A New Decompression Model To Increase Safety For Dive Computers

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Abstract

Today, the dive computer is a safe instrument. Nevertheless, improvements are possible for certain risk situations.

The new advanced decompression model ZH-L8 ADT is able to increase safety for cold water diving, exertion, repetitive- and jojo-diving and violations during the decompression procedure. This is possible by the introduction of variable blood perfusions in muscle- and skin-tissues and the integration of an algorythm for the formation and reduction of microbubbles. The variable perfusion and/or the obstruction of local perfusion due to the presence of microbubbles affect the nitrogen saturation and the tolerated ambient pressure.

A new generation of dive computers will use this model. Skin temperature is estimated according to water temperature and time. Workload is measured by monitoring the respiration. Microbubble formation is mainly based on the pressure/time profile and physical and physiological data.

The new computers are able to record detailed dive data. Therefore, the model could be verified by recording real dive data. Today, the data collection includes a large amount of real dives and controlled experiments. The evaluation of the data confirms the power of the new model.

1. Introduction

This paper presents an advanced adaptive decompression model for dive computers. The calculation model was developed with the help and cooperation of the diving physiologist Prof. A.A. Bühlmann. The presented model will increase security for diving by using many new features which allow for the very first time to calculate decompression data, depending on the diver's behavior.

If a diver avoids risk situations, he will profit by a decompression procedure that is similar to what he did until today. If the diver runs in risk situations or if he behaves in an incorrect way, the decompression will automatically change in order to prevent the diver from a possible injury.

Let us first have a short look at safety in diving today. Some statistic data will explain the motivation for the introduction of the new adaptive model:

2. Safety today

2.1. Survey

Today, the incidence rate for diving is very low. 1991, the Divers Alert Network (DAN) estimates an decompression- (DCS) and arterial gas embolism (AGE) incident rate of 0.07%, which is for example lower then for swimming or for water skiing [1]. 1991, DAN Europa estimates an DCS incident rate of 0.009% [2]. Within a 4 year period from 1989 to 1992, the number was 0.013%. 1992, the British Sub-Aqua Club (BSAC) estimates one incident on 30'000 dives [3].

About one half of all incidents are different accidents like drowning, circulation failure, all kinds of barotrauma, mechanical injuries, different illnesses and more. Some injuries like barotrauma, can be influenced by monitoring ascent rate and air supply. The other half of the injuries are decompression incidents (DCS) and arterial gas embolism (AGE).

2.2. Decompression analysis

Dive computers follow the actual dive profile very closely and calculate the decompression accordingly. The dive table will usually indicate a decompression, which is much longer due to the simplifications. Many people believe, that the table's longer decompression will extend the safety margins for DCS. However, one half of all decompression sickness cases occur within table limits. The statistics do not indicate a higher DCS risk for computer divers, although the decompression is usually shorter.

It seems therefore, that a general, more conservative decompression does not reduce the DCS incident rate. Why? There are some hypotheses for that:

- The so called "safer" table indications are still insufficient to reduce the incident rate significantly. In this case, a much larger extension of decompression times would be needed to increase safety. The vast majority of the divers would therefore be faced with unrealistically long decompression times. But only a very small percentage would actually need them. Few divers like to stay 5 minutes at the bottom and spend the rest of their dive time hanging around the anchor chain doing decompression...
- The majority of the remaining DCS cases might be caused by a right-to-left shunt, for instance a Patent Foramen Ovale (PFO), which allows microbubbles to pass into the arterial system. Studies show, that up to 30% of the people live with a PFO of variable size [4] [5]. To prevent decompression incidents due to a shunt, we would need a decompression profile that prevents the formation of any microbubbles. Doppler measurements show, that bubble formation can hardly be prevented, even when a diver ascends extremely slow. Following such an ascent, the diver will not suffer from DCS, but be out of air or frozen before he surfaces.

It seems that a general, more conservative decompression is either not practicable because it is too long, or doesn't show a sufficient reduction of DCS. Should we therefore simply accept the remaining DCS rate? Let's have a closer look at the statistics which name the main situations involving DCS cases.

The risk situations are about the same for table users and dive computer users. Tables and computers currently used do not consider these situations (see box below).

If we could calculate better what is really going on in the divers body in such risk situations, we could follow closely the body's adaptation to work, cold water and bubble formation and react accordingly. With such a model, we would be able to reduce the DCS risk without extending decompression times in general.

