Toward a Predictive Algorithm for Untoward Events in Elite Breath-Hold Divers

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Preprint Citation; Clarke, J.R. 2021. Toward a predictive algorithm for untoward events in elite breath-hold divers. In: Lang MA, Van Hoesen KB (eds). Proceedings of the SDCED Breathhold Diving Colloquium, pp. xx-xx. San Diego Center of Excellence in Diving: U.C. San Diego.

Background.

Breath-hold divers (also known as freedivers) have only one diving outcome that they strive for: the successful completion of a breath-hold dive. That requires freedivers to push their bodies to their physical and physiological limits. Yet, in pursuit of the elite breath-hold divers' depth goals, occasionally those limits are exceeded, resulting in a breath-hold diver's "untoward event."

Breath-Hold diver mishaps share a remarkable similarity with the type of incidents that mar the safety and performance of U.S. Navy divers. When diving using underwater breathing apparatus (UBA), mishaps or "untoward events" are influenced by environmental and physiological factors such as depth and exercise rate (Clarke, 1989a and b).

There are two rare but significant physiological events for Navy and commercial divers. One event is a feeling of extreme breathlessness, which leads to a diver suddenly stopping his underwater work. The other and potentially fatal event is a sudden and unexpected loss of consciousness.

Just as in the case of a working diver using UBA, the breath-hold diver's "event" can lead to a cessation of swimming effort due to loss of muscular coordination (loss of motor control or LMC, Lindholm, 2007), or to an unexpected loss of consciousness (Lindholm and Lundgren, 2006). In breath-hold diving competitions, untoward events are relatively common, occurring in 6-10% of dives (Lindholm, 2007).

These freediving neurological events have also been called Negative Neurological Events, NNEs, (Ridgeway and McFarland, 2006). Thanks to safety procedures established for both forms of diving, with and without breathing apparatus, untoward events are not often fatal…but they can be.

Like decompression sickness, untoward events in both forms of diving are probabilistic. That means that given enough opportunity, even improbable events will occur. The next section reviews the probability of everyday events in military diving and breath-hold diving.

Mathematical analysis of U.S. Navy diving data

Results from manned deep diving experiments at two Navy laboratories were collected and applied to statistical models using a model fitting technique called maximum likelihood (Clarke et al., 1989a and b; Clarke 1992, 2002). The result was a plot of dive successes and dive failures (Figure 1). A data point represented each dive. The point's X-coordinate is gas density, and the Y-value is maximum peak to peak mouth pressure (ΔP). Unsuccessful or untoward dives were colored red, and successful dives were colored cyan (Clarke 2002.)

As seen in Figure 1, dive failures tended to occur above a threshold line relating ΔP and inhaled gas density. The greater the distance above that threshold line, the greater the probability that one or more dive team members would have a "bad dive" or an untoward event.

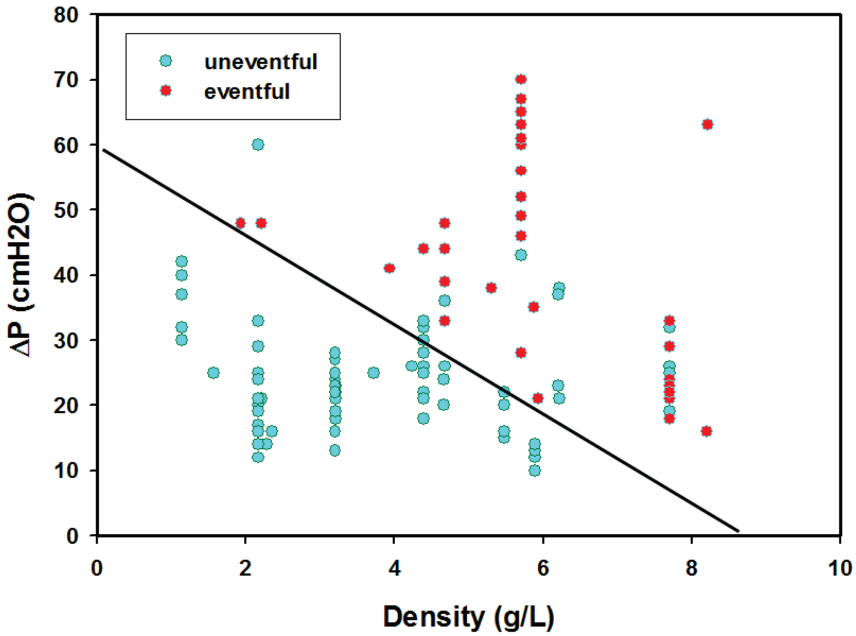

Figure 1. The demarcation between eventful and uneventful U.S. Navy dives involving heavy exercise. As gas density increased, the peak-to-peak mouth pressure required to keep a dive safe decreased towards zero. (Clarke, 2002)

In Figure 1, ΔP in units of cmH_2O reflects how hard a diver is working and breathing. The line separating normal and bad diving events shows that the threshold between success and failure is high at low gas density (shallow depth). However, that same threshold becomes increasingly narrow as das density and depth increase.

