Dive Computer Considerations

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Dive computers are standard pieces of equipment in recreational, scientific, and military diving. However, many commercial diving regulations state that they cannot be used to determine decompression status. The dive computer's ability to continually update decompression status results in more efficient use of dive time. Because few human subject studies have been performed to validate dive computer decompression algorithms, there needs to be a method to evaluate the associated decompression risk for commercial diving use. This evaluation protocol would approve, or reject, specific decompression algorithms. While this protocol could take many forms, this paper focuses on the performance of dive computers exposed to profiles with known human subject results. Approximate risks can be determined by running dive computers against dive profiles with high, moderate, or low risk. Dive computer responses to the same dive profile can vary greatly and decompression algorithms can be assigned levels of risk. For a "high risk" decompression dive, all of the computers went into decompression violation during the decompression (assigned "unknown risk"). If this comparison technique is merged with decompression risk models, different risk estimates could be assigned to the various decompression algorithms over a wide range of dives. The inclusion of dive computers with acceptable decompression algorithms in the commercial diving toolbox would increase the efficiency in multi-level diving operations.

INTRODUCTION

In less than 30 years, commercially viable electronic dive computers have almost completely eclipsed the teaching and use of decompression tables in recreational dive planning and execution. Some recreational training agencies no longer teach the use of decompression tables, training their students from the beginning to rely solely on dive computers. In scientific diving, guidelines (Lang and Hamilton, 1989) were put in place that allow researchers to utilize dive computers in their work, and dive computers have been specifically developed for military diving operations (Butler and Southerland, 2001; Gault, 2006; 2008). However, in commercial diving, dive computers have to date not been utilized to the same extent.

The objective of this workshop is to discuss the validation of dive computers for use by working divers, with an emphasis on inspection and repair dives done in support of Norway's salmon fisheries. Currently these divers must follow the Norwegian Diving and Treatment Tables (Arntzen et al., 2008). The Dive Computer section of this document states:

> "Commercial Diving: In principle, a dive computer will work equally well for commercial dives. However, for these dives the diving supervisor is responsible for dive management, depth/time control and decompression supervision according to

prepared procedures. Norwegian regulations require the use of Norwegian Diving and Treatment Tables and these regulations do not allow basing the depth solely on the diver's depth gauge. Further, since most commercial divers spend the entire bottom time at a fixed depth, there is little advantage in using a dive computer. On the contrary, due to the computer's typical extra conservatism, such dive profiles will tend to shorten the bottom time and increase the decompression obligation when using dive computers compared to the use of conventional decompression tables and techniques."

Realistically, dive computers could provide benefits for those divers who do not spend their entire bottom time at a fixed depth. The current diving practice within the salmon pen diving population is some type of multi-level dive with work as they ascend (A. Møllerløkken, pers. comm.) With past estimates of at least 35,000 dives per year on fish farms in Norway (Brubakk, 2001), the ability to use dive computers should have a major impact on improving the efficiency of these dives.

Even though regulations do not permit the use of dive computers in commercial operations at this time, divers have been using computers for years (A. Møllerløkken, pers. comm.) The Norwegian Labor Directorate would like to permit the use of dive computers in their regulations so that workers can improve efficiency in the water when performing multi-level dives, as long as the dives can be as safe as table dives (A. Møllerløkken, pers. comm.) This workshop attempts to answer the question how the safety of decompression algorithms programmed into dive computers can be validated in order to provide reasonable guidance to commercial divers regarding acceptable dive computers and their operational use.

This review addresses how dive computers work, the benefits and risks of dive computer use, potential methods to assess/validate dive computer algorithms, and operational issues that should be considered in determining the efficacy of dive computer use in commercial diving operations.

HOW DIVE COMPUTERS WORK

Dive computers are devices that can be programmed with a variety of decompression models (algorithms) and are able to calculate decompression status on the fly using the actual dive profile, thus freeing divers from the limitations of decompression table formats.