We have been working on this problem for a long time. Prof. Bühlmann with his wide experience in diving medicine, provided the physiological know how, whereas we developed the model. I would like to introduce you now to the model called ZH-L8 ADT (ZH=Zürich, L=linear, 8=tissue number, ADT=adaptive).

Risk situations:

- Non-Limit diving, extensive repetitive diving
- “Jojo” dives (up and down profile)
- fast ascents
- neglected decompression and safety stops
- work, exertion
- cold water diving
- deep diving
- flying after diving

3. The decompression model ZH-L8 ADT

3.1. Background

For many years, decompression models used for tables and computers did not change. Small modifications have been made mainly by changing the tissue's critical supersaturation coefficients, leading to shorter nostop times and longer decompression stops. Having in mind our conclusions of the preceding decompression analysis, I think that using this method will not further increase safety for the diver.

Therefore, we decided to develop the new model. A large amount of simulations and real dives have been done to optimize and confirm the correctness of the new model. Let's focus on some special problems of the new model. (see fig. 1)

3.2. Microbubble formation

There are three localities in the body, where bubbles can develop during a dive:

In the venous blood:

These are bubbles which develop during and after most dives

In the arterial blood:

Bubbles that develop during fast ascents.

In the tissues:

These are bubbles which form during and after insufficient decompression

3.2.1. Algorithms

A bubble in the divers body has to resist ambient pressure, mechanical and hydrostatic pressure of the tissue and surface tension (see fig. 2). Therefore, the gas pressure in the bubble has to be higher than the sum of all surrounding pressures. Sophisticated mathematical equations have been developed to describe the bubble formation [6] [7], but no theory has been completely proven until today. The theories are generally complex and can hardly be used for dive computer calculations. Turbulence in the blood vessels and various biochemical and physical reactions influence the bubble formation in the body.

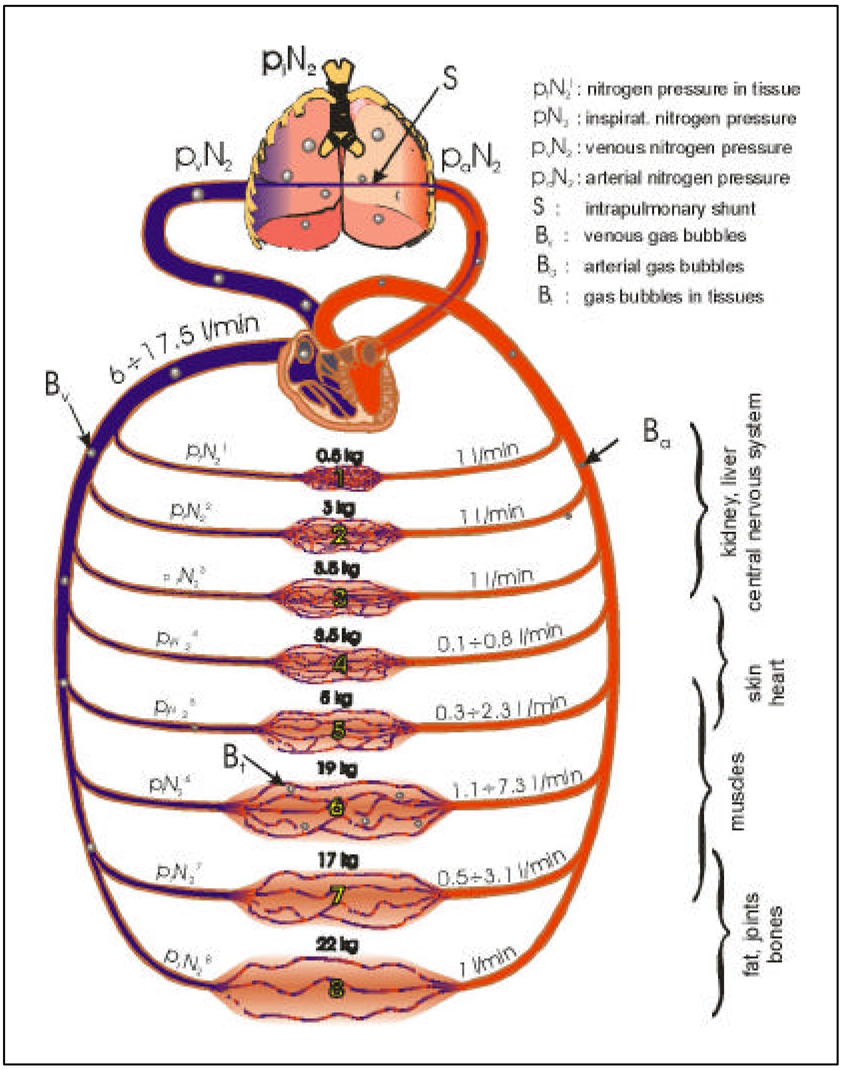

Fig. 1: blood circulation

We found a simplified algorithm to predict the appearance of microbubbles in the blood. It uses mainly the partial pressure of the inert gas, the ambient pressure and the blood pressure. In the tissue, we use the well known Bühlmann model with its linear supersaturation hypothesis for the prediction of microbubbles.

