing a couple of case studies to show that whilst the simplification to 'human error' is easy, it belies the complexity of the messy and ambiguous real world in which we dive (and live). It will then highlight ways in which the diving community can improve their performance and safety.

In 2004, a Royal Air Force C-130 was operating from Oman into Bagram airfield, Afghanistan to undertake an aeromedical evacuation of a Royal Marine who was very seriously ill and wasn't expected to survive the flight back to Oman or the UK for treatment. A standby crew was called out in the early afternoon and the flight was planned to land just after dark to afford the aircraft some level of protection from the surface to air missiles, rocket propelled grenades and heavy machine guns in the vicinity of the airfield. One of the roles of the navigator onboard was to ensure that the checklists were executed correctly both for normal flight operations, but also tactical operations such as making sure the defensive aids systems were operational. As the crew descended from the high altitude cruise into Bagram, the 'Field Approach Checks' needed to be completed. Their completion was signalled by the flight engineer stating 'Field Approach Checks complete' path rather than going through individual checks. As the aircraft landed on the runway in darkness, the captain put the engines into maximum reverse and at this point three of the four engines shut-down. The captain told everyone to sit on their hands and asked the flight engineer what was going on. He replied that the fuel control valves were incorrectly configured which meant not enough fuel was reaching the engines and they had shutdown due to fuel starvation - the fourth engine didn't fail as there was an engineering problem which was subsequently discovered! The reason for this configuration error was because the flight engineer hadn't executed his part of the checks and the navigator hadn't ensured that the checks had actually been done. This was a crew failure, not just the flight engineer's and the reason that the checks had been completed was because there was considerable stress in undertaking this mission, there was an urgency to rescue this soldier before he died, and the 'Field Approach Checks' were simple checks with only 3 things on them which shouldn't have been difficult to forget. However, they were forgotten. It would be easy to say 'human error' or 'complacency' but that wouldn't explain why the switch selections were missed and what could be done to prevent future occurrences.

In 2012, an experienced scientific diver was undertaking a training dive to 110ft with a buddy who had less than 20 rebreather dives after completing her certification. The plan was relatively simple with a low-workload but after nearly 20 minutes at depth, the subject diver had a seizure caused by oxygen toxicity when his breathing loop pO2 was more than 3.0. The unconscious diver was sent to the surface as the rescuer was loosing control of the ascent. Once on the surface they were recovered by the surface team and given CPR, first aid, and evacuated to a chamber where they made a full recovery. The simplistic reason for this near-death experience was that the diver in question was using a rebreather with cells which were 33 months old and they had missed the cautions which were displayed by the rebreather on the heads-up display and the handset. However, as will be explained later in the paper, the reality was far more complex than that.

‘Human Error’ in Diving

Figure 2: Modified root cause analysis (Denoble, Caruso et al. 2008)



Reviewing the literature it can be seen that ‘diver error’ is present in research papers and text books. Part of the reason the author believes this to be the case is because there is no taxonomy that allows human factors or a deeper understanding of the reasons for the accident to determined. In Bierens ‘Drowning: Prevent, Reduce and Treatment’ (section 175.2.6) [1] he states *“A thorough investigation usually reveals a critical error in judgement, the diver going beyond his or her level of training and experience, or a violation of generally accepted safe diving practices. In other words, the root cause is most commonly ‘diver error’”.* In Denoble’s paper presented at the 2014 Medical Examination of Diving Fatalities conference[2], he states that “*Fatality investigation is conducted by legal authorities focused on a single case. The main purpose is the attribution of legal responsibility and this determines how the causation is established. In most cases, the inquiry ends with establishing the proximal cause of death.”* In aviation, this attitude shifted in the 1980s from ‘the pilot was last to touch it, therefore it was his fault’ towards looking at systemic issues, including human factors. In 2008, Denoble, Caruso et al[3] published their research which determined the triggers, disabling agent/action, disabling injury and cause of death of 1047 diving fatalities from the DAN database. Speaking with Denoble in 2016, he stated that this classification process is recognised as being limiting but a pragmatic approach was needed and they needed to draw a line somewhere. This is understood. However, there needs to be more work down to understand why 41% of the 1047 divers who died in their study ran out of air. Most of the time such a situation is totally preventable, but telling people not to run out won’t solve the problem, any more than telling people the paint is wet, or the stove is hot.

What is ‘Human Error’

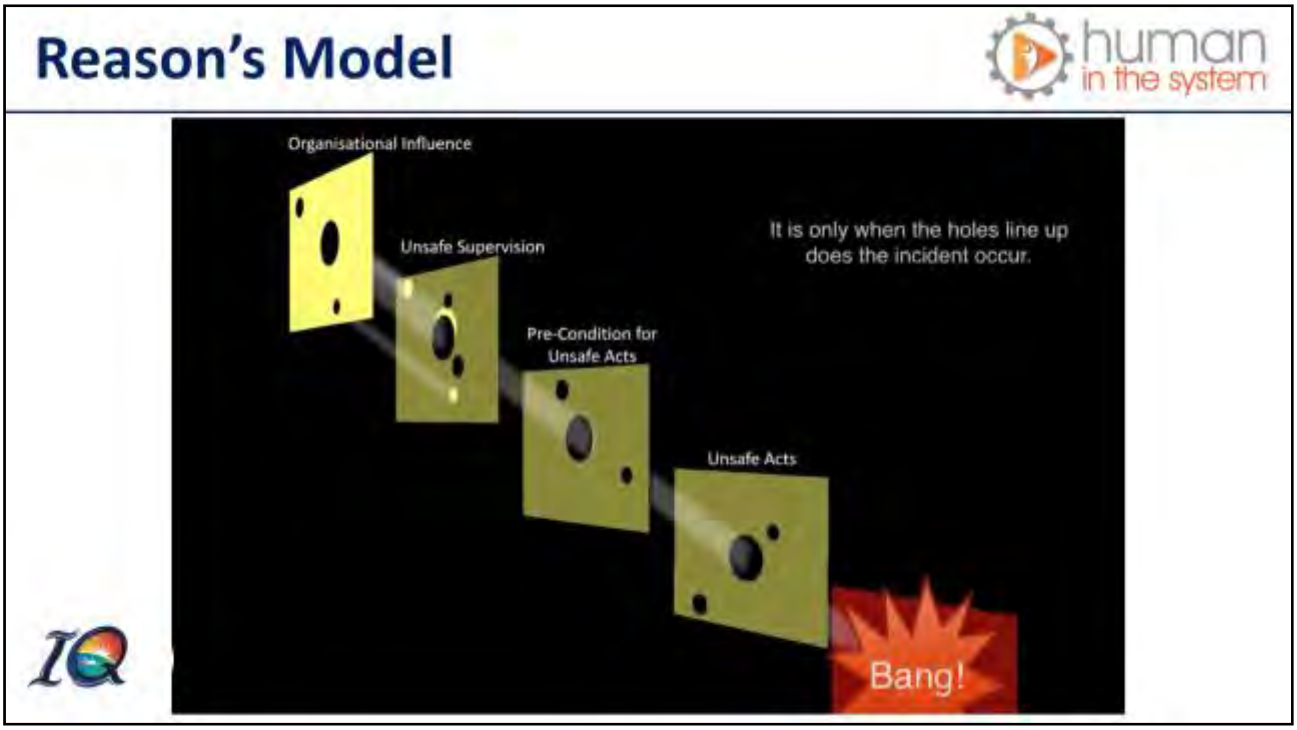
One of the problems encountered is that 'human error' can have a number of different meanings. Hollnagel[4] describes these as:

- Sense #1 – error as the cause of failure: 'This event was due to human error.' The assumption is that error is some basic category or type of human behaviour that precedes and generates a failure. It leads to variations on the myth that safety is protecting the system and stakeholders from erratic, unreliable people. "*You can't fix stupid*".
- Sense #2 – error as the failure itself, i.e. the consequences that flow from an event: "*The choice of dive location was an error*" In this sense the term 'error' simply asserts that the outcome was bad producing negative consequences (e.g. caused injuries to the diver).
- Sense #3 – error as a process, or more precisely, departures from the 'good' process. Here, the sense of error is of deviation from a standard, that is a model of what is good practice, but the difficulty is there are different models of what is the process that should be followed. In diving, given the vast variance in standards and skills, what standard is applicable, how standards should be described, and most importantly, what does it mean when deviations from the standards do not result in bad outcomes.

Consequently, depending on the model adopted, very different views of 'error' can result.