At a gas density of approximately 8.5 $g \cdot L^{-1}$ the margin of safety becomes vanishingly small. The model predicts that hard work cannot be conducted, even with no external breathing impedance. For example, NEDU's deepest dive was at 1800 fsw (548 msw) in 1979, a dive that temporarily confined some divers to their bunks due to respiratory and other difficulties. The estimated gas density for that dive was 9.3 $g \cdot L^{-1}$.

Figure 2 shows some of the factors that can influence the safety of a diver using UBA. Those factors are ventilation rate ($\dot{V}E$), respiratory impedance (Z or "work of breathing" of breathing apparatus), work rate (W), CO_2 production ($\dot{V}CO_2$), and dyspnea or breathlessness (Dysp.) Fatigue of the primary respiratory muscle, the diaphragm (Diaph), can result in loss of consciousness (LOC).

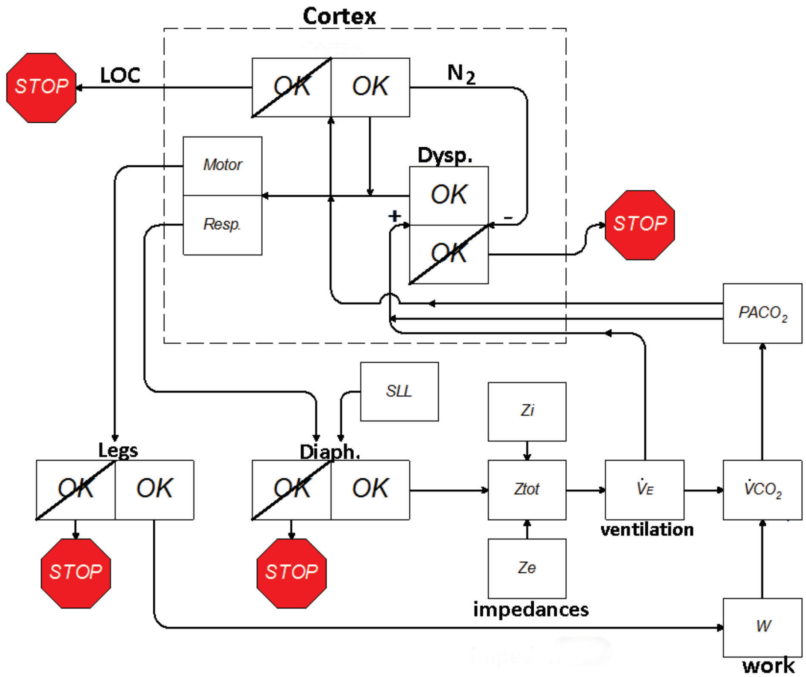

Figure 2. The network of physiological dive failure modes due to respiratory impedance (Z). SLL is static lung loading, Zi = internal impedance, Ze = external impedance, Ztot = total impedance, W = work, LOC = loss of consciousness. Details are in Clarke (1999).

Figure 2 illustrates that many factors can contribute to the probability that a UBA diver will safely complete the mission or not.

Figure 3 plots the resultant estimates of event probabilities in diving with UBA versus ΔP (peak to peak mouth pressure) for various gas densities (in $g \cdot L^{-1}$). As ΔP increases, the probability of an untoward event increases in a curvilinear manner. That probability is also negatively affected by gas density.

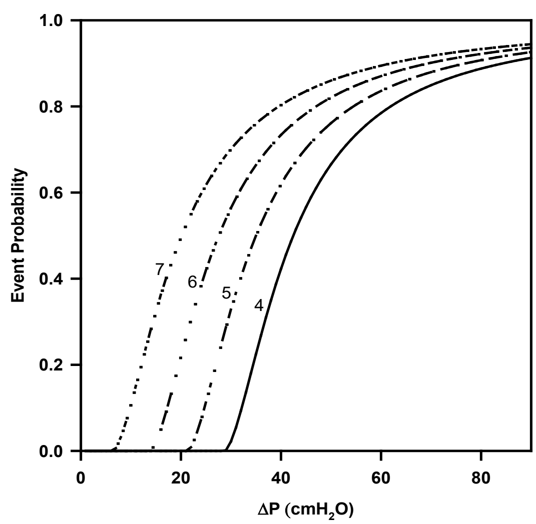

Figure 3. Estimates of untoward event probability in U.S. Navy data as a function of ΔP (peak to peak mouth pressure) and gas densities ranging from 4 to 7 $g \cdot L^{-1}$ (Clarke, 1999).