The dive computer senses depth every few seconds and calculates the decompression status from its programmed decompression algorithm. Some dive computers utilize additional variables in their calculations (i.e., temperature, air consumption, heart rate and profile sequence). Once the decompression status is calculated, it is displayed to the diver and the dive computer starts the calculation cycle over again. The diver will then use the calculated decompression status to make decisions about the dive while, hopefully, understanding the limitations of the dive computer. The major benefit of this flexibility is that it allows multi-level dive calculations, without the limitations of the "maximum depth for the entire bottom time" rule that accompany tables. For example, Figure 1 shows a dive to 25 msw for 40 min (the 80 fsw no-decompression limit on the USN 1999 Tables). A dive computer programmed with the table model taken to 25 msw for 35 min would show approximately 5 min of no-decompression time remaining, because the dive performed is the same assumed by the tables. If the computer was taken on the multi-level dive profile shown in Figure 1, then 35 min into the dive it would indicate approximately 135 min of remaining no-decompression time because it is basing its calculation on the actual dive profile and the depth of the dive computer at that time (13 msw). A diver using the tables on the same multi-level dive would only have 5 min of no-decompression time available since they must assume that their entire bottom time was spent at 25 msw.

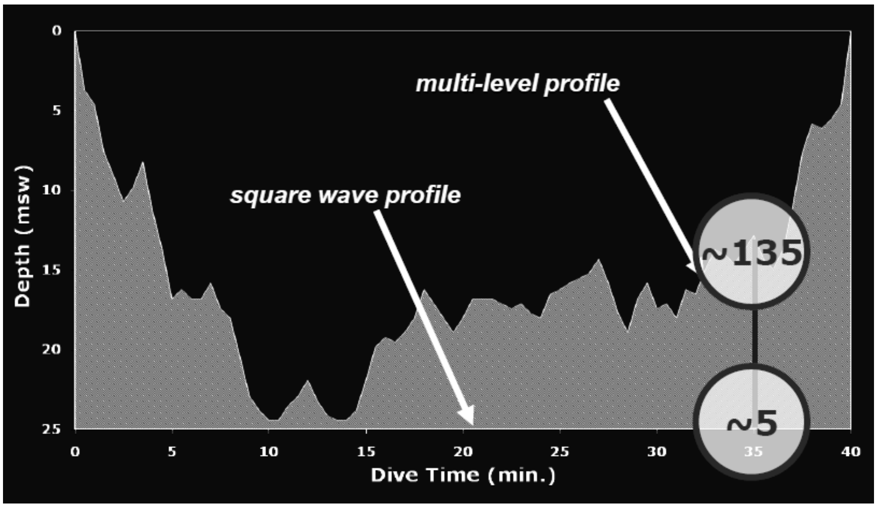

Figure 1. Square-wave (5 min remaining no-deco time) versus actual multi-level profile (135 min remaining no-deco time).

Other benefits include the decompression calculations based on the actual depth of the dive, without the need to round to the next deeper depth calculation, and repetitive dives based on the entirety of the decompression model. Most decompression tables use only one compartment in the model to calculate repetitive dive allowances. Dive computers have accurate depth readings (±0.5 msw) and provide the diver with information continuously throughout the dive, i.e., decompression status, depth, dive time, maximum depth, ascent rate indication, temperature, and if the computer is air-integrated, cylinder pressure and remaining air time will also be shown. Following the dive, the dive computer maintains a log of the dive and, in most computers, detailed dive profile information. A system set up to collect dive profile information from commercial diving operations would allow for feedback and modification of protocols established for dive computer use.

In order to gain the benefits of dive computer use the diver gives up some of the safety margins built into decompression tables. The assumption that the entire dive was spent at the maximum depth adds some safety to the diver who has performed a multi-level dive. Likewise, entering the table at the next deeper depth and following tested repetitive dive schedules that are based on a single compartment of the underlying decompression model also adds safety. Additionally, there is the potential for dive computer electrical or mechanical failure and user error. But the primary issue addressed by this workshop is the validation of the safety of dive computers. Since there has been very limited human subjects testing, most support for dive computer use has been due to their operational success in the recreational and scientific diving communities. However, operational safety does not translate to decompression algorithm safety since most dives performed do not push the algorithms to their limits.