Reason's Model of Human Error

Professor James Reason in his book 'Human Error'[5] described the 'Swiss Cheese Model' as a way of explaining how errors occurred, with the layers in the model being barriers or defences which are there to prevent the accident from occurring. These layers were entitled 'Organisational Influence', 'Unsafe Supervision', 'Latent Failure' and 'Unsafe Acts'. 'Unsafe acts' covered both errors and violations and could be considered the 'last straw which broke the camel's back'. Each of these layers described could have holes in them, in effect gaps in the defences which we put in place to prevent an adverse event. These holes are present because as humans we are all fallible and we often miss things or don't understand the complex interactions which are possible. In most cases, these mistakes or errors don't matter that much because they are picked up before the situation is critical. However, in some cases, the holes in the cheese line up and an accident happens. The diagram below shows this, but there is a need to recognise that this simple 2D static model doesn't replicate the real world in which the holes move and change size so the ability to detect the failures is much harder, especially given the limitations of the human brain and the



biases we are subject to.
As many researchers have shown, continual failures at the 'sharp end' often means that there are systemic issues at hand, including physical hardware design. This fact was known in the Second World War when B-17 bomber pilots were continually raising their landing gear instead of raising the flaps whilst taxying in. Selecting the gear up whilst taxying would cause the aircraft to crash. No amount of training could resolve the issue across the fleet. However, they invited Fitts, a psychologist, and his team to see what the pilots were doing and they noticed that both of the levers to raise the landing gear and the flaps were the same shape and size and next to each other on the control panel. He suggested that they be spatially separated and the gear handle have a wheel put on it so it was obvious it was the gear. The result, no more accidents!

Violations - A Special Sort of Error

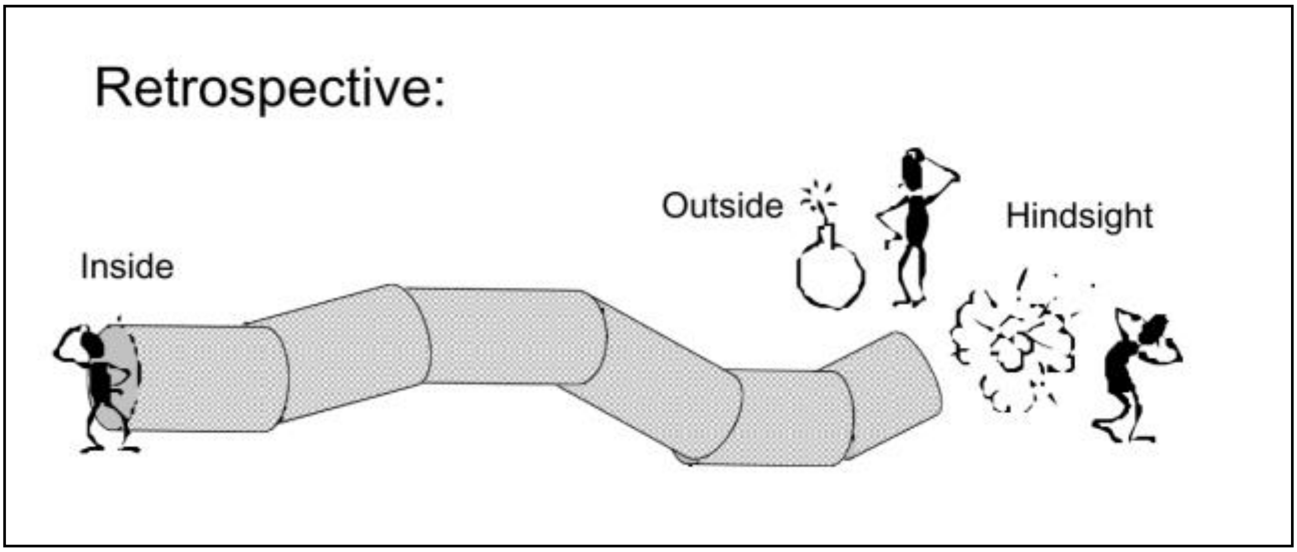
At the bottom of Reason's model within the 'Unsafe Acts' section, there are 4 headings - slips, lapses, errors and violations. Violations were defined as the operator (diver) being responsible for actively creating the problem by ignoring or wilfully breaking the rules. However, modern safety research has shown that violations are pretty normal and that workers are trying to achieve the best outcome given the pressures they are under and it would be better to change system rather than include more rules. Hudson[ERROR] showed that 78% of workers in an offshore environment had broken the rules or wouldn't have a problem breaking them if the opportunity arose and only 22% had never broken rules and wouldn't do so. Phipps et al[6], identified in the anaesthetic domain that doctors would break rules but that it would depend on:

- The Rule: How credible it was, who owned (wrote) it, what would happen it the rule was broken (punishment) and how clear the rule was.
- The Anaesthetist: What their risk perception was like, how experienced and proficient they were, and what the professional group norm was.

- The Organisational Culture/Situational Factors: How much time pressure were they under, how limited they were in terms of resources, the design of equipment and how many concurrent tasks were being managed.

In terms of diving, there are few formal rules which need to be followed and much of the adherence is based around risk perception, social or peer pressures to conform and time or financial pressures. If divers have broken ‘rules’ and something adverse has happened, it is better to look at why the diver did what they did rather than immediately judge and call them stupid for breaking the rules.

Hindsight Bias

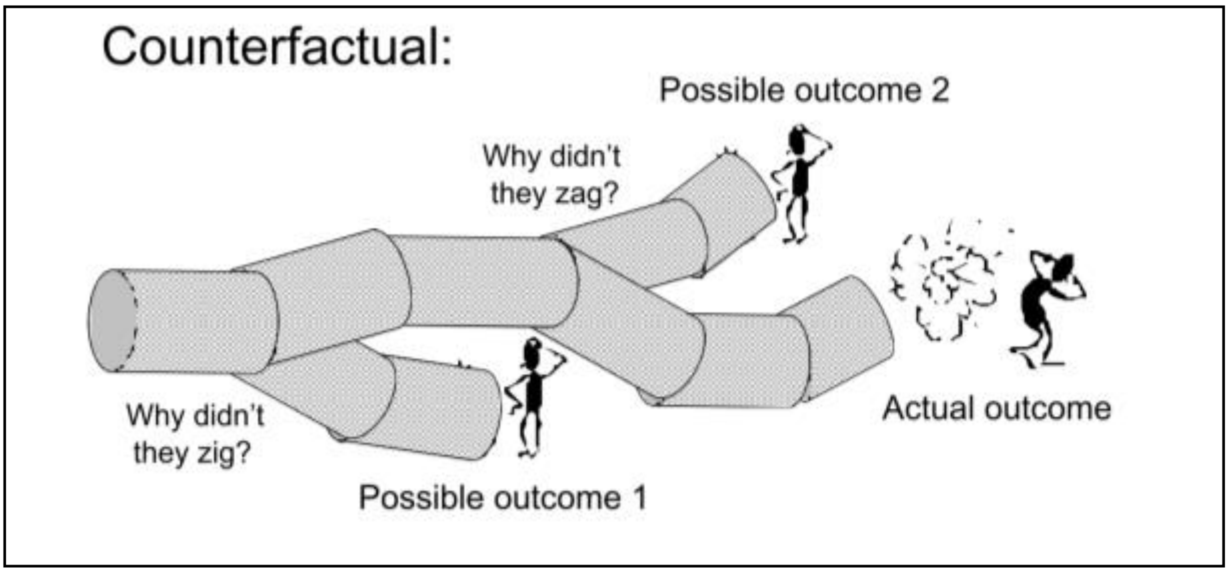


There are a couple of biases which divers are all subject to when it comes to incidents and accidents and how they are perceived in terms of causality and contributory factors. These are hindsight bias and outcome bias. A couple of examples of hindsight bias are shown in the cartoon images from Sidney Dekker’s ‘A Field Guide to Human Error[7]’. In terms of the retrospective view, this provide a different perspective to the person involved in the sequence of events. When looking from the outside and with hindsight, an observer has knowledge of the outcome and the dangers involved. However, from the inside, the diver has neither. Dekker’s use of tubes highlights the limited visibility about what is going on due to focused attention and limited Situational Awareness.