Application to Breath-Hold Diving

By substituting variables more appropriate to breath-hold diving, we see that mathematically breath-hold diving should share much in common with UBA diving. The appropriate substitution would be oxygen consumption substituted for ΔP and diving depth for gas density. While the rationale for the latter substitution may be intuitive, the former substitution may be less clear. However, it is an appropriate replacement because the harder a diver works, the more they breathe.

When breathing equipment imposes a resistance (impedance) to breathing, respiratory pressures in the lungs increase. Oxygen consumption correlates to how hard a diver is working, and in UBA diving, ΔP is directly correlated to that work. However, in breath-hold diving, there is by definition no breathing, and thus no ΔP, but the indicator of that work, oxygen consumption, still exists.

With those substitutions made, it makes sense that the faster oxygen is consumed, and the deeper the dive, the higher the probability of an unsuccessful breath-hold dive. That notion is explained below.

Theory

The math behind breath-hold diving is a distance = velocity x time problem, with the added concern for the amount of "fuel in the gas tank." Accordingly,

$$Dmax = R \cdot Tmax \tag{1}$$

where Dmax is the maximum depth obtainable on a given dive, and Tmax is the maximum time available for the dive based on fuel consumption and the size of the fuel tank. In breath-hold diving terms, fuel consumption is oxygen consumption. The fuel tank size is the amount of oxygen immediately available for maintaining arterial oxygen levels (PaO_2). R is the composite of the average rate of travel and other variables, most of them physiological.

$$Dmax = R \cdot \frac{VO_2}{\dot{V}O_2} \tag{2}$$

VO_2 is the volume of oxygen in the lungs and blood available for gas exchange, and $\dot{V}O_2$ is the rate of oxygen consumption. In automotive terms, VO_2 is the size of the gas tank in liters, and $\dot{V}O_2$ is the fuel consumption rate in liters per minute.

Obviously, the smaller the R, the shallower the maximum depth achievable.

Simulation

In reality, there are no single values for R, VO_2, or $\dot{V}O_2$. For this exercise, those values were assumed to be randomly distributed in a Gaussian or "normal" distribution. Students often refer to such distributions as the "bell curve."

For the sake of this demonstration, the mean of available oxygen in a breath-hold diver was taken as 1.68 L ± 0.5 L, (mean ± S.D., standard deviation). Oxygen consumption, $\dot{V}O_2$, was assumed to be 0.5 ± 0.2 L/min. The actual values are unimportant for this demonstration and will hopefully be refined by future measurements in breath-hold diving competitions.

These values of mean and S.D. were then operated upon by a random number generator within Sigmaplot, (version 11.0, Systat Software), with the selected numbers constrained to the Gaussian ("normal") distribution. By this Monte Carlo process, 1000 "breath-hold dives" were created for the purposes of the simulation.

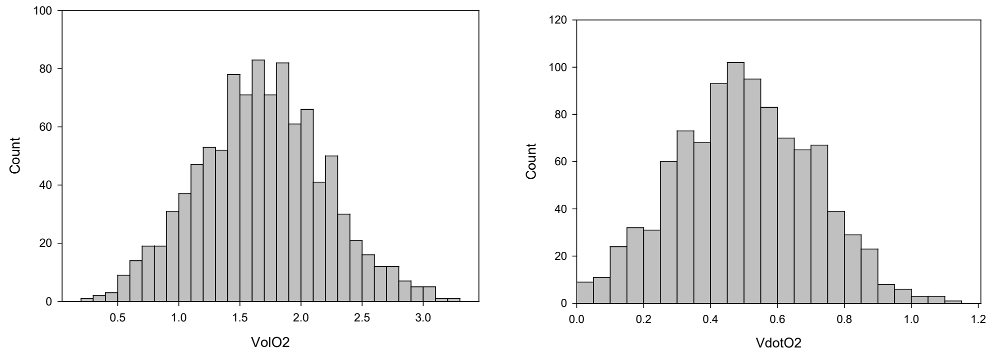

Figure 4. The left panel is an example distribution of 1000 samples for VO_2 (labeled $VolO_2$), the volume of available oxygen in liters. In the right panel is the distribution for the rate of oxygen consumption in liters per minute.