DIVE PROFILES: COMPUTER VERSUS TABLE

To gain an understanding of some of the operational benefits that result from dive computer use over table use, simulated dives were generated using the decompression software package GAP 2.3 using the ZH-L16C decompression algorithm at its most liberal setting. The ZH-L16C model is a derivation of Bühlmann's (1984) Swiss decompression model, of which variants are used in many dive computers and decompression software packages. The GAP software generated decompression requirements approximately equal to the Norwegian Decompression Tables for a square wave dive to 45 msw for 25 min (Figure 2). Therefore, the risk of decompression sickness, pDCS of these two dive profiles should be approximately equal.

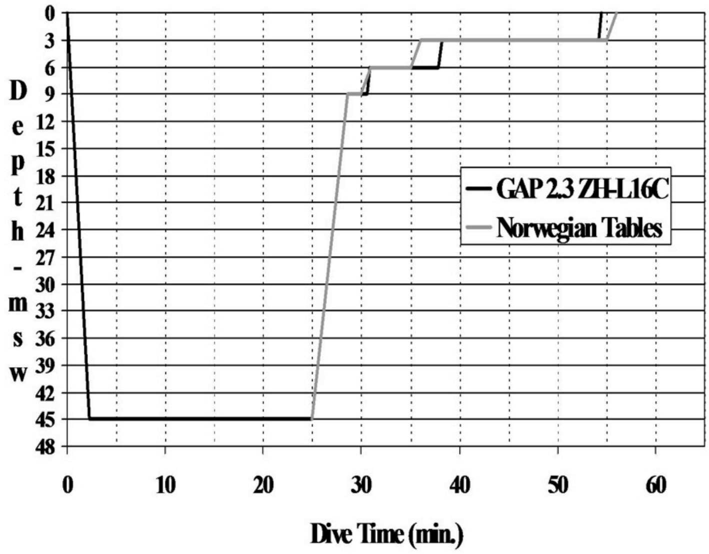

Figure 2. Square-wave dive decompression requirements, Model versus Table.
$p(DCS_{model}) \approx p(DCS_{table})$

A simulated inspection dive starting at 45 msw with a continuous slow ascent resulting in the same 25 min of bottom time, could, according to the model, be performed without going into decompression. Using the tables, the diver would be required to assume that the entire bottom time was spent at 45 msw, resulting in 30 min of required decompression upon reaching 9 msw (Figure 3).

In this case the pDCS for the diver following the tables would be less than the diver using a dive computer that allowed the continuous ascent no-decompression dive. What that difference is and whether it is significant is at the heart of the risk/benefit analysis being considered at this workshop.

While the inclusion of the type of continuous ascent dive shown in Figure 3 or some similar multi-level dive with equivalent bottom time seems reasonable, the ability to use dive computers could lead to other types of dive profiles where the difference in risks between model and table could become much greater. Figures 4 and Figure 5 show two types of no-decompression dive profiles that the model would allow.

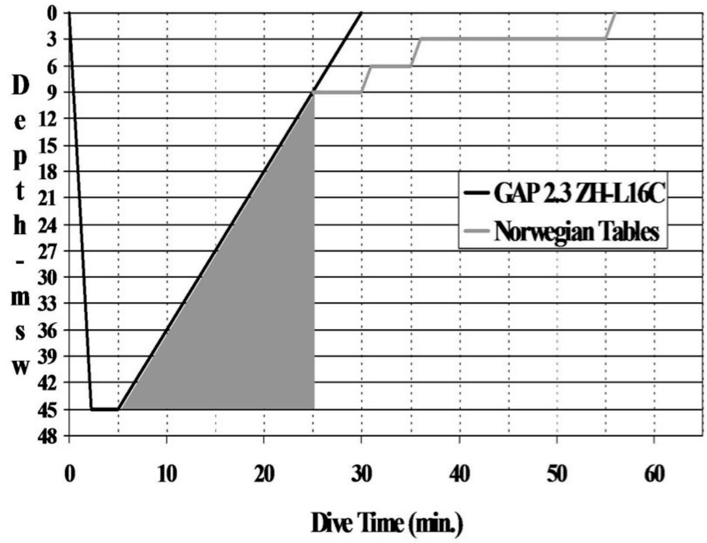

Figure 3. Continuous ascent decompression requirements, Model versus Table
p(DCS$_{model}$) > p(DCS$_{table}$)