3.2.2. Conformity with measurements

A rough comparison of the estimated arterial gas bubble formation with the reality can only be done retrospectively on dives that included fast ascents and ended up with AGE. Up to now, the actual pressure/time profile is unfortunately not precisely known for such dives, because no dive recorders were used.

The verification of bubble formation in tissues was not necessary, because we use the proved linear Bühlmann algorythm. For that reason, verification can only be done on the venous gas bubbles.

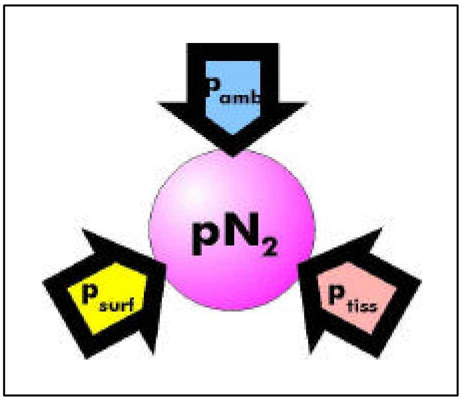

Fig 2: The physics of a bubble

We compared our simplified model with experiments, published in different papers and with data from the french company Comex. Bubbles are measured usually by using the ultrasonic doppler method. The amount of detected bubbles shows wide variations between different individuals, but we found a good conformity with the trend of bubble formation in our model [8].

1994, DAN Europe will launch a research project on venous bubble formation. We will provide DAN with the new dive computer generation as the dive recorder for the test dives. It will be very exiting to compare the model's output with the results of the study.

3.3. Microbubble effects, considered by the new model

3.3.1. Gas bubbles in the venous blood

Gas bubbles in the venous circulation form during and mainly after an ascent. They move to the lungs, where they accumulate and partly obstruct the lung capillaries. As a result, there is an incomplete gas exchange that depends on the proportion of blocked capillaries. This effect is called an intrapulmonary right-to-left shunt and causes an increased arterial inert gas pressure, if the venous inert gas pressure is higher then the inspiratory inert gas pressure.

As long as the bubble-supply from the venous blood exceeds the reduction of the bubbles in the lung through inert gas diffusion, the shunt increases. 10 to 40 Minutes after surfacing, the bubble reduction exceeds the venous bubble supply and the shunt decreases. About 2 to 4 hours after a dive, most bubbles in the lung capillaries disappear.

As the number of bubbles in the lungs increases, the possibility of a bubble to pass the lungs and to enter the arterial blood raises. Once these bubbles are in the arterial circulation, they behave like bubbles which are formed in the arterial blood.

3.3.2. Gas bubbles in the arterial blood and in the tissues

Bubbles in the arterial blood are dangerous because they prefer to move to tissues with a good perfusion, for example brain, spinal cord and eyes. Bubbles formed in a tissue or washed in from the arterial blood can obstruct capillaries and locally influence the gas exchange (see fig. 3). Around the blocked vessel, the diffusion distance for the inert gas molecules increases and therefore the tissue behaves like a tissue with slower tissue half time in this area. The desaturation is slower, but also the critical supersaturation is lower. The decompression procedure has to be modified regarding the locally obstructed tissue.

In such a situation, the model will change desaturation speed and critical supersaturation of the tissues to prevent further damage to the tissue. This leads to much shorter nostop limits and a decompression schedule which begins with deeper decompression stops and which lasts longer.

