environment has been questioned in the past. Trials conducted led to a revision of practices and changes were made to guard book procedures. The SURVIVEX provided the opportunity to verify the guard book in a realistic situation.

The ELSS capability had not yet been conclusively demonstrated. Pods which weigh approximately 100 kg when fully laden with life support stores, food, water, medications etc. can be posted by ROV into the escape tower, providing extra time for the rescue forces to prepare. Difficulties have been noted when trialling the pods and a formal evaluation of the pod posting according to guard book procedures occurred during BLACK CARILLON 98.

Monitoring System

How does the RAN manage such a process? The RAN has implemented an internal 2 stage certification process addressing the material, engineering and operational aspects of the SERS with an additional annual audit of the system addressing these issues. The Remora is certified by the classification authority, Det Norske Veritas (DNV) for material safety with the recompression chamber suite currently undergoing this certification process.

The SUBSAFE Board Submarine Escape and Rescue Subgroup (comprising operational, medical and engineering representatives) is responsible for ensuring no hazard items represent an unacceptable risk prior to the conduct of these trials and in future operations.

Australian Defence Medical Ethics committee approval has been sought and granted for each phase of the exercises.

Summary

The RAN has developed and implemented a sophisticated escape and rescue organisation, the concept of which is being adopted by other major submarine nations around the world. The organisation includes not only the material hardware but a framework for review, accountability and progress. The Black Carillon exercise series will be followed by future exercises planned to maintain the momentum and in-house expertise in submarine escape and rescue.

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MILESTONES OF THE DEEP DIVING RESEARCH LABORATORY ZURICH

J Wendling, P Nussberger and B Schenk

Key Words

Decompression, deep diving, history, hyperbaric facilities, hyperbaric research, mixed gases, research, tables.

Abstract

Between 1959 and 1963 the deep diving pioneer Hannes Keller performed a series of depth records using heliox. He was assisted by the lung physiologist Professor A A Bühlmann of Zurich University. In 1961 application of a modified multi-tissue, perfusion limited, decompression algorithm for nitrogen and helium enabled an open sea dive to 305 m at Santa Catalina Island off California. However the price was a fatality. This dive was a break through for commercial diving, proving the feasibility of deep diving with helium.

A research contract with Shell, to develop decompression tables for offshore work, allowed the restructured research team at Zurich to construct a 100 ATA hyper- and hypobaric, multichamber, research and treatment facility, planned and directed by one of the authors (BS), an engineer. Experimental dives were continued down to 220 and 350 m at Alverstoke, UK, in 1969, and to 575 m in Zurich in 1981. The original decompression tables were empirically modified and became widely used. The problems of calculated tables and true reality will be discussed.

Altitude dive tables for scuba bounce diving were produced to meet the needs of military and police divers in Switzerland. Dive tables using the same algorithms as used for the deep dive experiments were calculated and tested for different altitude ranges. Bühlmann postulated a linear relationship of his supersaturation tolerance coefficients to the external pressure. In 1972 the first altitude table was produced using a 12-tissue model and in 1986 the actual set of tables was produced based on 16 tissues.

In a period of general rejection of any diving practices using computers as on-line dive planners, Bühlmann supported the adaptation of the Zurich tables for diving computers. The 1986 model has been further adapted to take into account workload, temperature, respiratory rate and inadequate decompression procedures specially considering the bubbles load of the lungs during certain phases.

The actual activities of the hyperbaric facility can be divided into the development of deep dive breathing apparatus and research into clinical hyperbaric oxygen (HBO) therapy.

Proving the feasibility of deep diving with helium (1959-1963)