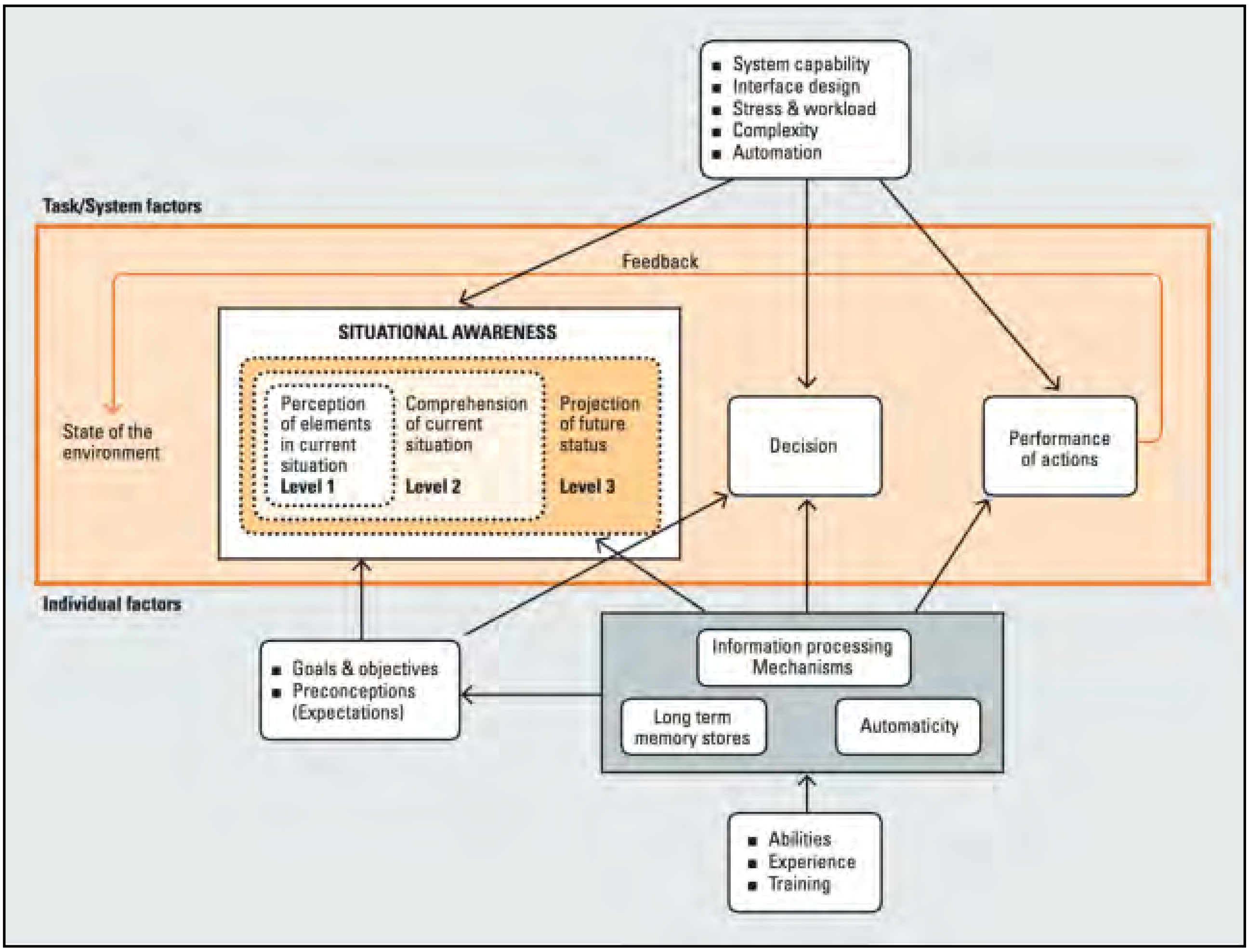
Another take on this is the counter-factual approach to explaining an accident or incident. This is where people go back through a sequence of events and wonder why others missed the opportunities to direct events away from the eventual outcome. Whilst this can explain where the diver went wrong, it does not explain failure.

Hindsight bias is something that everyone involved in looking at diving accidents and incidents should be aware of. Not least because as Hidden QC, the barrister who lead the report examining the Clapham Junction train crash in the UK, where 35 people died and more than 450 people were injured said, *"There is almost no human action or decision that cannot be made to look flawed and less sensible in the misleading light of hindsight. It is essential that the critic should keep himself constantly aware of the fact"*

Situational Awareness



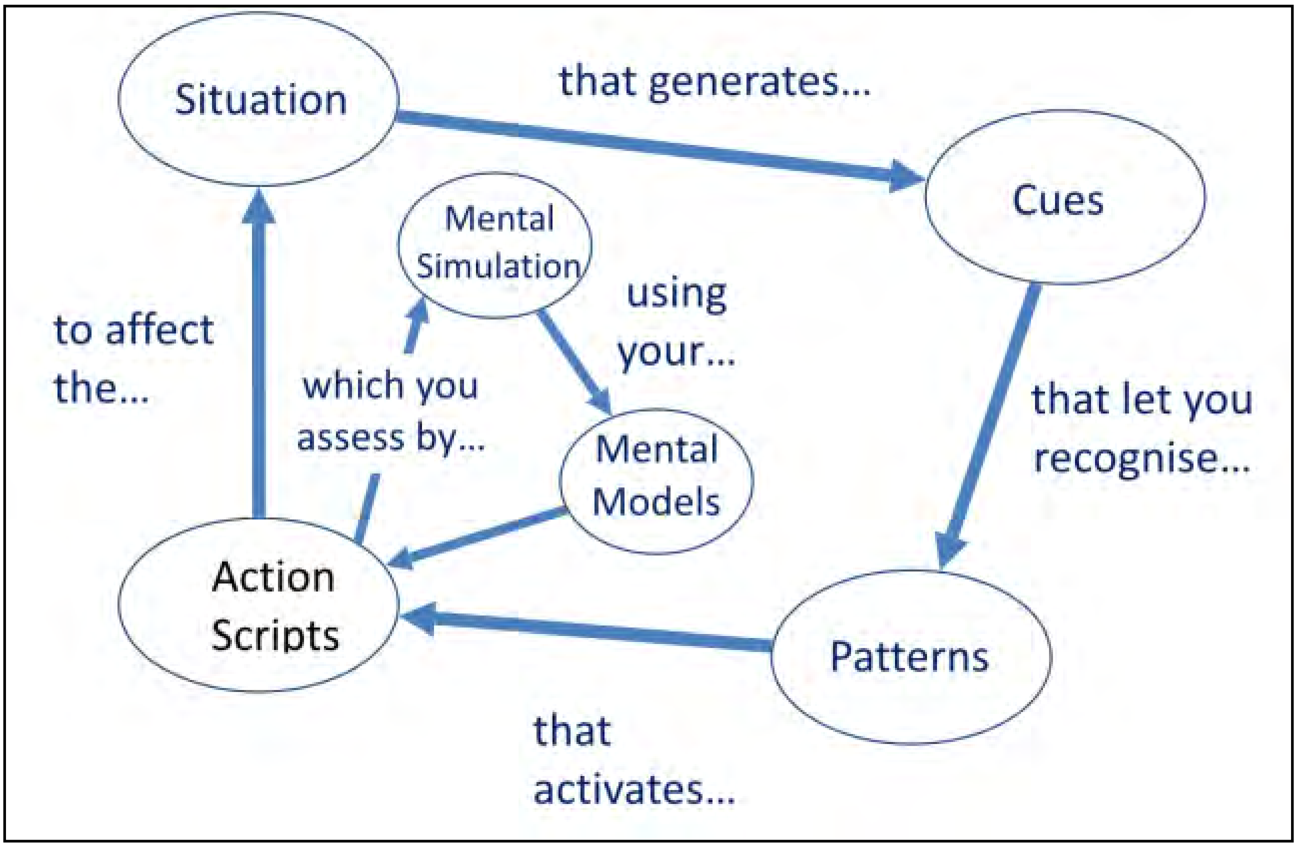
The model below was created by Mica Endsley in 1988[8] and shows how situational awareness is not just the here and now as described by her *"Situational awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and a projection of their status in the near future."* but that individual factors and task/system factors can have an influence as to what is 'relevant' or what can happen to reduce situational awareness. Something to consider is that situational awareness is what it is for the diver and to say that situational awareness has been lost misses the point that there is a finite resource when it comes to attention and if something grabs the attention of the diver, or is perceived to be more important, then the brain will drop the 'apparently' lesser important activity and focus on the new one. Unfortunately it is only after the event when something has gone wrong that it is possible to determine if the element which was 'dropped' was actually a relevant element or one which should have been monitored more closely. Again, the reduction of an accident or incident to 'loss of situational awareness' is flawed as it is really just another term for 'human error' - there is a need to understand why the prioritisation of elements was perceived to



be correct for the activity at hand.

Decision Making - All models are wrong, but some are useful

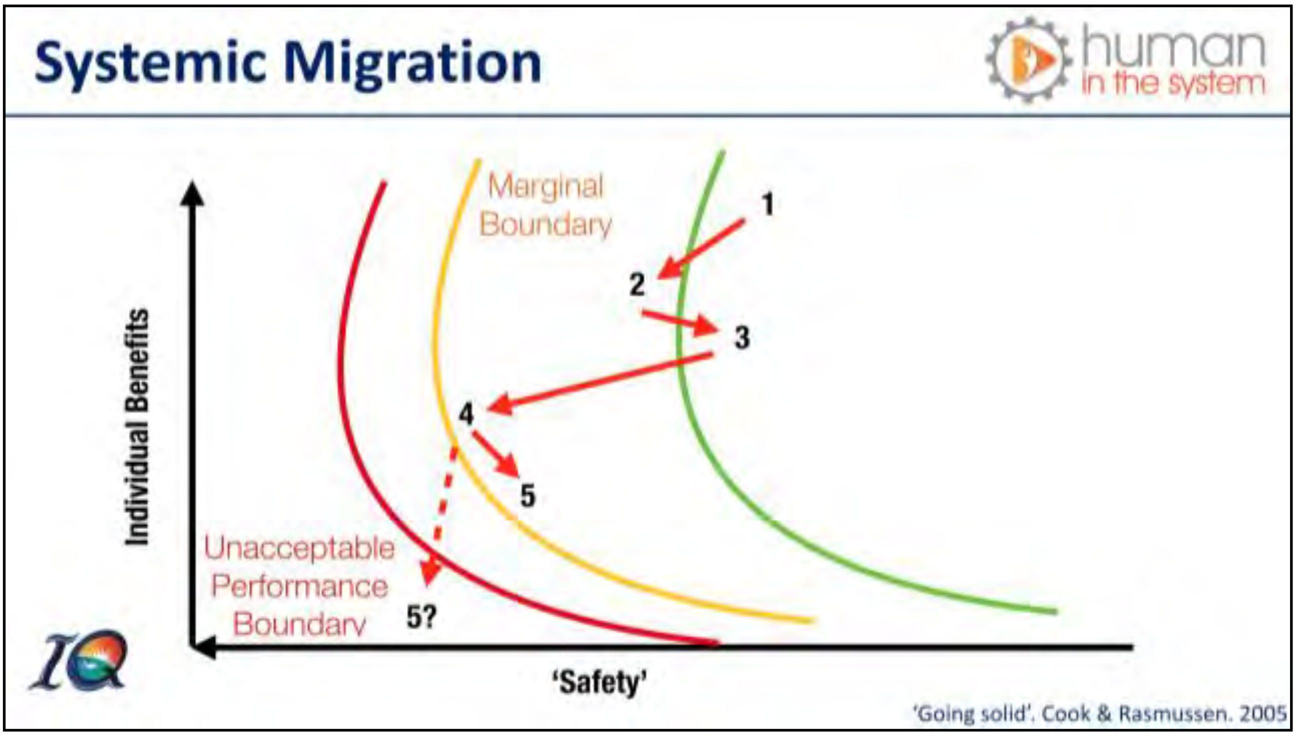
Our situational awareness and decision making processes are influenced by mental models which are created based on experiences. Those experiences can be direct where the diver has physically encountered the activity or subject, or via learning materials or telling stories. The ease by which it is possible to recall those models is influenced by a number of cognitive biases as well as the emotional significance attached to the event when it was experienced and encoded in the long-term memory. Of note, those events with higher emotional significance will be recalled more easily which in itself biases our decision making process. Gary Klein, one of the world leading researchers on decision making, produced the simple model below which comes from '*Streetlights and Shadows*[9]' and explains this cyclic process.