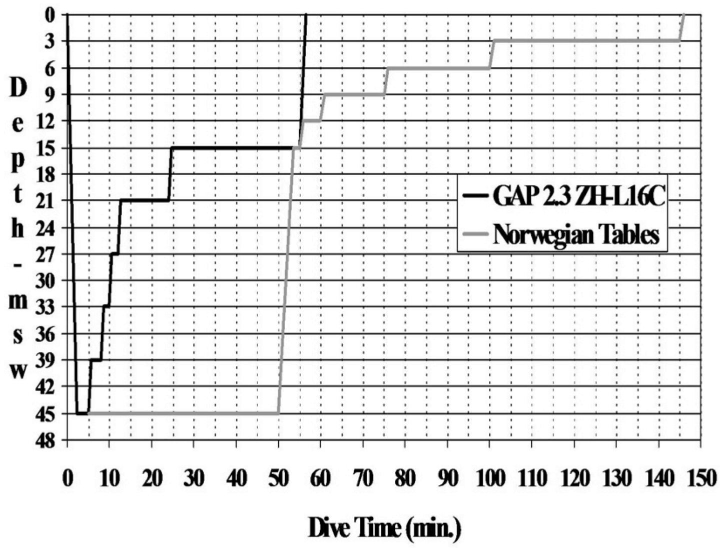

Figure 4. Multi-level no-D dive pushed to model limits, Model versus Table
p(DCS$_{model}$) >> p(DCS$_{table}$)

Figure 4 is a multi-level dive that runs the no-decompression time at each level (except the last) down to less than 1 min. This technique produces a 45 msw/55 min no-decompression dive. While the model does not require any decompression, the Norwegian tables would require 95 min of decompression. In this case the risk disparity would be much greater than the continuous ascent dive in Figure 3.

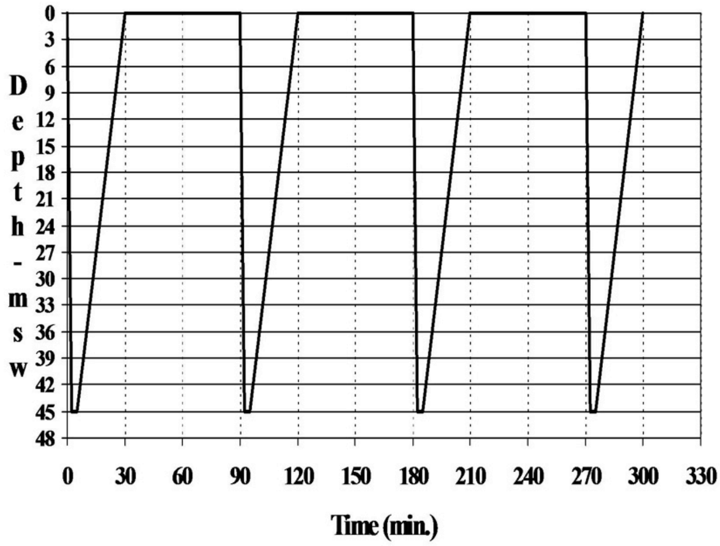

Figure 5. Repetitive deep dives allowed by model.

Other types of no-decompression dives, like the repetitive deep dive series shown in Figure 5 may be allowed by some dive computers. These dives greatly exceed decompression table limits, but do they produce an unacceptable risk of decompression sickness?

There are many ways to assess the risk of the decompression algorithms programmed into dive computers. These include human subjects' tests, monitored pilot programs, comparison to dives with know decompression sickness risk, comparison to risk models, etc. The focus here is on the performance of dive computers when exposed to profiles with known human subject results.