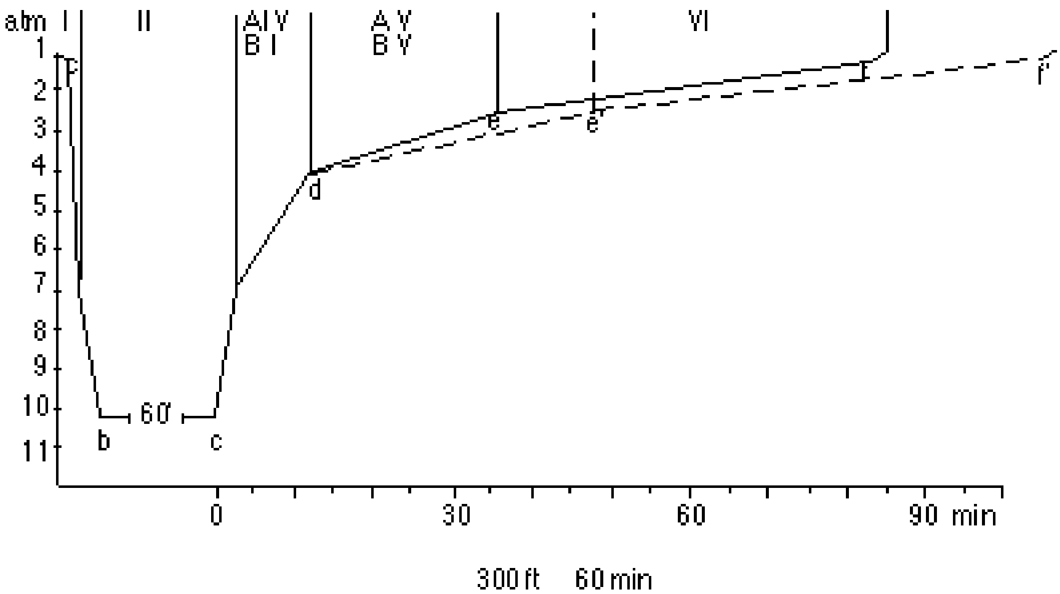
In 1958 the young mathematics teacher Hannes Keller, an enthusiastic sports diver, was fascinated by the idea of breaking the deep diving limits by optimising the known tricks and introducing some of his own ideas which he kept secret for many years. To get financial support, he had to consult a medical scientist , whom he found in Dr A A Bühlmann, a lung physiologist from Zurich University Medical Centre. Bühlmann had first to be convinced that helium is necessary to avoid nitrogen narcosis, which he believed to be a CO_2 retention effect. A trial in a monoplace chamber, with Bühlmann as the subject, convinced him.

Keller's secrets were:

- ability to calculate rapidly using his advanced experience with mathematics and the newly installed IBM computer in Zurich. Using the perfusion limited multi-tissue model (Haldane, Dwyer)[a,b] he calculated the decompression for the gas fractions of different gases.
- reduction of the gas load by ultra-rapid descent (20-50 m per minute)
- reduction of inert gas load by performing normo- and hyperbaric pre-oxygenation
- reduction of decompression time by multiple gas changes using the counter diffusion effect, which produces a temporary reduction of the total inert gas tension when changing to a gas with heavier molecular weight.
- reduction of decompression time by breathing with a PO_2 of up to 2.5 bar.

Using these principles he succeeded in several record dives (122 m in the Lake of Zurich 1959 and 222 m in Locarno 1960). However, technical support was minimal compared with similar tests performed by the US, French and British Navies.[1] Keller never used surface supplied underwater breathing apparatus, but developed handy tube valves that enabled refilling and gas changes of his scuba rebreather system on the diving platform.

The team achieved a 60 minute working time at 90 m depth with a total decompression time of only 85 minutes using six gas mixtures, two of them containing argon. (Fig 1)



A 85 min decompression time

	Gas	O_2	N_2	He	Arg.	min
	I	21	79	-	-	-
	II	20	-	80	-	3+60=66
A	IV	30	-	-	70	10
	V	50	-	-	50	24
	VI	100	-	-	-	50

B 110 min ibid

	Gas	O_2	N_2	He	Arg.	min
	I	21	79	-	-	10
	II	8	-	92	-	3+60+3=66
B	V	50	50	-	-	35
	VI	100	-	-	-	75

Figure 1. Compression and decompression profiles and gases used for a dive to 90 m (300 ft) for 60 minutes bottom time, nine subjects. (Figure 2 in Keller and Bühlmann[1]).