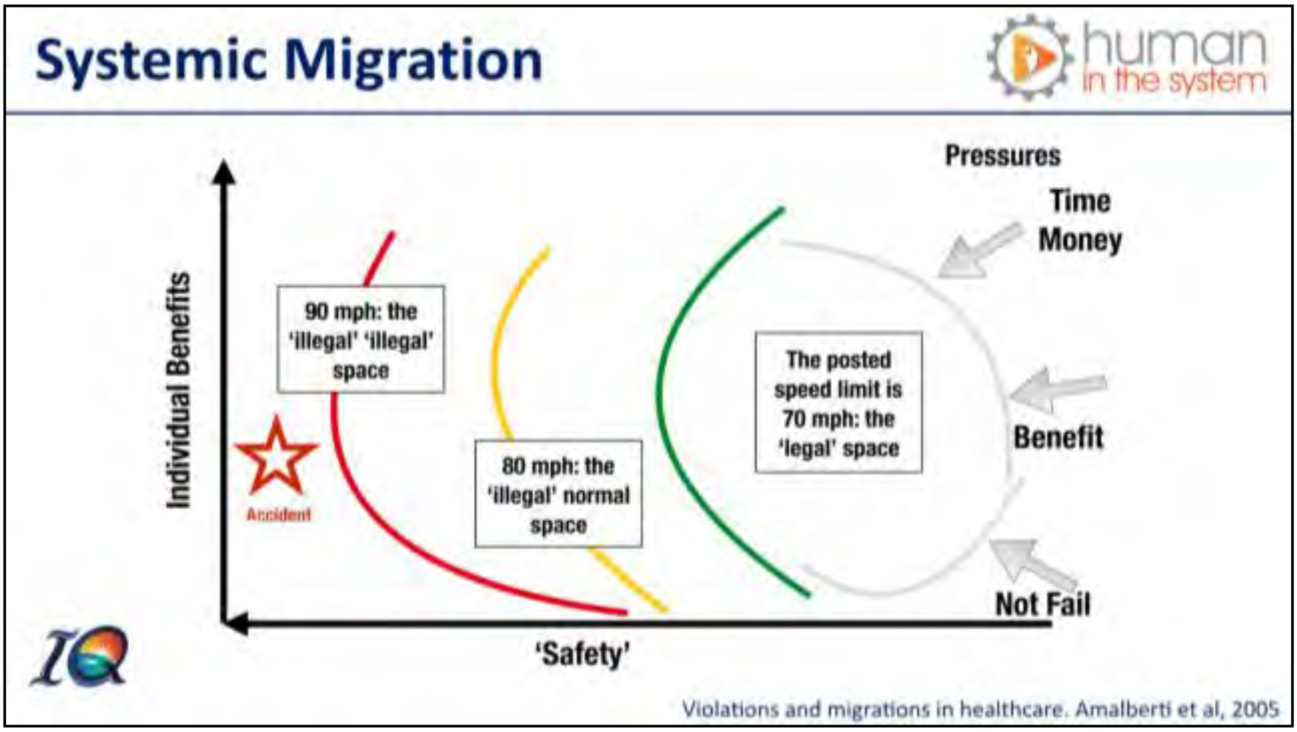


A point to note is that experts have more models with which to create these subconscious mental simulations and they can determine which are the more relevant elements (cues/patterns) to look for in a dynamic and ambiguous scene than novices. This is why they make better and faster decisions. In the context of diving, this is why it is essential that skills and experience are developed outside the training environment to expose the diver to the uncertain and ambiguous environment we dive in - the training system cannot teach every situation and every answer.

Being a deviant is normal

Over time the mental models that are created drift from the standards which are taught or should be adhered to. As the performance drifts, new baselines or models as to what is 'correct' are created. In diving, there is a lack of standards about what is 'right' and, in the main, no formal process to reassess performance after a period of time. Consequently, this drift is normally only picked up when something major goes wrong, or divers have 'safe, scary' moments which identify their deviance. This regular and accepted reseting of new baselines is known as 'Normalisation of Deviance' and came from the investigation by Diane Vaughan into the Challenger Shuttle disaster in which she identified this problem with NASA at an organisational level. The systemic migration to a more risky environment is a natural tendency, something which was identified by Amalberti[10]. A simplified and adapted model of this progression is shown in the diagram immediately below.





In the second diagram, adapted from work by Cook and Rasmussen[11] it can be seen that normal operations stitch between 'safe' and 'unsafe' but as deviations become 'normal' a new baseline is set. Operations continue here but at some point something happens and the activity moves over the ‘unacceptable performance boundary’ and an accident happens. The difficulty is that it is not possible to determine where that boundary is, or what specific combination of factors are needed to combine to cause the adverse event.

Analysis of The Oxygen Toxicity Event

As a review, the diver in question suffered a seizure due to high partial pressures of oxygen in their breathing loop (pO2 was more than 3.0) and the cells in the rebreather were 33 months old.

Now to the context. The team who had this event used two sorts of rebreathers. The most prevalent, when serviced would come back with new oxygen cells fitted. However, the rebreather in question had gone back to its manufacturer in the Jul for a service and did not have its cells replaced with new ones. The reason being that they were struggling with the reliability of oxygen cells and customers were complaining about losing dives. As a consequence, the manufacturer decided to return units with customer’s cells fitted but would run a test on them to see if they performed to specification and provided a service note to the customer about changing the cells. The team received the unit back, noted the cells performed 100% but missed the piece about replacing them. The unit went on the shelf for 4 months. The day before the dive in question, the unit was dived and performed without an issue. This was the first time it had been dived post-service and there was likely an assumption was made that the cells were in date as no-one had noted the ‘change cells’ comment from the manufacturer. The checklist they were using at the time did not state to check the cell dates.

On the day of the incident the diver and his buddy entered the water. They descended to approximately 100ft to carry out their dive. After 9 mins there was a caution displayed on the handset along with a HUD indication. The diver looked down and could not reconcile what the error meant (cell millivolt (mV) error) as they had not seen it before. The HUD colour indicated a caution and not a warning (RED) so carried on. After 12 mins the HUD colour changed back to normal as the system was designed to do. What was happening was that two cells had failed and were now current limited. The rebreather uses a voting logic which is simplified to 2 cells reading the same take primacy over a single cell, even if the 2 are incorrect. The 2 cells which had failed had failed at a pO2 of approximately 1.0. This meant that no matter how much oxygen was injected into the loop, the system believed it was below the set point of 1.3, and would keep injecting oxygen into the loop taking the real pO2 higher and higher. The only indications to the diver that this would be the case would be to check the mV readings on the handset which should happen, but divers are believed not to do this that regularly. At 19:30 mins into the dive, the loop pO2 was 3.02 and the third cell was now failing - it is believed that the loop pO2 reached a maximum of 4.1 using extrapolated date. At approximately 26:50, the diver suffered a seizure and was rescued. The rescue and extraction of the divers to the chamber and medical facilities went without flaw and was commended in the subsequent investigation.