R was defined as a lumped variable composed of the following: average rate of travel (down and back), and the so-called diving reflex consisting of a slowing of heart rate (bradycardia) during the dive, relocation of blood from the periphery to the thorax to counter lung squeeze, and the rate of increase and decrease in arterial oxygen pressure as a function of depth. Anderson et al. (2008) concluded that “the augmented diving response during face immersion apneas is associated with slower reduction of the pulmonary (and arterial) oxygen store, probably delaying the occurrence of a hypoxic syncope.” In other words, wetting of the face may help prolong useful consciousness during a breath-hold. De Bruijn et al. (2009) also suggested an oxygen-conserving effect of facial immersion.

Other physical and physiological factors may be associated with R, dependent upon the diver’s rate of descent and ascent in ways not yet understood.

<u>Result</u>

For didactic purposes, before moving to the final result, R was fixed at 10 m/min in Figure 5. Each dot in Figure 5 represents an estimate of total dive time and maximum depth for 1000 randomly generated “dives,” where the relations defining the dive are defined by Equation (2). Based on the assumed distributions of VO_2 and $\dot{V}O_2$, there are very few dives with a very short duration (less than a minute). Likewise, there were a small number of dives with durations longer than 8 min or so.

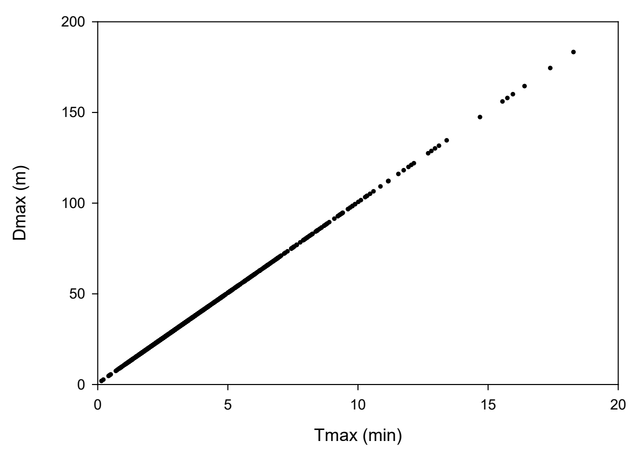

Figure 5. Solutions of Equation (2) assuming a fixed R, and allowing VO_2 and $\dot{V}O_2$ to vary as shown in Figure 4. Each dot represents the results of a single simulated breath-hold dive.

Since R determines the slope of the Tmax-Dmax line, and was fixed in this example, the dots representing individual breath-hold dives fall on a straight line.

However, that situation changes dramatically when the compound variable R is distributed. Instead of R remaining fixed at 10 m/min as in Figure 5, we now arbitrarily assume it would vary in keeping with the Gaussian distribution with a mean of 10, and a standard deviation of 2 meters/min.

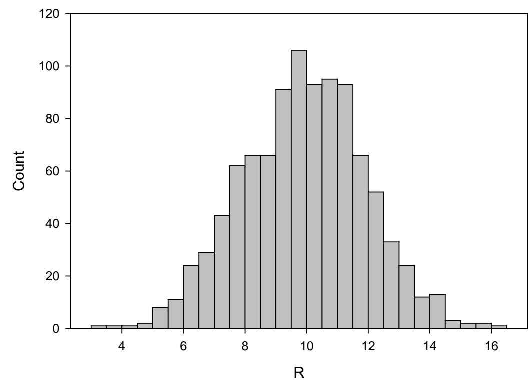

Figure 6. Distributed R, based on an assumed mean of 10 ± 2 m/min.

While Tmax represents "fuel" storage, in terms of oxygen storage divided by oxygen consumption, R represents the slope of the relationship relating Tmax and Dmax. The straight red line in Figure 7 is the prediction for dive time and maximum depth assuming the mean values for VO_2, $\dot{V}O_2$ and R.

The modeled variance of R translates into many different "slopes" of the Dmax-Tmax relationship (Figure 7), so instead of yielding a straight-line relationship, the modeled data spreads out; the greater the Tmax, the greater the spread in Dmax. Unfortunately, therein lies the problem for breath-hold divers.

