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IMPORTANT POINTS OF A DIVE-COMPUTER DESIGN

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ABSTRACT

An engineer designing a dive computer cannot restrict himself to search for merely an ideal theoretical solution only. He must also take into account the technical and economic limitations, which decide whether or not a project can be realized.

This paper concentrates, therefore, on some difficulties involved in designing dive computers. Several dive computers are now on the market. They used different techniques in hard- and soft-ware design and use different calculation models. It is impossible to give general information for this variety of dive computers. Therefore, and because I have particular experience with the ALADIN PRO decompression computer, I will use this instrument as an example to explain some important points of dive computer design. I will touch, in particular, on hardware problems like energy consumption, sensor properties and signal conditioning, and describe some of the problems in software design, such as modifications to the decompression-model and safety aspects.

INTRODUCTION

The dive computer has changed recreational diving to a great extent. On the one hand diving has become more comfortable and mistakes in reading the decompression tables are no longer possible. On the other hand the diver may become less attentive under water, relying only on his electronic guide.

In discussions surrounding the dive computer the designing engineer's point of view has rarely been asked and the technical aspects of the dive computer have seldom been discussed. In this report I would like, therefore, to present for once some of the specific problems that occur when designing a dive computer. For this purpose, it is necessary first to give a short review of the basic aspects of a dive computer.

THE STRUCTURE OF A DIVE COMPUTER

A dive computer consists of two basic parts:

- The *hardware* is the part of the computer which can be "touched". It consists of mechanical and electronic components which are manufactured or bought.

- The *software* (the computer program) which contains the calculation model and defines the way in which the data can be used and read. The software is stored in a chip.

Apart from the reliability of the hardware, it is the software which is mainly responsible for the quality of a dive - computer. Aspects such as universality, the amount of information used or presented, safety margins and many more are defined by the software.

THE HARDWARE

THE HARDWARE CONCEPT

The hardware can be structured in many different ways. The solution applied with the ALADIN PRO is displayed in a block diagram (Fig.1). It shows that the hardware consists of the following parts:

- single-chip microprocessor, consisting of:
  - processor unit
  - software-memory (ROM, Read Only Memory)
  - data-memory (RAM, Random Access Memory)
  - display driver
  - input/output-device
- pressure sensor recording air and water pressure
- signal conditioning for the output of the pressure sensor
- sensors for operating and controlling the computer (switches)
- time-base for the operation of the clock
- display to indicate the data for the diver
- beeper for accoustic warnings
- battery (not displayed in the block-diagram)

PROBLEMS INVOLVED IN DESIGNING THE HARDWARE

The energy consumption of today's computers is far lower than it was with the first generation of computers. Still, a low energy consumption rate is imperative. Modern devices must carry out large-scale calculations and they must continually measure the changing ambient pressure. Nevertheless, the battery's service life should extend to several years even under extreme temperatures. Since a micro-processor consumes more energy with increasing processing speed, the calculation speed is limited. As you will see in the following discussion, energy consumption is a central problem of hardware-design.

Figure 1. Block diagram of ALADIN PRO dive computer.

The Pressure Sensor
Modern dive computers use piezoresistive pressure sensors to measure air and water pressure. Since vacuum is the reference employed, the absolute pressure can be measured and there is no difference between measuring atmospheric and water pressure. Such a pressure sensor is illustrated in Figure 2.

Figure 2. Piezoresistive pressure sensor.

The sensor output depends on the ambient temperature and must therefore be temperature-compensated. Offset and range are adjustable, which can be done by means of the hardware or the software. Long-term effects, in particular a drift of the offset, must be taken into account in the calculations. Since the pressure sensor is one of the biggest energy consumers in the dive computer, it must only be switched on when measuring the pressure is really necessary.

The Display
The production of light consumes a comparatively high amount of energy. Therefore, dive computers are almost exclusively supplied with LCD-displays. Modern "Liquid Cristal Displays" are readable only with a minimum of external light and consume very little energy.

In order to improve the legibility when little light is

available, we applied a fluorescent background to the ALADIN PRO display (Fig. 3). This feature was not available on the LCD market and had to be developed by ourselves. LCD's use polarizing filters to make their displays visible. These filters absorb a large amount of the incoming light. Because the light passes through the filters twice (the light is reflected on the background to the display), the demands for the fluorescent background and the filters are much higher compared with normal applications.

Figure 3. Full LCD display of ALADIN PRO dive computer.