Given that the aim of the paper is to look at human error in context, a review of the why it made for the diver to do what they did, the context and factors will now be revisited. The rebreather had come back from the manufacturer with a clean bill of health saying the sensors were performing 100% of specification. However, the team missed the comment about changing the cell. Consequently, their mental model was that the cells had been changed based on their experiences of the other manufacturer which was a more prevalent rebreather in the team. The unit went into the dive locker for four months before being used again. The unit was dived the day before and performed as expected. They did not check the cell dates because there was no checklist which asked for this and the unit had come back from the manufacturer four months prior. On the dive in question, the diver had noticed the HUD caution and handset information, but not seen this specific error before during their training (it is not possible to simulate it) and because it was a caution, not a warning, they did not believe it to be that serious and when it went away, they presumed the fault was transient. The diver was likely relatively task loaded having not dived a rebreather for a while and they were also looking at after an inexperienced diver, so didn't check the handset as often as they should have done. The HUD didn't give any indication that something was wrong because the voting logic was working as designed. As a result, the diver made an assumption, based on previous experiences which informed their mental models, that everything was ok when in fact it was heading for a disaster if nothing was done.

The key theme to this paper is about learning from events, positive or negative. So what happened with this team to make improvements and learn from failure? The manufacturer recognised the human machine interface issue and escalated this specific caution to a warning in the system and changed the wording on the handset to something more relevant. The manufacturer ceased sending units back with cells fitted and at the same time found a more reliable supplier. The team went back to basics in terms of how they managed risk, and rewriting many of their procedures in the process. They also reinforced their life support and rescue skills as this was shown to be crucial in not having a fatality during the event. Finally, the team have also undertaken three training sessions with the author to develop their non-technical / human factors skills with a view to becoming a higher performing team which includes developing a learning and just culture so that the team can talk about mistakes more easily.

Summary

A key point to recognise from this paper is that human error is normal and that accidents and incidents will happen, no matter what operators, supervisors and organisations try to do to mitigate them. Consequently, there is a need to take a different view of safety, something which can be summarised by this quote

"Safety is not the absence of accidents or incidents, but rather the presence of defences and barriers and the ability of the system to fail safely." - Todd Conklin

There is an urgent need to change our attitudes if diving safety is to be improved, blaming people for being 'stupid' is not going to make a difference to safety. In fact, it could be argued that it is having a detrimental effect because failures are not being talked about and therefore the real risk which is being faced is not known. The author believes that the investigation and discussion of fatalities is not the most effective way of improving diving safety, especially when litigation is about pinning the blame on one party or another and therefore the context and real decision making is often missing especially when it comes to violations and rule-breaking. Furthermore, in many cases, the person who knows how it made sense to make the decisions they did is dead. Therefore, there is a need to create the culture within the communities and organisations to be able to recognize human error for what it is and allow those who have made mistakes, errors and violations to talk about them, free from the fear of social or legal retribution. This is known as a 'Just Culture' and one of the reasons why aviation is as safe as it is.

This paper will close with a quote from a chapter called 'Mistaking Error'[12] from the Patient Safety Handbook by Woods and Cook to highlight the complexity of the situation so that when something does go wrong, look deeper than 'human error'.

"…in practice, the study of error is the nothing more or less than study of the psychology and sociology of causal attribution…Error is not a fixed category of scientific analysis. It is not an objective, stable state of the world. **Instead, it arises from the interaction between the world and the people who create, run and benefit (or suffer) from human systems for human purposes.**" - author's emphasis.

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Diver Fatalities . . . Lessons Learned

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An important component of diver safety is education. In fact, it is NAUI's motto: "Safety Through Education" that provides a basic framework around which NAUI's diver education programs have grown since the 1960's. The author was impressed with the NAUI philosophy and teaching methodology when he took his first diver certification course in 1964 from Ray Tussey (NAUI #007). From the early years of our sport, the focus has always been to develop equipment, skills, and an overall philosophy with diver safety as the guiding principle. Every diver training organization has encouraged diver of all levels to take full advantage of every opportunity to learn. Divers have been encouraged to participate in continuing education courses, read books, and magazines about diving, spend time with experienced divers sharing information and experiences (many of which are actually true!), attend dive club meetings, seminars, and dive consumer shows, and participate in lectures or seminars on diving safety in person or those that may be available online. In other words, divers have always been encouraged to take advantage of every opportunity to learn and apply what you've learned. Experienced divers understand that during many openwater dives situations occur requiring some level of quick decision making. Safety-conscious divers use all unexpected incidents that occur while diving as opportunities to learn. They brainstorm and discuss response options, contingencies, and prevention strategies with those they dive with. The more knowledgeable a diver is, the more tools they possess to identify, avoid or manage things that occur during a dive. Those divers with limited knowledge, skills and experience are at greatest risk when situations occur because their limited abilities may not be equal to the demands of what could possibly turn out to be a potential emergency situation.

Another way we learn is through organizations that collect, analyze, and disseminate information on diving accidents and fatalities. Originally, diving fatality information was collected and published by the National Underwater Accident Data Center at the University of Rhode Island. That role was eventually taken over by Divers Alert Network (DAN). DAN, the world's largest diving safety association, publishes an Annual Diving Report that provides information collected from across the diving world. DAN also conducts research on the causes of diving injuries, accidents and fatalities.

In 2008, DAN researchers led by Dr. Petar Denoble, analyzed nearly 1,000 recreational diving fatalities occurring between 1992 and 2003 from the DAN fatality database, conducting a root cause analysis to determine what circumstances and events led to recreational open-circuit diver deaths. In this analysis, DAN researchers identified four different phases in the cascade of events leading to a fatality: the triggering event, the disabling agent, the disabling injury, and, ultimately, the cause of death.

Triggering Events in Recreational Diving Fatalities

Triggering events are the earliest identifiable root causes that transform otherwise enjoyable recreational dives into emergencies. Identifying these triggering events is essential so divers can learn to avoid or manage unplanned situations that occur during openwater dives.

In the DAN fatality analysis, the triggering events and their frequency (%) were identified as follows:

- Running out of breathing gas 41%
- Entrapment 21%
- Equipment problems 15%
- Rough water 10%
- Trauma 6%
- Buoyancy 4%
- Inappropriate gas 3%

Reviewing how these triggering events affect diving safety can help divers identify and mitigate the risks, thus reducing diving accidents and fatalities.

Running Out of Breathing Gas

The most frequent triggering event was running out of breathing gas. Of the diving fatalities analyzed, 41% were unable to properly manage their breathing gas supply and ran out of breathing gas before returning to the surface. With pressure gauges or air-integrated dive computers a standard part of every diver’s equipment repertoire, running out of breathing gas underwater should simply never happen.

There are numerous cases in the diving accident literature where divers failed to change cylinders between dives only to run out of breathing gas during the subsequent dive. Unfortunately, a number of situations like this precipitated a series of events including a failure to properly exchange breathing gas with a diving partner resulting in multiple fatalities.

Being "air or breathing gas aware" should be every diver’s primary safety mantra. Always begin dives with a full cylinder of breathing gas, and end dives (standing on the boat, dock or shore) with breathing gas remaining. Before starting a dive, you and your diving partners should decide how to communicate information about your remaining breathing gas supplies, how frequently you will share that information during the dive, and specifically what hand signals will be used. You should firmly establish a point at which you and your diving companions will begin making your way to the exit point or surface and, quite frankly, live by that decision. When the first diver in your group reaches that predetermined point in your breathing gas supply, you and your partners must begin your return to the exit point. Even if you have significantly more breathing gas remaining than your partner when you turn the dive, the dive should be over for both of you. Simply letting your partner who was low on breathing gas return to the surface alone is not fulfilling your buddy obligation and it puts your partner at significant risk. There are numerous cases in the diving accident literature where one diver needed to “call” the dive and the other simply waved “goodbye” never to see that diver again.

Entrapment

The next most common triggering event in dive fatalities is entrapment. That is, 21% of the divers from DAN’s fatality analysis, found themselves in an overhead environment and were unable to get back to openwater before their breathing gas supply expired. An overhead environment is any diving situation where there is no direct, vertical access to the surface or openwater— such as a cave, cavern, wreck, under ice, or when there is significant surface hazard including boat traffic. A decompression obligation is considered by many to be a “virtual overhead.” Every diver training organization warns divers about the dangers of entering such environments without appropriate training, experience, planning, redundant equipment, and proper gas management. Many divers who enjoy diving in overhead environments use what is called “the rule of thirds”, meaning that you use the first third of their breathing gas supply for the dive, the second third for the exit from the overhead environment or the ascent, and the final third to be reserved for emergencies. This may seem conservative for openwater diving, but the idea of leaving a significant reserve for emergencies or other unexpected circumstances is absolutely relevant. Anything short of effective management of your breathing gas puts you, your buddy, and every diver in the vicinity at risk.

The way to mitigate the hazard of entrapment as a triggering event is very simple: Don't enter overhead environments without being fully qualified, experienced, and prepared to do so. Quite literally, *when in doubt, stay out!*

Equipment Problems

The third most common triggering event identified in the DAN fatality analysis was identified as “equipment problems.” This triggering event initiated 15% of the DAN fatality cases studied. In the author’s experience and years of reviewing diving accidents and fatalities, it is more likely “problems with equipment” or “user error” rather than a true equipment malfunction or some sort of design flaw. These errors include improper use, equipment configuration error, lack of regular or qualified maintenance, and insufficient familiarity with the equipment in an emergency situation. Dr. George Harpur, Medical Director of the Tobermory Hyperbaric Facility, Coroner for the Province of Ontario, "*We are not able to document a single case in which equipment malfunction directly caused a diver's death or injury. It has been the diver's response to the problem that results in the pathology.*"

It's important to remember that the equipment you use is truly "life-support equipment" and must be treated with the utmost care. Learn about all its features and functions, practice with it simulating the "worst case scenario", and have it maintained regularly by a qualified equipment repair technician at a professional dive center; take care of your gear so it can take care of you.