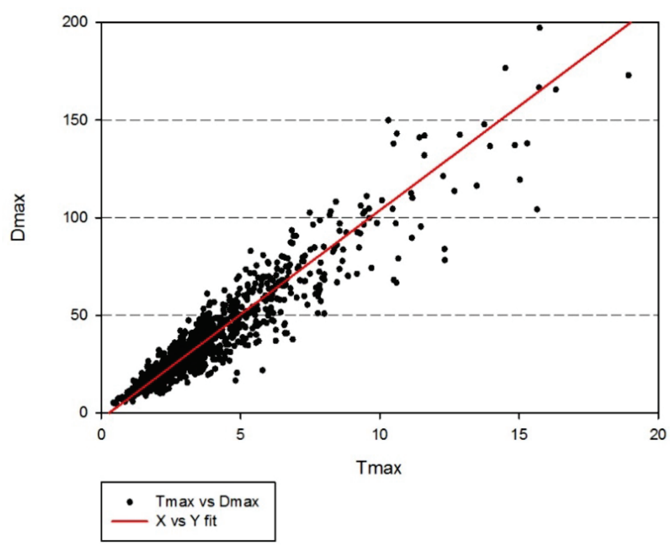

Figure 7. Solutions of Equation (2) allowing R to vary as in Figure 6, and allowing VO_2 and $\dot{V}O_2$ to vary as shown in Figure 4. Each dot represents the results of a single simulated breath-hold dive.

<u>Risk</u>

One way to estimate risk to a breath-hold diver is by the difference between their desired Dmax and their actual Dmax. If we assume that the red line in Figure 7 represents a breath-hold diver's expectation at the beginning of the dive, and the dots in Figure 7 show their actual Dmax for their given time underwater, then it's logical to think of the difference as an indicator of "risk" for that dive. If the difference in actual and expected depth is great, then the expected risk is great as well.

Figure 8 illustrates the same simulated dataset as Figure 7 but plots Tmax versus the difference between expected (according to the red line in Figure 7) and actual depth (Dmax). The graph shows that the longer the dive is expected to last (Tmax is long), the greater the probability that random events can generate risk for the breath-hold diver.

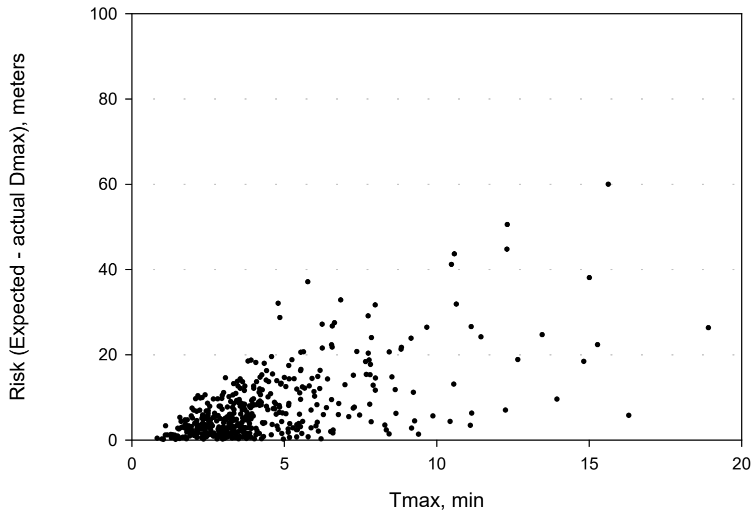

Figure 8. Risk as a function of breath-hold dive expectations and reality.

A mismatch in expectations and the reality of a few meters may not cause concern, especially with safety divers on standby. However, a mismatch of 20 to 40 meters or more could be very concerning. According to this particular example, a large mismatch in the expectation and the actual dive is likely to be rare but potentially deadly.

In general, just as was found in the case of divers using underwater breathing apparatus (Clarke, 1992, 2002), the greater the discrepancy between the intended dive result and the actual physiological limits, the greater the risk to the diver. In other words, the more likely it is that the diver will experience an untoward event, namely, loss of motor control or loss of consciousness.

Conclusion

This paper illustrates how personal risk to a breath-hold diver can accumulate through random factors. This simple mathematical model suggests that there seems to be no way to maintain the same margin of safety on a long, deep dive as on a shallow dive, no matter the amount of training and practice.

Despite that ominous warning, breath-hold records continue to be set by elite freedivers. That suggests to this writer that record-holders either have an exceptional physiology or exceptional control over their physiology. It also suggests that competition safety procedures have been honed to the point where almost any untoward freediving event can be safely managed.

Perspective

Having lost a military friend to a non-competition, solo freedive, I am painfully aware that untrained freedivers diving under poorly controlled conditions can succumb to the randomness of a body that betrays them.

Likewise, I've watched a determined and well-trained underwater swimmer wash out of military training simply because his oxygen stores were not up to norms. He did all he could physically, until he lost consciousness.

Unfortunately, underwater, there is no "A" for effort.

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