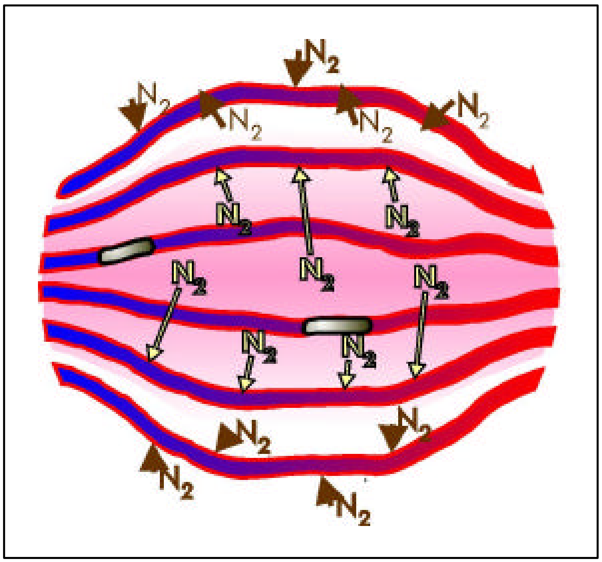

Fig 3: Desaturation around a blocked blood vessel

I would like to show two examples for the behavior of the new model:

1. In a paper for the Repetitive Diving Workshop at the Duke University Medical Center, Durham, Lewis postulates, that computers should not allow numerous deep short dives with short surface intervals [9]. We found, that exactly these dives produce a considerable right-to-left shunt which increases with each dive. There is a high risk of bubbles passing the lungs and entering in the arterial circulation for this kind of diving.

A comparison between the model used for our previous dive computers ZH-L6 and the new model ZH-L8 ADT shows the influence of considering the micro-bubbles in the arterial blood for 6 consecutive dives to 30 meters for 16 minutes with surface intervals of 75 minutes. The first dive is a dive within the nostop limit (see fig. 4).

While there is only a very small difference for the first dive, the difference can increase to a total ascent time which is about 3 times as long for the new model.

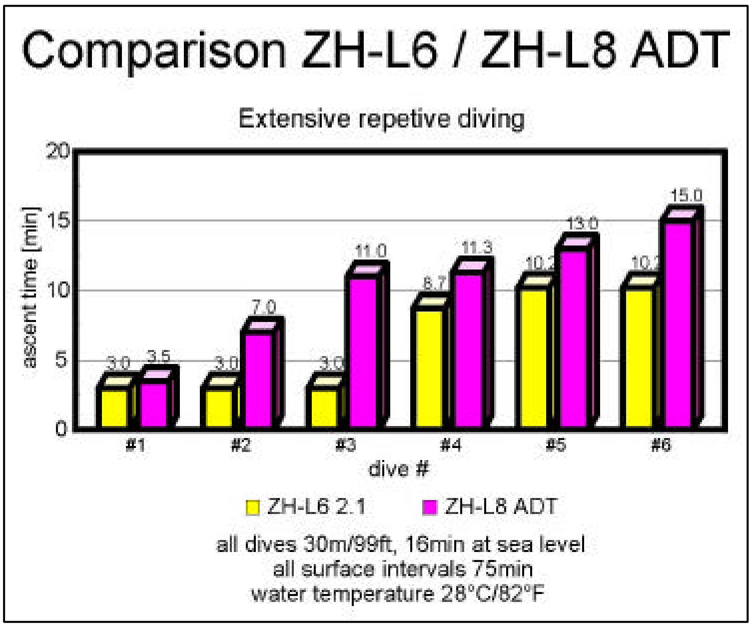

Fig. 4: Repetitive Dives with short Intervals

2. The second example is a rescue training. It is very common, that the instructor does two or three ascents consecutively with his students. For novices in rescue ascents, the ascent speed can easily reach 30 m/min. Let's have a look on such a situation (see fig. 5).

   On the first descent, the nostop limits are the same for both models. After the second descent, the nostop limit for the ZH-L8 ADT is clearly shorter and after the second ascent, it indicates a decompression stop on 3 meters. After the third ascent, the new model indicates a stop of 7 minutes in 3 meters depth. One minute after surfacing, an additional stop of 1 minute at 6 meters will come up, because of the ignored decompression stop at 3 meters. The ZH-L6 allows the diver to leave the water at that time. Desaturation time is extended due to the estimated bubbles in the tissues.

   Both examples showed extreme situations. Most divers know, that such dive schedules have to be avoided, but nevertheless, such diving is done from time to time. In these cases, the model is able to adapt to the extraordinary situation and can probably prevent an incident.