The three triggering events addressed here, running out of breathing gas, entrapment, and equipment problems represent 77% of the events that triggered a diving emergency. The remainder, rough water, trauma, buoyancy, and inappropriate gas, are all important issues that need to be addressed from an overall diving safety perspective.

Becoming A Safer Diver

Knowing what triggers the cascade of events that, ultimately, leads to a diving injury or fatality only advances the discussion so far. For the sport of diving and divers themselves to improve safety, we must apply the lessons learned from these tragic events. How can we, as divers, reduce the likelihood that these triggering events will cause problems for us?

Practice

Diving and emergency-management skills require constant practice and reinforcement. Many of these skills are complex psychomotor skills that require frequent practice to be used successfully in a crisis situation. This is especially true of emergency skills such as the exchange of air in an out of breathing gas situation. There are numerous cases in the DAN diving fatality database where the attempted exchange of breathing gas went terribly wrong causing the deaths of both divers. In many of these cases, one of the dead divers still had more than sufficient breathing gas for both divers to have made it successfully to the surface. Another critical emergency skill that is not practiced frequently is the diver's removal of weights in an emergency. Some weighting systems, especially those integrated into the diver's buoyancy compensator, may require multiple movements to jettison weights in an emergency and, therefore, practice is essential. Numerous case histories exist where dead divers were recovered with their weighting systems intact when removal could have provided sufficient buoyancy to get them to the surface where the possibility of a successful rescue was significantly greater.

Refresh these and all other critical diving skills often, especially when you haven't been diving in a while. Take time to familiarize yourself with all new equipment in a controlled environment and, possibly, under the expert supervision of an instructor before using it in openwater. Although practice may not make you perfect, it will help you make the correct decisions and manage problems that occur underwater appropriately rather than initiating a cascade of events that could result in a tragedy.

Experience

The value of experience cannot be overstated. Divers with limited experience, including those returning to the sport after a long absence, are at greatest risk. According to the DAN fatality data, 88% of the divers died on the first dive of their dive series. This could indicate that divers who may have been away from the sport for some extended period of time due to career or family obligations thought they could return to diving at the same level without a refresher course or recent familiarity with their equipment or skills. Consider that the number of dives in your logbook or the date on your certification card do not automatically qualify you for the challenges you may experience on a given openwater dive. To truly be prepared for a return to the sport, slowly and methodically return to the water, increasing the complexity and task loading of your dives as you progress. Expand your horizons gradually, making sure you don't outpace your training, experience and your level of comfort. Certification is definitely not the same thing as proficiency. Remember: *Don't dive your C-card, dive your recent experience.*

Health

Approximately one-third (33%) of the fatalities in the most recent DAN Annual Diving Report involved cardiac-related issues. Amazingly, in 60% of the cases with cardiac involvement, the divers had symptoms that they or their diving companions recognized such as shortness of breath, chest pain, or fatigue but proceeded to dive anyway. Divers should be aware of the importance of good general health and fitness for diving, but comfort and well-being at the time of the dive are also important. If you're not feeling up to a dive, don't dive.

The diving medical community recommends that everyone older than 35 have an annual physical examination, or any time there is a noticeable change in your health. A physical is also recommended following any noticeable change in an individual's health status. Divers would certainly benefit from having their physical exam performed by a physician trained in diving medicine. Remember that a physician who scuba dives is not necessarily an expert in diving medicine. If you don't know a physician trained in diving medicine in your area, contact the DAN Medical Department (www.dan.org). DAN has a physician database with over 700 referral physicians familiar with diving medicine.

Pre-Dive Preparation

As you prepare to go diving, it's a good idea for you and your diving companions to configure and assemble your equipment together so you can identify and correct anything that looks unusual or out of place. In DAN's diving fatality analysis and the list of triggering events above, it is apparent that in 63% of the triggering events there is some equipment-related component. With thorough and comprehensive pre-dive preparation, qualified and experienced divers may be able to significantly reduce the likelihood that equipment-related issues would initiate a diving emergency resulting in a diving injury or fatality.

Complete pre-dive preparation also provides an opportunity for divers to familiarize themselves with each other's equipment. It is far better to familiarize yourself with your diving companion's equipment long before the dive begins rather than trying to do so while desperately trying to manage a diving emergency. If boat diving, it may be helpful to set up your equipment before the boat leaves the dock. This is especially true if you are subject to seasickness, since it minimizes the amount of time you'll spend trying to manage tasks while the boat deck is rocking. Also, hastily assembling your equipment in rolling seas while feeling nauseated increases the likelihood of potentially hazardous errors.

Before diving, review your dive plan with your buddy to ensure you have a shared understanding of the plan and your goals for the dive. You'll also want to agree on the route you'll take and possible alternatives to your primary dive plan. It's much easier to communicate the switch to plan B if you decided what plan B was before you enter the water. Establish the fact that anyone can terminate the dive at any time for any reason, even before the dive begins, without repercussions. Creating an environment in which divers feel comfortable making such calls builds a strong culture of diving safety.

The use of a pre-dive checklist is definitely recommended. At Rebreather Forum 3 in 2012, the development and use of pre-dive checklists was identified as one of the most important factors in diver safety. Along with a checklist, the author finds it useful to develop and continually reinforce a pre-dive ritual that you and your diving companions use on each and every dive. It should involve equipment checks, dive plan review, hand signal review, diver separation protocol review, and out-of-breathing-gas procedure review. This may seem unnecessary if you dive with the same people regularly, but the use of a checklist and pre-dive rituals are highly recommended and time well spent if they give you confidence and reduce the likelihood that you are in any way unprepared to dive. Along with that, never hear or say, "*Don't worry, I'll take care of you*." That means one of the divers is not as qualified or prepared for the dive as he should be — a formula for disaster. Anyone making a dive should do so only if he is fully prepared and wants to dive, not because someone else wants them to.

The Dive

Once in the water, conduct a visual check of each other making sure all equipment is secure and in place, there are no leaks and that your buoyancy is what it is supposed to be. Give and receive the OK signal from everyone in the dive group, initiate your preparatory ear-clearing procedures, and begin a controlled descent. Descending feet first using a fixed line makes it easy to stop the descent should the need arise and may be advisable if there is the potential for a current at the site. It may also be useful to make a short stop 15 to 20 feet (4.5m-6.1m) below the surface to give and receive the OK sign before proceeding to the bottom.

It is also critically important to be situationally aware throughout the dive. Situational awareness means knowing the status of your dive relative to your breathing gas consumption, your dive plan and the environmental conditions. Being situationally aware will allow you to make changes in your dive plan if conditions occur which may compromise your safety. It's always wise to plan your dive and dive your plan, but you can modify your dive plan if conditions call for a more conservative approach. If you are working harder during the dive than anticipated, you may want to watch your air consumption more closely and possibly limit the time you spend at depth. If something does occur that may increase your risk you may be able to mitigate that risk by reducing your bottom time, ascending to a shallower depth during the remainder of your dive or increasing the time at your safety stop. Being situationally aware is another important tool in diving safety.

As you move underwater, the slowest diver in your group should dictate your pace. Never assume another diver can keep up with you. If a recreational dive starts to feel like work, something is wrong and you may choose to discontinue or “call” the dive. If you're diving in a group of three and one diver decides to return to the surface, either end the dive as a group or escort the diver back to the exit point and make sure they are safely out of the water before continuing the dive.

In the author’s understanding of the risks associated with recreational diving, it is clear that recreational diving is inherently safe but it can be very unforgiving of mistakes. If the safety-conscious diver follows the steps suggested in properly preparing for and executing a recreational dive, the real risks are minimal. After all, there are millions of certified divers around the world making tens of millions of safe, enjoyable dives without incident every year. It has been said many times that there is far greater risk simply getting to the dive site than during just about any dives a diver is going to make. There is, after all, risk in anything you do. Life itself is certainly not risk free! Are the risks we’ve identified in recreational diving unreasonable? The answer is certainly likely to be a resounding, “No”. We understand and appreciate the fact that a degree of risk will always be part of the sport we love, but the safety-conscious diver knows that as part of our preparation to dive, we identify and manage those risks.

Scuba diving is a sport enjoyed the world over by young and old alike. Diving safety experts agree that the focus should always be to maximize enjoyment while, at the same time, minimizing risk. To quote from “Scuba Diving Safety”, “*You overcome challenges in and under the water by thorough preparation, and the effective application of knowledge and skill*”.

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TWO DECADES OF DEEP STOP TRAINING

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Deep stops – what are they?