Signal conditioning
Electronic signal conditioning is essential in the hardware design. On the one hand, the analog parts and the analog-to-digital converter must be high precision. On the other hand, they must use up as little energy and space as possible.

All of these requirements can only be met by using custom-designed chips. Obviously, such chips can only be made with great expense, both of time and money. In the case of the ALADIN PRO, for instance, the development of such a chip took about a year. As you can well imagine, this can only be justified from an economic point of view if high numbers of chips and dive-computers are to be produced.

THE SOFTWARE

THE STRUCTURE OF THE SOFTWARE

The software consists of a number of instructions to control the processing unit. By means of these commands, the computer is asked to perform certain tasks, such as to measure water pressure or time, to record certain factors, to add up or to indicate a certain figure. These commands can be formulated in one of the high level computer languages like Pascal, FORTRAN or BASIC, simple languages very similar to English. With these languages mathematical operations such as additions, subtractions, multiplications, divisions and so on, can be performed in a familiar way.

In programming a micro-processor as used in a dive computer things are, unfortunately, much more complicated. It is important to know that the commands are written in a very low level processor-specific language called assembler. A time optimized multiplication routine for the ALADIN PRO, for instance, involves around 120 assembler commands. Many operations like calculating an exponential or logarithmic function can only be performed by means of extensive algorithms consisting of lengthy sequences of commands.

THE MODEL - THE CORE OF THE SOFTWARE

The model applied by the software of the dive computer must meet certain requirements. In the first place of course it must have successfully passed extensive tests in adequate numbers and quality, both in the laboratory and in practice. Dives at high altitude are among the most important tests. There, the diver's sensitivity during decompression at a given depth is much higher than at sea-level. Even the slower tissues can be tested here very well through short adaption times at altitude.

In order to guarantee accurate functioning of the computer in any situation, the model must be as universal as possible. This concerns, in particular, its application to reduced atmospheric pressure as when diving in mountain lakes or when flying after diving. An advanced decompression model must also be continuously altered in the light of new research data. The model must therefore be as transparent as possible, since only this allows for a quick and safe adaption to any new findings.

All these requirements are met by the Bühlmann model. Therefore we decided to use a modified version of this model in our computers. The following two sections will give you an idea about some of the modifications to this model that are used in the ALADIN PRO dive computer.

Reducing the number of tissues
One modification to the model, necessitated by present technical limitations, concerns the number of tissue compartments used in calculations. This number must be

limited, since their number is directly proportional to the number of calculations that have to be executed by the dive-computer.

Very slowly saturating tissues with tissue half-times of more than 300 to 350 minutes can be neglected for the recreational diver since their saturation never reaches a level which may influence the decompression time, not even with frequent, repetitive dives. These tissues are only significant when the dives are either exceptionally long (several hours) or in case of saturation dives. The air requirement for these dives exceeds the air content of any normal dive-tank. As long as dive computers are not used for this kind of professional diving, a spectrum of tissues with tissue half-times up to 300 to 350 minutes is entirely sufficient. Similarly, tissues with half-times of less than 6 minutes will always be desaturated to a low level during ascents, and these also do not need to be considered.

In our opinion, a range of at least 6 tissues is therefore good enough to allow for sufficiently precise calculations for recreational divers. However, since the tissues are graduated less finely, the tissue coefficients must be slightly adjusted so that the decompression data will always be on the safe side of Bühlmann's 16-tissue standard model, the so-called ZHL-16C. Consequently, the no-decompression limits will, in most cases, be slightly reduced and the decompression times a little extended. These adjustments are, however, only very small, usually not more than a fraction of a minute and rarely up to a few minutes (see Figure 4).

Figure 4. Comparison of tissue no stop limits for 6 and 16 tissue models.

Consideration of the Right-Left-Shunt
Even if ascent time and decompression time are strictly observed, we know today that at every ascent micro-bubbles are washed into the lungs' fine capillary network where they are filtered out and leave the lungs through normal breathing. These micro-bubbles reduce the surface between the venous blood and the alveoli. A small fraction of the blood passes through the lungs without reducing its nitrogen content, which is called a Right-Left-Shunt. This results in a slowing down of desaturation as long the micro bubbles are present. If another dive or a flight follows within the first few hours, the difference between the calculated and the real arterial nitrogen pressure may cause minor bends for very sensitive divers. Statistics such as, for example, from the Diving Alert Network and the British Sub-Aqua Club confirm a higher risk of a decompression sickness for repetitive dives.