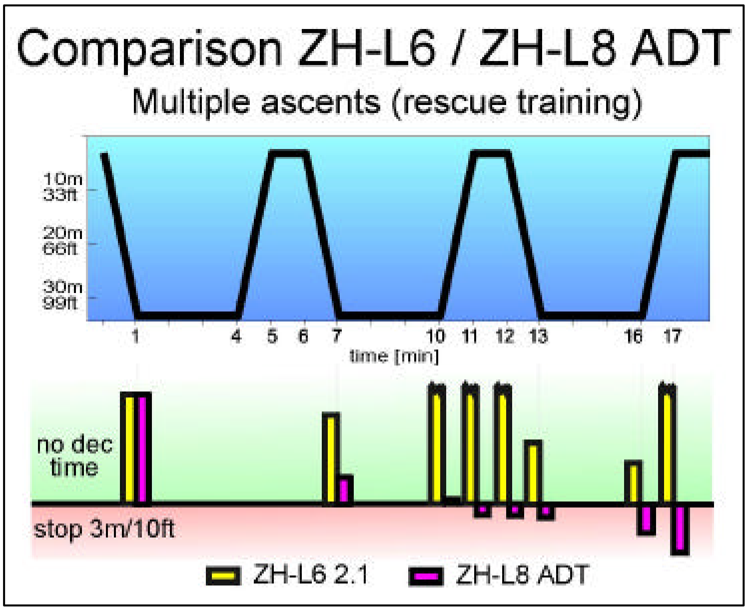

Fig. 5: Rescue training

3.4. Adaptation of the body to work and cold water

3.4.1. Adaptation to work

Many tables were designed for an average workload of the diver. Bühlmann took 50 Watts as a basis for his tables. Already a long time ago it was known, that decompression time may be longer, if the diver works during his dive. I refer for example to studies of Lanphier/Camporese [10] and Schibli/Bühlmann [11].

The working diver has a higher blood perfusion rate in the muscles, which speeds up the inert gas saturation in these tissues. Other tissues like the Central Nervous System (CNS) or bones are not affected by the diver's work.

Normally, the diver is relaxing during the decompression procedure. The perfusion rate returns to the normal value and desaturation slows down. The decompression time, necessary to ensure proper decompression for the muscles, has to be extended.

3.4.2. Adaptation to cold water

If the diver enters cold water, he will cool down depending on temperature, time, isolation of the dive suit and exertion. The body minimizes the heat loss by contracting the blood vessels in the skin. The blood perfusion in the skin is reduced to keep the normal body temperature of 37°C in the body core as long as possible. The reduced perfusion causes a reduction in the inert gas saturation speed and changes the critical supersaturation.

The maximum cooling of the skin is usually reached at the end of the dive, when decompression is carried out. In this moment, the skin desaturates slower than it was saturating. The inert gas that accumulated in the skin during the dive, needs a long time to leave the body due to the slower tissue half time.

No literature was found containing information about skin temperature during real dives. Therefore, we had to do the measurements ourselves. The skin temperature was measured by placing sensors between dive suit and skin at the shoulder and the hip. Measurements were done for different divers with different suits in cold lakes and in the warm sea to get the data we needed.

3.5. Work and temperature effects, considered by the new model

The perfusion rates in different tissues and their variation are well known [12] [13]. Tissue half times and critical supersaturation depend on the perfusion rate [14].

The model is able to change the saturation speed and the critical supersaturation of the muscle and skin compartments according to the diver's exertion and/or cooling.

Workload can be measured indirectly by monitoring the diver's air consumption [15]. The skin temperature can also be measured. But this is not very handy and reliable, if it has to be done by a recreational diver. Based on our measurements, we were able to estimate the diver's average skin temperature for diving in wetsuits with a mathematical algorithm.

We know by our own experience, that diving with a dry suit increases the risk of skin and muscle problems. The reason for that is not clear and there are multiple factors that take effect on that. But the risk may possibly also be reduced by considering the skin cooling and giving a more conservative decompression procedure for the diver with a dry suit.

As you can see, the algorithm is a rough estimate for the skin temperature. But the possibility to decrease the risk of getting skin problems without any inconvenience for the diver justifies the simplifications in our opinion.

At surface, the average workload is usually lower then during the dive. As soon as the diver is dressed, the body begins to warm up. Due to the change in skin temperature and exertion, saturation and critical supersaturation have to be modified also after a dive. The slower desaturation and the lower tolerated ambient pressure mainly lead to an important extension of the waiting time before flying.

4. A new dive computer generation, using the model ZH-L8 ADT

4.1. Description of the new dive computer generation

4.1.1. Hardware structure

A computer that is able to use all the possibilities of the new model, has to meet certain hardware requirements (see fig. 6).