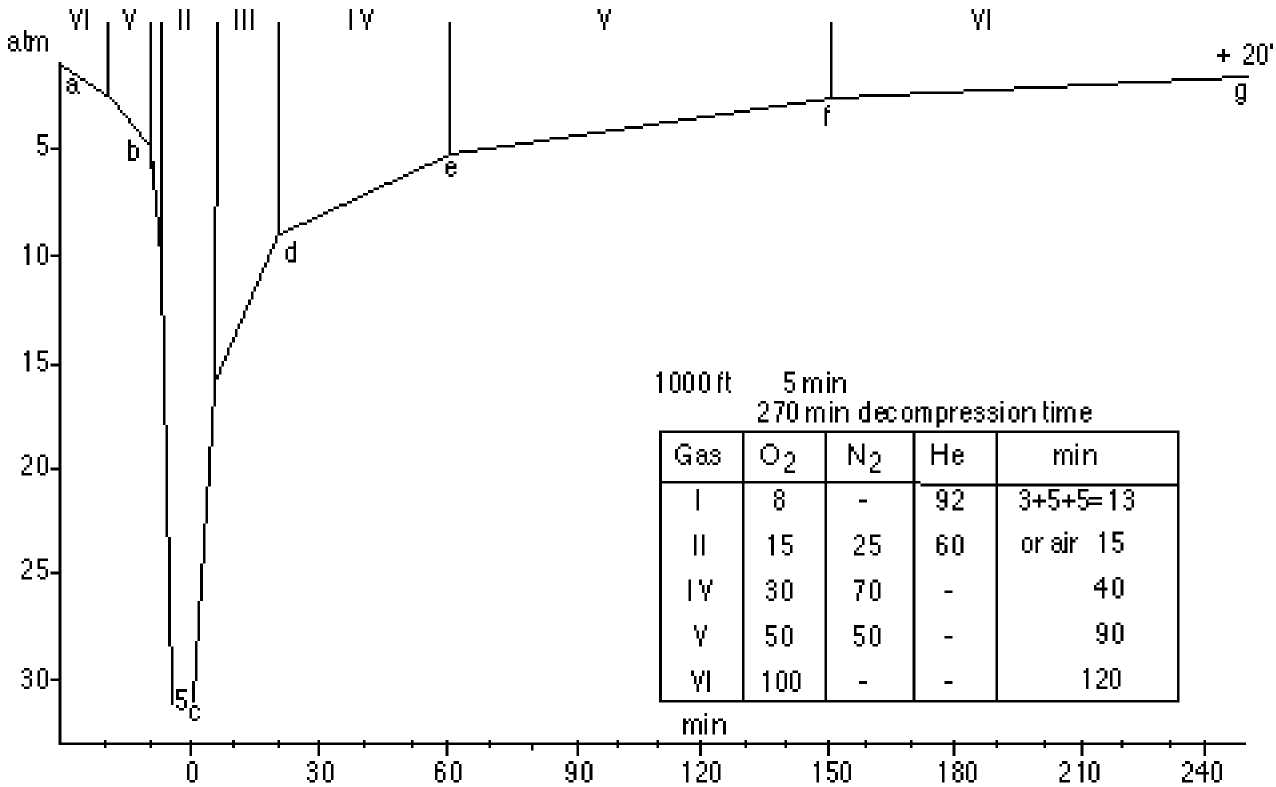
A dive of ten minutes bottom time at 220 m, followed by only 140 minutes of decompression, was planned using simulations in a monoplace chamber capable of 5 ATA by performing profiles with identical decompression ratios and gas mixes, going from 4.4 bar into hypobaric pressures up to 0.2 bar. The dive was demonstrated successfully in Toulon and Washington 1961 in a hyperbaric chamber. (Fig 2)

The deepest dive was 5 minutes to 305 m with a decompression totalling only 270 minutes (Fig 3). This dive was performed in the sea using a bell with a wet excursion at the bottom. The ascent was complicated by a tragedy. Keller's diving buddy died from hypoxia, due to missing gas reserves and because he failed to open his mask glass. Keller was in trouble, probably due to the high pressure nervous syndrome (HPNS), which resulted in loss of time and incorrect manipulation of the chamber. In addition a stand-by diver from the US Navy lost his life trying to close the chamber door in 60 m.

Development of decompression tables for off-shore work (1964-81)

Based on the success of the deep dive experiments, Shell Oil International signed a research contract with the Zurich team for the development of deep dive procedures that could be applied for diving operations on the

Figure 2. Hannes Keller (front) and Professor Bühlmann in the Toulon chamber before a 220 m chamber dive.



Gas	O_2	N_2	He	min
I	8	-	92	3+5+5=13
II	15	25	60	or air 15
IV	30	70	-	40
V	50	50	-	90
VI	100	-	-	120

Figure 3. Compression and decompression profiles and gases used for a dive to 300 m (1,000 ft) for 5 minutes bottom time, two subjects. (Figure 6 in Keller and Bühlmann[1]).

continental shelf. As a result the diving bell "Atlantis", supplemented by a lock module and a detachable monoplace unit, was transformed into a 30 bar experimental living chamber.

The application of the usual algorithm used for the calculation of the deep bounce dives was now tested for longer bottom times up to saturation in 30 m simulation dives. This showed that much longer half times were needed (8 hours or 480 minutes for N_2 and 3 hours or 180 minutes for He, using the multi-tissue model). Ninety nine percent saturation was achieved after 64 hours (N_2) and 24 hours (He) respectively.[2]

The resulting long range and saturation diving tables were in use for many years in the diving company Micoperi or later SSOS (a Shell daughter company). During the subsequent experimental series the safe decompression limits for deeper dives, around 200 m, were tested using the experience of the early pioneer dives. These dives showed that all the advantages of the ultra rapid compression and multiple gas switches were lost when bottom time was increased. A new 100 bar chamber (Fig 4), a complex designed by Benno Schenk, who now acts as technical director, allowed simulations to much greater depths.

Although during the pioneer series HPNS was never observed, the somewhat longer and deeper dives showed tremor and other symptoms. For example, the 500 m experimental dive of 1977, using heliox, was not a success because the test subjects (divers) suffered badly from HPNS and their decompression had to be modified due to decompression sickness (DCS).