Today it is possible to introduce algorithms for this slowed-down desaturation into the Bühlmann model. This revised model was applied for the first time in the ALADIN PRO dive computer. It is also used now in the ALADIN no-decompression computer and in the MONITOR I and MONITOR II computers sold by Aqualung. For repetitive dives, particularly those with surface intervals between 30 and 120 minutes, there is a prolongation of the decompression time (or a reduction of the no-decompression limit respectively). By taking into account the Right-Left-Shunt, the risk associated with repetitive dives can be reduced to a normal level, and this has been confirmed by tests on divers who previously experienced problems with repetive dives.

In the future, we will be able to simulate the effects of micro-bubble production during ascents even better. In the case of yo-yo dives or fast ascents this will result in extended decompression times to prevent decompression problems.

THE DEVELOPMENT OF THE SOFTWARE

Before we can start writing our software program, we must first develop a concept for the function of the dive computer. This concept defines the relation between the diver and his dive computer and determines whether or not the display is intelligible and how easily the computer can be operated. It also defines the future possibilities of the device.

The structure of the program is next described in detail by means of state diagrams and flow charts. Very soon, we arrive at the crucial problems of developing the software. They consist, for instance, of solving the mathematical problems as well as developing the appropriate algorithms and the programs's timing in the micro processor.

After having solved these problems in theory, we create a simulation program on a personal computer. This allows us to verify the program's correct function, to check the algorithms and to test calculation accuracy before we actually start with

the definitive software work. Often, this procedure results in subsequent changes in the concept or in an algorithm.

After our simulation program is completed, there follows a very important and time-consuming optimising phase, during which we set down, among other things, the tissue data. This is done by comparing the data of different dive profiles with Bühlmann's "master-model" and with other earlier software versions. This phase incorporates the simulation of several hundred dives.

Only now can we translate the program into assembly language, transfer the software onto a so-called development system and test it. Unfortunately, the possibilities of mistakes in this hardware-close language is much higher than in using a higher level computer language. This is why we put the utmost importance on a reliable debugging and a lengthy test phase.

THE TEST PHASE

First of all, a series of tests are performed in the laboratory. For this purpose, we devise a test-program, which anticipates as many of the situations that could occur later. If changes become necessary, they are accounted for in the software.

After the most important tests have been passed successfully, prototypes are produced, which are equipped with One Time Programmable processors. Unlike the final processors, these so-called OTP-processors have a programmable memory for the software and can therefore be programmed by ourselves.

Some several dozens of these prototypes are then distributed to diving instructors and diving bases all over the world, where they are in daily use. In this way, several thousand dives can be performed in a comparatively short time. In case of problems, the hard- and soft-ware can still be adapted to a certain extent.

After the test program is completed, we order the production of the micro-processor mask, which will later be used for the production of the final processor series. Delivery terms are about 6 months. During the test-phase, the engineer is confronted with a big problem. He must decide on the best point in time when to release the series. On the one hand, he would like the test program to be as widespread and extensive as possible. On the other hand, the test-phase should not last an unreasonable time. Here, he must find a compromise between the contradicting technical and economical demands.

SOME CONSIDERATIONS CONCERNING SAFETY

Finally, I would like to present some thoughts on safety. Aspects of diving technique will be excluded here, however.

DIFFERENCE BETWEEN TABLES AND A DIVE COMPUTER

A dive computer makes use of a multi-level calculation procedure. Consequently, the decompression follows the pressure profiles very closely and the decompression time of a multi-level dive will usually be reduced compared to the decompression time as calculated by a table.

Electronic sensors measure much more precisely than mechanical devices. With tables, therefore, which are mainly used with mechanical depth gauges, there should be a depth addition, which is, for the Bühlmann table, 1 meter plus 3% of the maximum depth. The safety margin for the dive computer is extended by adjusting the tissue coefficients. This means that for a rectangular dive-profile, the safe ascent depth is actually deeper, and therefore safer, compared with the table.

The tissue saturation calculated by the dive computer follows very closely the actual course of the saturation, much more then a table can do. This is why it is reasonable and necessary to take into account all the physiological peculiarities which determine the course of the saturation such as, for example, the Right-Left-Shunt.

THE MEASUREMENT OF AIR PRESSURE COMPENSATION

It is important to realize how the dive computer accounts for atmospheric pressure. If a computer, which is in standby-mode, starts measuring the pressure only when immersed in water, its basis for calculating the actual depth might be wrong. The reason lies in the length of time that elapses between the moment of immersion and the first pressure measurement. During this short moment of time, the diver might already have reached a certain depth, which the computer is unaware of. In this case, it bases its calculations on a depth which is too shallow and an atmospheric pressure which is too high.