Actually, just what the name suggests. Deep stops are decompression stops made at deeper depths than those traditionally dictated by classical (Haldane) dive tables or algorithms. They are fairly recent (last 25 years) protocols, suggested by modern decompression theory, but backed up by extensive diver practicum with success in the mixed gas and decompression arenas - so called technical diving. Plus they have been correlated with computer downloaded, dive profiles and bubble models. Tech diving encompasses scientific, military, commercial, and exploration underwater activities. The impact of deep stops has been a revolution in diving circles. So have slower ascent rates across recreational and technical diving. In quantifiable terms, slower ascent rates are very much akin to deep stops, though not as pronounced as decompression stops. Deep stops plus slow ascent rates work together. And they work together safely and efficiently.

Deep stops usually reduce overall decompression time (hang time) too. And when coupled to the use of helium in the breathing mixture (trimix) to reduce narcotic effects of nitrogen, technical divers report feeling much better physically today when they leave the water. The reduction in hang time ranges from 10% to as high as 50%, depending on diver, mix, depth, and exposure time. Feeling better while decompressing for shorter periods of time is certainly a win-win situation that would have been thought impossible not too long ago. The basic tenets of conventional decompression theory (neo-classical dissolved gas theory) postulate that deeper exposures (deep stop plus bottom time) incur greater offgassing penalties in the shallow zone.. Many dive computers still stage divers using Haldane approaches. But that is changing rapidly too. New computers invoking the dual science of dissolved gases and bubbles are now mainstays on the market, The good thing here is that both deep stop and shallow stop models work and are safely utilized by divers. But let’s look at deep stops first. Shallow stops will be covered in later Parts.

The depth at which the first deep stops are made can be dramatically deeper than those required by conventional tables. For instance, a dive to 300 *fsw* on trimix for 30 *min*, with switches to progressively higher enrichments of nitrox at 120, 70, and 20 *fsw*, calls for the first deep stops in the 250 *fsw* range. Conventional tables require the first stops in the 100 *fsw* range. If trimix is substituted for nitrox on the way up, total deco time can be further reduced, and divers today leave the water feeling *better* than they would on nitrox. This comes from reports not tests.

Early Testing And Ad Hoc Procedures

Haldane originally found that deep stops were sometimes necessary in his decompression tests and staging regimens [1], but either abandoned them, or could not incorporate them naturally into his (just) dissolved gas, critical tension (called $M - values$) model on first principles. Too bad some think, he might have saved future generations of divers much deco scheduling controversies and unnecessary hang time. World Navies then never tested deep stops either. Deep stops do not emerge naturally in dissolved gas models for deco scheduling. Probably Haldane also didn't go deep enough to see real diving differences and time savings. Deep stops are really a *deep* protocol. Having said that, nothing detracts from the original research and pioneering work of Haldane for sure.

But even before modern deep stop protocols and models emerged, utilitarian diving practices among diving fisherman and pearl gatherers suggested traditional staging was in need of rethinking. And early deco models, such as the so called thermodynamic model of Hills, suggested why and how. Deep stops likely evolved from cognizance of operational diving practices and early models by technical divers worldwide. Here's why.

[illegible]

Similar schedules and procedures have evolved in Hawaii, among diving fishermen, according to Farm and Hayashi [5]. Harvesting the oceans for food and profit, Hawaiian divers make beween 8 and 12 dives a day to depths beyond 350 *fsw*. Profit incentives induce divers to take risks relative to bottom time in conventional tables. Repetitive dives are usually necessary to net a school of fish. Deep stops and shorter decompression times are characteristics of their profiles. In step with bubble and nucleation theory, these divers make their deep dive first, followed by shallower excursions. A typical series might start with a dive to 220 *fsw*, followed by 2 dives to 120 *fsw*, and culminate in 3 or 4 more excursions to less than 60 *fsw*. Often, little or no surface intervals are clocked between dives. Such types of profiles literally clobber conventional tables, but, with proper reckoning of bubble and phase mechanics, acquire some credibility. With ascending profiles and suitable application of pressure, gas seed excitation and bubble growth are likely constrained within the body's capacity to eliminate free and dissolved gas phases. In a broad sense, the final shallow dives have been tagged as prolonged safety stops, and the effectiveness of these procedures has been substantiated *in vivo* (dogs) by Kunkle and Beckman [6]. In-water recompression procedures, similar to the Australian regimens, complement Hawaiian diving practices for all the same reasons. There's a bit more.

In recent times, the experiments of WKPP cave and exploration divers in Florida are certainly noteworthy [4]. Maybe experiments is too strict a description. Individuals, particularly in the cave diving community, toyed with decompression regimens in hopes of minimizing their decompression time. The cave exploration Woodville Karst Plain Project (WKPP), mapping subsurface topographies in Florida, pioneered deep stop technology, establishing many rule-of-thumb protocols to be imposed on conventional tables, successfully conducting 6 hour dives at 280 ft in the Wakulla cave complex with deep stop decompression times of 8.5 hours versus traditional Haldane hang times of 16 hours. Also, the horizontal penetrations of 19,000 ft are likely records. Certainly such contributions to diving science and spinoff model validations are extraordinary and not easily tendered in the laboratory or hyperbaric chamber.

So deep stops work. But what are the mechanics behind them?

Dissolved Gas Versus Bubble Dynamics

The dynamics [7] are fairly simply. It's just a matter of how dissolved gases and bubbles behave under pressure changes. We use to think that controlling dissolved gas buildup and elimination in tissue and blood was the basis for staging divers and astronauts. And that bubbles didn't form unless dissolved gas trigger points *(M-values)* were exceeded. At least that was the medical presumption that went into conventional (Haldane) tables. Chemists, physicists, and engineers never bought off on that. When *silent bubbles* were tracked in divers not experiencing any decompression problems, of course, this changed. And since bubbles need be controlled in divers, decompression focus changed and switched from just-dissolved-gases to both bubbles and coupled dissolved gases. Deep stops then emerge naturally. Here's how.

To eliminate dissolved gases, the driving *outgassing gradient* is maximized by reducing ambient pressure as much as possible. That means bringing the diver as close to the surface as possible. But, to eliminate bubbles (gases inside them), the *outgassing gradient* is maximized by increasing ambient pressure as much as possible. That means holding the diver at depth when bubbles form. Deep stops accomplish the latter. Bubble staging and deep stop paradigms have a few more salient features as follows

Clearly above, dominant modes for staging diver ascents depend upon the preponderance of free (bubbles) or dissolved phases in the tissues and blood, their coupling, and their relative time scales for elimination. This is now (will always be) a central consideration in staging hyperbaric or hypobaric. To eliminate dissolved gases (central tenet of Haldane decompression theory), the diver is brought as close as possible to the surface. To eliminate free phases (coupled tenet of bubble decompression theory), the diver is maintained at depth to both crush bubbles and shrink bubbles by gas diffusion across the bubble film surface. Since both phases must be eliminated, the problem is a playoff in staging. In mathematical terms, staging is a *minimax* problem, and one that requires full blown dual phase models, exposure data, and some agreement of what is an acceptable level of DCI incidence. In bubble models, at the same risk level [9], staging in deeper but overall run time is less, somewhere in the 10-20% range.

Other *ad hoc* prescriptions for deep stops were imbedded in conventional tables. Something like this was employed, trial and error, and this one is attributed to Pyle [4], a fish collector in Hawaii:

1. calculate the decompression schedule from tables, meters, or software;
2. half the distance to the first deco stop and stay there a minute or two;
3. recompute the decompression schedule with time at the deep stop included as way time (software), or bottom time (tables);
4. repeat procedure until within some 10 -30 *fsw* of the first deco stop, then follow regular (computed) decompression procedures.

Within conventional tables, such procedure was somewhat arbitrary, and usually always ended up with a lot of hang time in the shallow zone. Such is to be expected within dissolved gas deco frameworks. So, deep stop pioneers started shaving shallow deco time off their schedules. And jumped back into the water, picking up the trial and error testing where it left off. Seasoned tech divers all had their own recipes for this process. And sure, what works works in the diving world. What doesn't is usually trashed. Decompression hang time can be boring and cold.

Diving Models And Protocols

Not only did deep stops evolve self consistently in these models, but dive software and personal computers put deco scheduling with these new models in the hands of real divers. More recently, the LANL Data Bank, housing deep stop data from actual diving with the TM, VPM, RGBM, TBDM and Pyle stops discussed above and below, has been employed to validate and correlate deep stop models with computer downloaded diver profiles. One thing about these bubble models, collectively referenced, that is common to all of them is deeper stops, shorter decompression times in the shallow zone, and shorter overall deco times. Without going into gory details, a few of the more important ones can be summarized. The Pyle half stop model was discussed earlier. The Thermodynamic Model of Hills really got the ball rolling so to speak:

1. **Thermodynamic Model (TM)** – Hills [3], 1976. assumes free phase (bubbles) separates in tissue under supersaturation gas loadings. Advocates dropout from deco schedule in the 20 ft zone originally, but later modified to put a shallow tail on the schedule;

2. **Varying Permeability Model (VPM)** – Yount [9], 1986, assumes preformed nuclei permeate blood and tissue and are excited into growth by compression-decompression. Model patterned after gel bubbles studied in the laboratory;

3. **Reduced Gradient Bubble Model (RGBM)** – Wienke [10], 1990, abandons gel parametrization of varying permeability model, and extends bubble model to repetitive, altitude, and reverse profile diving. Use EOS for bubble skins. Employed in recreational and technical diving meters, and basis for NAUI nitrox, heliox, and trimix tables;

4. **Tissue Bubble Diffusion Model (TBDM)** -- Gernhardt and Lambertsen [11], 1990, assumes gas transfer across bubble interface, and correlates growth with DCS statistics. Diffuses diving gases assumed ideal in EOS. Reportedly employed in some commercial diving sectors.