PERFORMANCE OF DCs EXPOSED TO PROFILES WITH KNOWN HUMAN SUBJECT RESULTS

Ongoing studies at the USC Catalina Hyperbaric Chamber ran dive computers against a group of dive profiles that have been tested with human subjects, or have a large number of operational dives (Huggins, 2004). Profiles were rated as "high risk" if they produced cases of DCS or high Doppler bubble scores, "moderate risk" if there was no DCS and moderate Doppler bubble scores, and "low" risk if there was no DCS and no or low Doppler bubbles detected. Dive computer decompression responses to the profiles were compared to the decompression schedules. Conclusions about the decompression algorithm were based on the dive computer's response to the profile (Table 1).

The profiles the dive computers were tested against include two "low risk" multi-level dives (40 msw and 20 msw maximum depths) from the PADI/DSAT RDP test series (Hamilton et al., 1994), a "moderate risk" short 50 msw decompression orientation dive performed at the Catalina Hyperbaric Chamber, and a "high risk" long 36 msw decompression dive from a DCIEM air decompression study (Nishi and Lauchner, 1984).

Table 1. Risk rating versus dive computer response to profile.

Dive Computer Decompression Requirements	Profile Risk Rating		
	“High” Risk DCS High VGE	“Moderate” Risk No DCS Low to Moderate VGE	“Low” Risk No DCS No VGE
Less than tested profile	Algorithm too Liberal High Risk	Algorithm too Liberal Moderate Risk	Algorithm risk greater than profile risk Unknown Risk
Greater than tested profile	Algorithm risk less than profile risk Unknown Risk	Algorithm risk less than profile risk Unknown Risk	Algorithm Conservative

The dive computers were immersed in water inside the chamber and the profile was run. Remaining no-decompression times, or required total decompression times, were recorded from each computer 1 min prior to departure from each depth in the profile. Results from the 20 msw multi-level no-decompression dive showed a range of responses from 20 min of remaining no-decompression time to 19 min of required decompression time just prior to the final ascent. The results for the 40 msw multi-level no-decompression dive were similar, 26 min of no-decompression time remaining to 15 min of required decompression time (Figure 6).

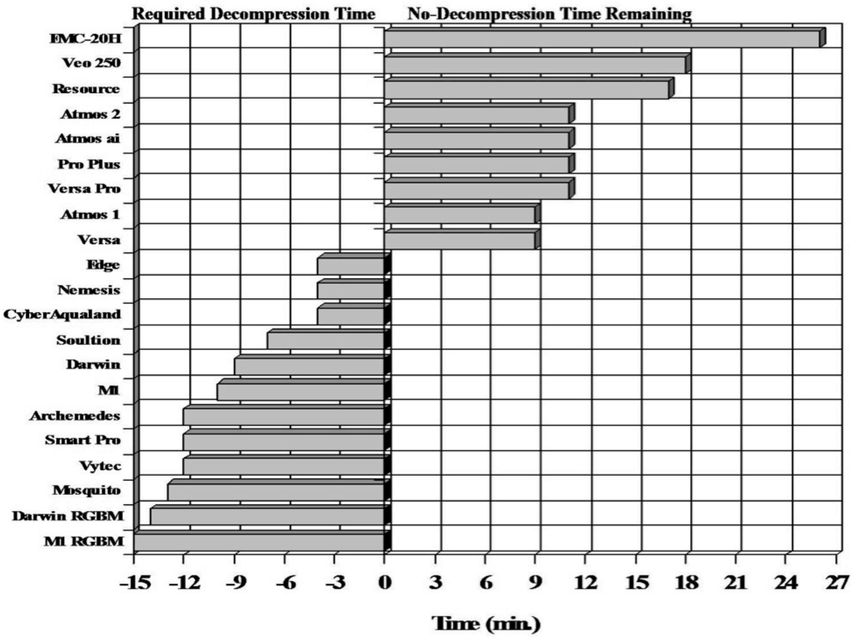

Figure 6. Responses of dive computers to 40 msw no-decompression multi-level dive prior to ascent from 15 msw.