This consequently affects all its future calculations. On the one hand, the computer calculates with a lower saturation than is actually the case. On the other hand, the diver will stay on decompression levels that are too deep. So, it may very well be the case, that the decompression times as calculated are too short by a factor of 1.5 or even 2!

There are two ways to avoid this problem. First, the software blocks the function of the computer, until the proper air pressure measurement is done. This was what we did with the first ALADIN generation by showing an error display in that case. Or, second, the computer is kept compensated all the time in measuring the atmospheric pressure periodically even when "switched off". The current ALADIN and MONITOR models use this system.

ALARMS

By controlling important parameters, the computer may considerably contribute to the safety. Many diving incidents do not concern decompression sickness, but damage to the ear or the lungs, for instance. By supervising the diver's ascent speed, the computer enables the diver closely to observe his ascent speed and therefore to avoid the danger of such damage.

During decompression, the computer can also check whether or not the decompression stops and times are observed. This might help to avoid the disregard of decompression rules. By recording mistakes of this nature in the computer's logbook, it is possible for divers and dive instructors to recall this information at any time after the dive.

LIMITATIONS TO DEPTH AND DECOMPRESSION STOPS

Lots of complaints today concern the maximum diving depths and decompression times which are possible with dive computers. In my opinion, a limitation of these factors has to be absolutely refused. Even if the diver behaves in a reckless way, the dive computer should supply him with the correct decompression data. The responsibility for the dive, however, still lies within the diver, not within the computer! Diving associations and their instructors should teach defensive and responsible diving and teach the diver to use advanced decompression computers in an appropriate way.

FINAL REMARKS

The designing engineer is confronted with many problems throughout his work, starting with the concept, including physiological problems and ending with the design of the final device. Safety aspects are one of the essential guidelines for the designing engineer.

The whole designing process for the ALADIN PRO took about 4000 hours. This does not include the work of the chip supplier, neither does it contain the time spent in the field studies. The costs for such a development including the external suppliers run up to at least 1 million Swiss francs at best, plus the costs for the production which has then to be started.

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DECOMPRESSION COMPUTERS AND THE POT: AN INSIDE VIEW

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ABSTRACT

On reviewing cases of Decompression Sickness (DCS) treated under the auspices of the Institute of Naval Medicine (INM), the impression is gained that, whilst decompression (dive) computers may be capable of safely assessing no-stop dives, there may be difficulties to resolve with deep, repetitive and complex dive profiles. It is emphasised that a computer is no substitute for a thorough dive plan.

INTRODUCTION

Diving accident records for the years 1988 and 1989 held at INM, the principal diving diseases treatment centre in the United Kingdom, were examined to identify cases in which decompression computers had been used. Individual cases were scrutinised to determine whether the use or abuse of a computer had contributed to the development of DCS.

Sykes (1989) has reported a rise in the number of sports divers with DCS presenting for advice or treatment to the Ministry of Defence in recent years. Whilst the burgeoning popularity of recreational diving may account for part of the rise, other factors which may, conceivably, be implicated include the promotion of novel decompression tables, the appearance on the market of increasingly sophisticated equipment allowing greater depth-time exposures and the reliance on computers to calculate decompression obligations.

In 1988, 114 cases of DCS were treated by INM Physicians. Of these, 37 (32%) are recorded as having used a decompression meter as the sole or principal means of determining their decompression profiles. In 1989, of the 148 cases treated, 42 (28%) used decompression meters in a similar manner.

CAUTIONARY TALES

1. A 33 year old man undertook an air dive to 41.4 metres. Duration (defined throughout the text as time from leaving surface to leaving bottom) was 27 minutes. Five and a half hours after surfacing he dived again, this time to 34.8 metres with a duration of 26 minutes. On both occasions he spent 5 minutes at 5 metres in accordance with the instructions given by his dive computer. Shortly after surfacing for the second time, the diver developed type II DCS and was successfully recompressed. According to Royal Naval rules (BR2806 - Diving Manual, 1987) this represents a "combined dive" to 41.4 metres of duration 53 minutes. Had he been diving in accordance with RN table 11, which is widely used and accepted as being very safe, the patient would have been deemed to have missed 85 minutes of decompression time.