The central unit is run by a high end microprocessor with a large read only memory (ROM) that keeps the program. Ambient pressure and water temperature is measured by sensors and processed by a special sensor processor, that was developed by us. The resolution for the ambient pressure is very high (approx. 1 centimeter). We need this resolution for a fast and accurate ascent speed measurement. Data is kept in RAM (random access memory) and in a EEPROM (Electrically Erasable and Programmable Memory) and accessible through a serial interface.

Tank pressure is used to predict the remaining Gas Bottom Time (RBT) and to determine the divers workload. An accurate temperature compensation is necessary to avoid a temperature-dependent tank pressure due to changes in water temperature. A temperature dependent tank pressure would lead to a wrong RBT and influence the workload determination.

Tank pressure measurement and temperature compensation take place in a second microprocessor/sensorprocessor system. The resolution for the tank pressure measurement is about 15 mbar. This allows us to detect one single breath.

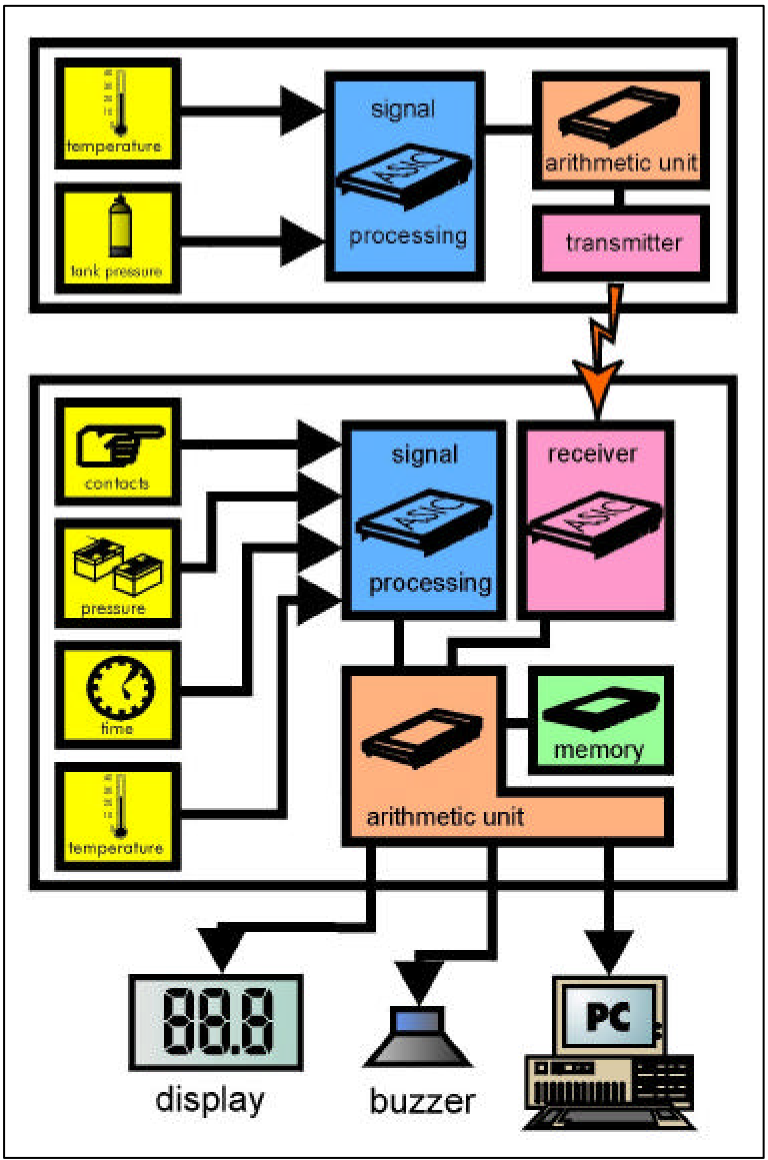

Fig. 6: dive computer block diagram

4.1.2. Some special features

The algorithm for the prediction of microbubbles in the arterial blood can be used to determine an optimal ascent speed. Of course, the ascent speed that comes out is slow for shallow water and can be higher in deeper water. The upper limit for the speed in greater depth is not given by the bubble algorithm, but by a comfortable and controlled ascent. The lower limit for the speed is given by the algorithm and also helps to reduce the number of venous gas bubbles after the dive.