On the “high risk” decompression dive, none of the computers tested would allow the profile to be performed. All of them went into decompression violation at some point while following the profile. On the “moderate risk” decompression dive, all of the computers tested cleared their decompression requirements within 4.5 min of reaching 10 msw. According to the computers, there was no need to continue with the 6 min stop at 10 msw, 7 min stop at 6 msw and 10 min oxygen stop at 3 msw.

For the no-decompression multi-level dives, the dive computers that required additional decompression from the dives were ranked "low risk." For the dive computers that allowed more remaining no-decompression time, no assessment of the risk could be made, since the outcome of following these dive computers to their limits has not been tested.

None of the computers received a "high risk" rating since none of the decompression algorithms allowed the "high risk" decompression dive to be performed. What is unknown is the risk associated with following the dive computer decompression schedules, since those profiles have not been tested. However, all received a "moderate risk" rating when compared to the standard Catalina Hyperbaric Chamber 50 msw orientation dive. Response to the 50 msw dive indicates that more conservative dive computer algorithms would be appropriate for short deep decompression dives. Again, it is unknown what the actual risk would be if the shorter dive computer decompression schedules were followed, because they have not been tested.

COMPARATIVE ASSESSMENT AND VALIDATION

Establishing a battery of previously tested dive profiles against which to run dive computer decompression algorithms would permit evaluation of decompression algorithms without the need of human subjects' tests and could provide a rudimentary baseline for dive computer comparisons. In Table 1 half of the cells indicate "unknown risk". Estimates of these unknown risks could be made without human subjects' tests by analyzing the decompression requirements from the computers with decompression risk models (Nishi and Lauchner, 1984; Gerth and Thalmann, 2000). This would allow general and relative risks to be computed for dive computer responses and the previously tested dive profiles.

The following is a proposed protocol for assessing the risk of dive computer algorithms for use in commercial diving:

1. Select profiles that have been tested and have known outcomes (high, moderate, and low risk) similar to operational dives: Inspection dives, cleaning dives, repair dives;
2. Select a risk model that estimates pDCS values in line with the dive profile test results;
3. Run computers against the test profiles;
4. Assess general computer response ("high", "moderate", "low", or unknown risk);
5. Use risk model to calculate pDCS of the dive computer decompression schedules; and,
6. Determine if the pDCS risks associated with the dive computer for this type of profile are acceptable.

OPERATIONAL CONSIDERATIONS

If the decompression algorithm in a family of dive computers is considered to be acceptable for commercial diving operations, with or without additional usage guidelines, then there are operational issues that need to be considered:

1. Is the dive computer simple to operate? If it is too complicated to operate then it will probably not gain acceptance.
2. Can the display be easily read in low visibility conditions? If the computer cannot be read on low visibility working dives then it cannot be effectively used.
3. Is the display clear and easily understood? Since some dives in the net pens exceed 39 msw on air (A. Møllerløkken, pers. comm.) if the dive computer display is not clear and easy to understand, the result could be confusion while trying to make decisions, especially while suffering from nitrogen narcosis.

4. Can the decompression algorithm be adjusted to more conservative settings? Divers may want to add conservatism to their diving practices and many computers allow adjustment.
5. Is the dive computer easy to download to collect profile data? If follow-up analysis of dives performed with dive computers is to be done, then the dive computer downloading process should be simple and consistent. Many frustrating hours have been spent trying to download dive computers worn by diving accident victims and their buddies. Often the download is successful after repeated attempts, but sometimes not. To date, the easiest and most consistent download technique is wireless infrared (IR) data transfer. Other wireless techniques like Bluetooth may make profile downloading easier.

CONCLUSIONS

Dive computers are used to safely calculate decompression schedules in recreational, scientific, and military diving operations. There is no reason to assume that they cannot be valuable tools for commercial diving operations, especially on multi-level dives. Comparing dive computer responses to tested dive profiles is one of many ways to assess decompression algorithm risk and validate acceptable safety levels for commercial operations. The inclusion of dive computers with acceptable decompression algorithms in the commercial diving toolbox should greatly increase the efficiency of multi-level dives of the type done on fish farm pens.

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