2. A 35 year old male performed the following series of dives over three consecutive days:

TIME	DEPTH (metres)	TOTAL DIVE TIME (leaving surface to surfacing) (minutes)
Day 1		
1200	22	32
Day 2		
1100	22	27
1440	27	29
Day 3		
1100	26	31
1500	31	28

The ascent rate was 10 metres per minute. All were "no-stop" dives according to the computer. The Royal Navy's rules for air diving would have demanded decompression stops for the last three dives if performed singly. Even more hazardous was the computer's failure to allow for "combined dives" on days 2 and 3. Fortunately, a good recovery from the ensuing type II DCS was made on therapeutic recompression.

3. A 57 year old male undertook a dive of 13 minute's duration to a depth of 55 metres in order to compare two brands of dive computer. Both instruments indicated a "no-stop" dive; advice which was followed. The diver was subsequently treated for typeII DCS and it was noted that, according to RN table 11, 25 minutes of decompression time had been omitted.

4. A 34 year old male dived to 35 metres for 40 minutes decompressing as instructed by his dive computer. At 3 metres, with some 20 minutes of decompression time outstanding, he ran out of air, surfaced, acquired more air and descended to complete his stops. The subsequent debilitating type II DCS was not fully amenable to therapeutic recompression.

A lack of pre-dive planning, encouraged by the temptation to rely exclusively on his dive computer to calculate stops meant that the diver was unable to fulfil the decompression requirements correctly demanded by the computer.

DISCUSSION

These case reports illustrate a range of possible difficulties with dive computers. There is no doubt that they are seductive tools, pleasant to use and apparently obviating the requirement for the diver to think about his dive and to plan ahead. As Lang and Hamilton recorded (1988), divers tend to regard decompression tables as providing information whilst they see dive computers as giving instructions.

A careful dive plan is essential to safe diving practice. This is not merely a matter of following decompression profiles as laid down by either table or computer software. Allowance must be made for variable factors such as water temperature, age, physical state, exertion and past history of DCS. These demand added conservatism which, it may be argued, is more readily incorporated into a dive plan designed using dive tables.

McGough and Desautels (1989) subjected a number of dive computers to a range of dive profiles and reported that decompression time demanded by the computers was predominantly less than that required by tables. When either the depth or time exposure for a given dive does not match precisely the relevant value given in standard tables, the practice of applying the next greater value increases the time spent in decompression and hence improves the safety margin of the dive. McGough and Gallagher (1989), on reviewing 557 diving accidents, suggested that decompression meters might be less reliable than tables for repetitive and deep diving. This supported earlier recommendations by Edmonds (1988) that the use of dive computers should be restricted to single, shallow dives. The clinical impression obtained from cases treated by the Royal Navy supports this.

The reliability of dive computers, particularly the older models, has been questioned and there is reluctance in some quarters to rely on inherently fallible instrumentation. There does appear to be a problem with profile reproducibility although Edmonds (1988) was impressed by the reliability of computers as recording instruments. Dive details reported by divers are notoriously inaccurate. It may be, therefore, that dive computers will prove to be useful in augmenting the dive history, perhaps benefitting treatment decisions. As data

gathering instruments it is easy to see that there is potential for dive computers to improve our understanding of DCS and to assist in the formulation of better mathematical models of the disease leading perhaps, in a circular fashion, to upgraded dive computer software. The possibility of a contribution to improvements in the extant, largely empirical algorithms on which all decompression profiles are based would be particularly welcome at a time when currently accepted profiles are coming under increasing theoretical scrutiny (Ingle and Novotny, 1989).

Dive computers are extremely versatile and will calculate stops for deep, multi-level dives without the type of qualifications presented with accepted dive tables. In defence of dive computers it has been pointed out by Heinmiller (1989) that aspects of at least one computer algorithm may, in fact, be more conservative than standard tables as computer no-stop limits in the instrument discussed were generated using doppler score data rather than by relying on symptom based limits as is the case with conventional tables.

CONCLUSION

The reservations of physicians responsible for treating divers with DCS are based on experience of cases such as those described above. Such experience has demonstrated the danger of individuals using dive computers without adequately understanding their operation and limitations. Use should be in conjunction with a careful dive plan incorporating allowances for factors which might demand added conservatism when calculating decompression obligations. Caution should be applied particularly when using dive computers to calculate stops for deep and repetitive dives and dives with complex profiles. It is emphasised that, in common with any mechanical item, added scope for error is introduced when a dive computer is used and reliance would wisely be placed on a careful dive plan in the event of a diver being unhappy with the instructions given by his computer.

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