Tank pressure data is transmitted wireless to the dive computer, which is located at the divers wrist. A small unit that contains the electronic circuit is mounted at the high pressure outlet of the divers regulator. A sophisticated and patented transmission procedure includes 6 stages of security and ensures an extremely reliable transmission to one single dive computer. The dive computer can be paired to any transmitter by the diver with a very simple operation. If no transmitter is installed, the system works correctly, but without the tank pressure measurement and the consideration of workload. If a surface air supply is used, the transmitter cannot be used.

The Remaining Bottom Time (RBT) given on the display, predicts the gas time on the current depth for the current gas consumption. It takes into account the air consumption for the ascent and all decompression stops that will be necessary, when the air time will have expired. The RBT will also take into account a certain reserve (for example 40 bar) after reaching the surface. A symbol comes up, when the diver's gas consumption increases. This focuses the diver's attention in an early stage on a possible shortening of the Remaining Bottom Time.

Dive data like water pressure, skin-temperature, workload, bubble occurrence and all warnings, is recorded every 20 seconds and stored in the memory. An interface allows the readout of this data to a Personal Computer for further treatment (see fig. 7). Additional information like time and date of the dive, water temperature and dive characteristics can be received this way. A program on the PC receives, holds and manages the data in a logbook. The information can be displayed, sorted, completed with personal remarks and printed out on a page for the divers logbook.

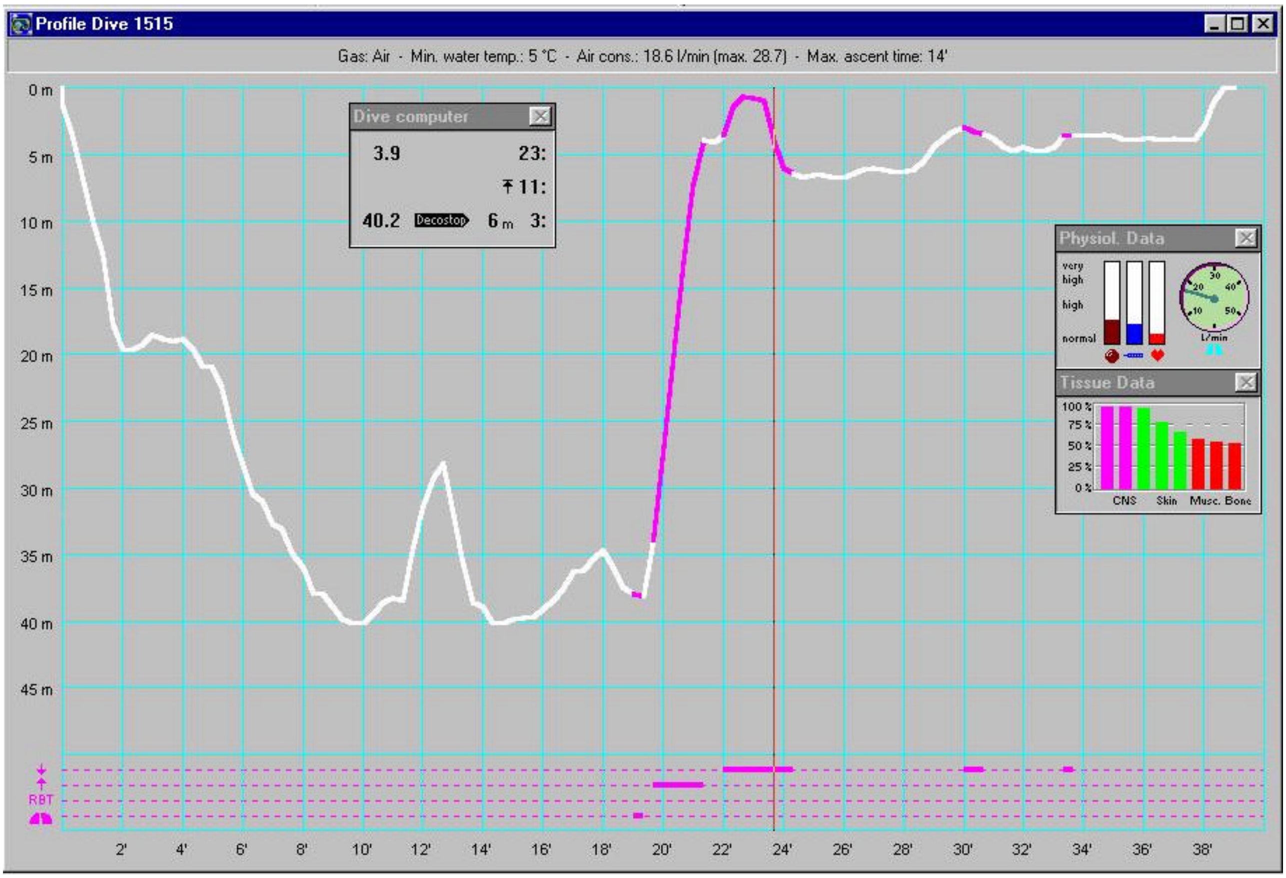

Fig. 7: dive profile

A new dive planner combines the well known nostop dive planner with an easy to use decompression dive planner. Additional to that it is possible to choose a surface interval before the dive. This makes it possible to plan a dive some time before it is really carried out.