Field Testing And Diver Deep Stop Poll

Models need validation and testing. Often, strict chamber tests are not possible, economically nor otherwise, and bubble models employ a number of benchmarks and regimens to underscore viability. In addition to computer downloaded profile data, the following are some specific field data supporting bubble models and NAUI released RGBM nitrox, heliox, and trimix diving tables:

1. LANL exercises have used the RGBM (full up iterative deep stop version) for a number of years, logging some 3000+ dives on mixed gases (trimix, heliox, nitrox) with low (less than 1%) incidence of DCI on OC and RB systems deco dives with at least 2 hr SIs, and in the forward direction (deepest dives first). Such deep and decompression diving was used to build and validate the NAUI Tables;

2. NAUI Technical Diving has been diving the deep stop version for the past 25 yrs, some estimated 5000 dives, on mixed gases down to 250 *fsw*, without any alarming DCS problems

across training and actual field diving. NAUI Technical Dive Tables [12] are the result of these activities;

3. modified RGBM recreational algorithms (Haldane imbedded with bubble reduction factors limiting reverse pro-file, repetitive, and multiday diving), as coded into GAP and ABYSS software and Suunto, Mares, Dacor, UTC, Plexus, Aqwary, Atomic Aquatics, Hydrospace, Mycennae, and CressiSub decometers, boast a low DCI incidence rate of approximately 1/10,000 or less. More RGBM decompression meters, including mixed gases, are in the works. These couple closely to the NAUI Tables and software.

4. a cadre of divers and instructors in mountainous New Mexico, Utah, and Colorado have been diving the modified (Haldane imbedded again) RGBM at altitude, an estimated 450 dives, without peril. Again, not surprising since the altitude RGBM is slightly more conservative than the usual Cross correction used routinely up to about 8,000 *ft* elevation, and with estimated DCI incidence less than 1/10,000;

5. divers and instructors using bubble model decometers, tables, or NET software have been asked to report individual profiles to DAN Project Dive Exploration (Vann, Denoble and others at Duke) and to the LANL Data Bank (Wienke and O'Leary) as computer downloads;

6. *GAP, Free Phase, RGBM Simulator and ABYSS* are NET software package that offer the NAUI RGBM and have a fairly large contingent of tech divers using them without noted DCS problems or incidence spikes. Same said for RGBM Dive Planners provided to customers by the meter manufacturers listed above. *Free Phase RGBM Dive Planner* is a software package available from NAUI Headquarters. It correlates one-to-one with released NAUI Dive Tables;

7. NAUI Worldwide also released a set of tested no-group, no-calculation, no-fuss RGBM Tables for recreational sea level and altitude air and nitrox diving, with simple rules linking surface intervals, repets, and flying-after-diving. These are used in NAUI air and nitrox training;

8. WKPP dives on trimix to 300 *fsw* near 6 *hr* served to calibrate bubble models and parameters in the very extreme region (both VPM and RGBM).

There is much more [4] in field testing reports but this gives a NAUI flavor for widespread safety and usage by NAUI Instructors and Divers.

At the Deep Stop Workshop [1] in Salt Lake City in 2009, training agencies, decompression computer manufacturers and dive software vendors were queried prior to the Workshop for estimated DCS incidence rates against total dives performed with deep stops. Both recreational and technical diving is lumped together in their estimates (guesstimates if you like). Keep in mind that polling does not involve controlled testing (not pure science) and only echoes what the agencies, manufactures and vendors glean from their records and accident reports. A rough compendium of the poll follows and is denoted *total dives/DCS incidence*:

1. **Deep Stop Decompression Meters** (Suunto, Mares, Dacor, HydroSpace, UTC, Atomic Aquatics, CressiSub) – *4,000,000/47* with 750,000 meters marketed;

2. **Deep Stop Software Packages** (*ABYSS, GAP, NAUI GAP, ANDI GAP, Free Phase, NAUI RGBM Dive Planner, RGBM Simulator, CCPlanner) – 920,000/68* with 30,000 CDs marketed;

3. **Deep Stop Agency Training Dives** (NAUI, ANDI, FDF, IDF) – *1,020,000/28* as open water training activities.

One last item concerning deep stop science remains. What about controlled laboratory testing and data correlations? These are important.

Experiments

Briefly let's consider some recent tests, and how they relate to deep stops and bubble models.

Analysis of more than 16,000 actual dives by Diver's Alert Network (DAN), prompted Bennett [13] to suggest that decompression injuries are likely due to ascending too quickly. He found that the introduction of deep stops, without changing the ascent rate, reduced high bubble grades to near zero, from 30.5% without deep stops. He concluded that a deep stop at half the dive depth should reduce the critical fast gas tensions and lower the DCS incidence rate.

Marroni [14] concluded studies with DAN's European sample with much the same thought. Although he found that ascent speed itself did not reduce bubble formation, he suggested that a slowing down in the deeper phases of the dive (deep stops) should reduce bubble formation. He will be conducting further tests along those lines.

The Bennett and Marroni findings were formally incorporated into the NAUI Recreational Air and Nitrox Tables [12] in 2008, for both conventional USN and no-fuss RGBM Tables.

Brubakk and Wienke [15] found that longer decompression times are not always better when it comes to bubble formation in pigs. They found more bubbling in chamber tests when pigs were exposed to longer but shallower decompression profiles, where staged shallow decompression stops produced more bubbles than slower (deeper) linear ascents. Model correlations and calculations using the RGBM agree. Others [1] are also interesting but not included here for space and time.

More tests will develop as time passes and operational usage of deep stop (bubble) models continues and grows. A more global approach to validating models is seen in statistically correlating profile data with models throughout the dive. Single chamber or laboratory tests are restricted, expensive and limited in scope. To rectify this, a collection of global dive profiles with DCS outcomes is better. One such collection is the LANL Data Bank [8] housing deep stop data from decompression diving.

Profile Data Bank Correlations

The LANL Data Bank houses computer downloaded dive records. Records are long and taken every 5-10 *sec* underwater. Mixed gas, decompression, OC and RB records are the mainstay. Presently, some 2879 dive profiles with 23 cases of DCS are recorded in digital format. Information comes directly off decompression computers and bottom timers downloaded after diving. Diver attributes are also stored for each profile. A breakdown of deep stop dive profile numbers and DCS occurrences is given below.

Mix	Dives	DCS
OC Nitrox	344	8

RB Nitrox	550	2
All Nitrox	894	10
OC Trimix	636	4
RB Trimix	754	4
All Trimix	1410	8
OC Heliox	116	2
RB Heliox	459	3
All Heliox	575	5
Total	2879	23

Dives down to 840 *fsw* are included with the bulk of dives in the 150 – 350 *fsw* range. The incidence rate is low, 23/2879 = 0.0080 = 0.80%, and the collection process continues. The popular USN, ZHL16 , VPM and RGBM models were correlated [16] against this deep stop collection. The USN and ZHL16 models (shallow stop) correlated poorly, as expected, while the VPM and RGBM models correlated well, as also expected. These models are the mainstay of modern recreational and technical diving. And they all work and are safely used. Against a shallow stop data bank, the correlations would reverse. That is a for the future discussion.

LORE

The following discuss a number of perceptions about deep stops and trend from the foregoing discussion. Hope they are helpful.

1. *The Pyle ½ stop (ad hoc) protocols correlate with the VPM and RGBM?* No, not rigorously but, like the Bennett and Marroni prescriptions, ½ stop protocols mimic broad features of bubble models.
2. *The deep stop VPM and RGBM models can be tweaked to yield shallow stops?* Only using very strange bubbles or very large permissible bubble-dissolved gas gradients as occur with non stop diving in the shallow zones. Deep stop and shallow stop models converge for non stop diving in the recreational zones (less than 150 *fsw*).
3. *Gradient factors (GFs) applied to dissolved gas M-values mimic bubble models?* Yes, in some broad uncorrelated sense. GFs fall in the same ad hoc category as ½ stops and have never been tested nor correlated with data. GFs are a spinoff of tested and published RGBM reduction factors (RFs) for recreational diving as found in tables, meters and software. GFs are used by technical divers mostly and are often passed around by word of mouth. They reduce *M-values* at depth yielding deep stop diving schedules. To reduce *M-values,* GFs must be less than 1.
4. *Deep stop models attempt to control both bubble growth and dissolved gas buildup?* Quite so in what is called the mathematical minimax approach in restricting permissible bubble-dissolved gas gradients on the way up. That means controlling both bubble growth and dissolved gas buildup.
5. *Deep stop and shallow stop staging both work?* Yes, and safely when the staging model is correlated with meaningful actual data or tests. More on this in the next installment.

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