4.2. Diving with the new computer generation

4.2.1. Single dives

For single dives in warm water and without risk situations, nostop time and decompression stops are about the same as for our current dive computers. Small differences can occur due to the different tissue compartments. For deep dives, there is a slight decrease of the decompression time due to the faster ascent in deep water.

In cold water, decompression can be longer due to the reduced skin blood perfusion during decompression. Dependent on the temperature and the duration of the dive, decompression times can be up to twice as long as before. If multiple decompression stops are required, mainly the shallow stops are longer.

If the diver works, blood perfusion increases in the muscles, skin and joint tissues. During work, these tissues are saturating faster than while resting. This can cause longer decompression stops or shorter nostop times due to the higher nitrogen saturation. Dependent on the dive profile and the diver's workload, decompression times can be doubled.

Fast ascents and ignored decostops produce microbubbles in blood or/and tissues. The model keeps a possible damage of the tissues as small as possible by correcting the decompression. This means for example, that a diver can get decostop(s) of some minutes after a very fast ascent, even if he was far within the no stop limit before the ascent started. I showed an example (rescue training) for that earlier.

4.2.2. Repetive dives

After the first dive, there are several effects that have an influence on a following dive:

- The pulmonary right-to-left shunt reduces desaturation speed in general. If the shunt is high, bubbles may slip through the lung capillaries into the arterial circulation and can change saturation and critical supersaturation of a tissue locally.
- A low skin temperature further reduces desaturation speed of the skin tissues. The average workload of a diver is lower on surface than during a dive. This again reduces desaturation speed of the muscles.
- The influence of these effects on the following dive depends on the type and the conditions of the preceding dive. A combination of these influences will shorten the nostop times and extend the decompression times of the following dive considerably.

4.2.3. Desaturation and no fly time

Due to the effects in the surface interval, desaturation time and no fly time are much longer for the new computers as for the currently used generation. The no fly time can be several hours longer for short dives and reach 30 hours for very long dives and extreme repetitive diving. This corresponds with the guidelines of the UHMS Flying After Diving Workshop [16].

5. Summary

The new model ZH-L8 ADT is extraordinary useful in helping us to understand better what is going on in the diver's body. Because of the multidimensional influences on the diver's decompression, the model very complex. The calculations must be done online, using the actual measurements as input. Therefore, general guidelines - for example for table users - can hardly be given in advance. The model is ideally used in a decompression computer.

In contrast to the current computers, the new generation can be used for any kind of diving that is carried out with breathing air and Nitrox. All kinds of professional diving including saturation diving is possible and safe, if the diver stays within his physiological limits. In one single instrument, the diver has access to all dive data. Acoustical and optical alarms are available for all important parameters which increases security again.

For the first time, a dive computer can adapt to the diver's behavior and to a disadvantageous environment. Incorrect dive techniques will result in a changed decompression procedure, which takes into account a possible bubble formation. Unfavorable situations like cold water and exertion are automatically considered and will reduce the risk for skin and muscle problems.

There is no question, that the average recreational diver can continue to use current dive computers. For divers that often run into risk situations and for professional diving, the new generation of dive computers will be the better choice. These divers will profit from additional safety and a reduced risk for DCS and long term damage.

The model ZH-L8 ADT will make a contribution to higher safety in diving. It will also promote a riskless dive technique and still keep diving fun for the diver. Diving is fascinating not least because we can move in all three dimensions. I'm completely convinced that diving safety is not increased by removing the 3rd dimension or by forcing the diver to do unnecessary decompression in a normal single dive.

Safety can be improved mainly by avoiding risk situations or - if this is not done or not possible - by adapting the decompression information according to the situation. It is the instructor's job to promote the diver's sense of responsibility and it's our job to design instruments, which work correctly in every situation. The new decompression model, implemented in an advanced decompression computer, fully meets this demand.

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