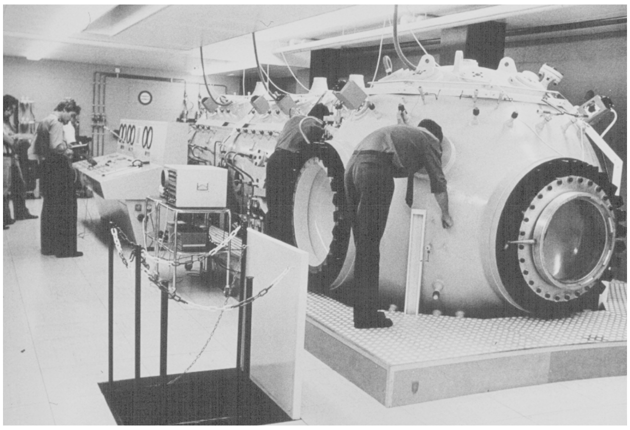


Figure 4. The three compartment research chamber at Zurich University.

After this, staged compression was introduced with good results. A 575 m chamber dive was achieved in 1981 with some HPNS in one subject and reduced working performance at maximum pressure (Table 1). Decompression from up to 300 m in the experiments resulted in newly

TABLE 1

OCCURRENCE OF HPNS WITH VARIOUS COMPRESSION PROCEDURES

A. Continuous compression, increasing with depth

215 m	in 3‘	(20-50 m/‘↓)	O_2-N_2-He	**HPNS -**	(n=2, 1961)
250 m	in 5‘,10‘	(20-50 m/‘↓)	O_2-N_2-He	**HPNS -**	(n=3, 1960/62)
300 m	in 16‘	(20-50 m/‘↓)	O_2-N_2-He	**HPNS (+)**	(n=5, 1961/62)

B. Continuous compression, constant

220 m	in 22‘	(10 m/‘↓)	O_2-He	**HPNS -**	(n=16, 1965-68)
250 m	in 25‘	(10 m/‘↓)	O_2-He	**HPNS +**	(n=11, 1967-80)
300 m	in 30‘	(10 m/‘↓)	O_2-He	**HPNS +**	(n=30, 1967-80)
350 m	in 35‘	(10 m/‘↓)	O_2-He	**HPNS ++**	(n= 6, 1977)
500 m	in 50‘	(10 m/‘↓)	O_2-He	**HPNS +++**	(n= 3, 1977)

C. Staged compression, continuous compression rate

300 m	in 155‘	(10 m/‘↓)	O_2-He	**HPNS (+)**	(n=6, 1978)
350 m	in 325‘	(4 m/‘↓)	O_2-He	**HPNS -**	(n=3, 1969)
400 m	in 255‘	(10 m/‘↓)	O_2-He	**HPNS ++**	(n=3, 1979)
400 m	in 415‘	(10 m/‘↓)	O_2-He	**HPNS -**	(n=3, 1981)
500 m	in 700‘	(10 m/‘↓)	O_2-He	**HPNS +**	(n=3, 1981)

calculated tables using an algorithm that will be explained later.

However, diving contractors found it inconvenient to work with the safety level given by the Bühlmann tables and modified the decompression procedures on an empirical basis. Bühlmann however strongly believed that his algorithm (which resembles the Workman formula) reflected the physiological processes during a dive on the grounds that, since it had been successful experimentally, it *had* to be correct physiologically. This attitude, not always appreciated by the diving operator, together with Shell's fading interest in deep diving, were the reasons for the almost complete non-publication of the results of experimental dives by the Zurich investigators during that period.

The altitude dive tables for scuba bounce diving (1972 – 1986)

In spite of modest recognition by the deep diving industry of Bühlmann's ideas, the algorithm proposed by Bühlmann and Schenk was embraced by the sports diving community. By 1971, as computers offered more calculation capacity, the number of "tissues" (or more properly half-times) was increased to 16. The longest N_2 half-time represented a 635 minute (just under 11 hours) tissue. They found that, when using linear rather than exponential functions, it appeared that knowing the molecular weight of a gas was sufficient to deduce the a- and b- values.[3] These two parameters describe the tolerated supersaturation as a function of ambient pressure per tissue, represented by its half-time. Figure 5 shows Bühlmann's theoretical maximum tolerable partial pressures, on returning to 1 bar after exposure to pressure, calculated for different tissue half times. The experimentally determined limits are shown by dots, each is the occurrence of decompression sickness symptoms

With this formula it was easy to alter a particular experimental dive profile using a hand-held calculator. Validation experiments at various altitudes were performed. Reducing the decompression stops to cause an increase of about 10 % in the decompression stress resulted in a series of experimental dives with a 30 % incidence of DCS (these were immediately treated).

These studies were supported by the Swiss army and police divers. Extreme mountain lake validation dives at

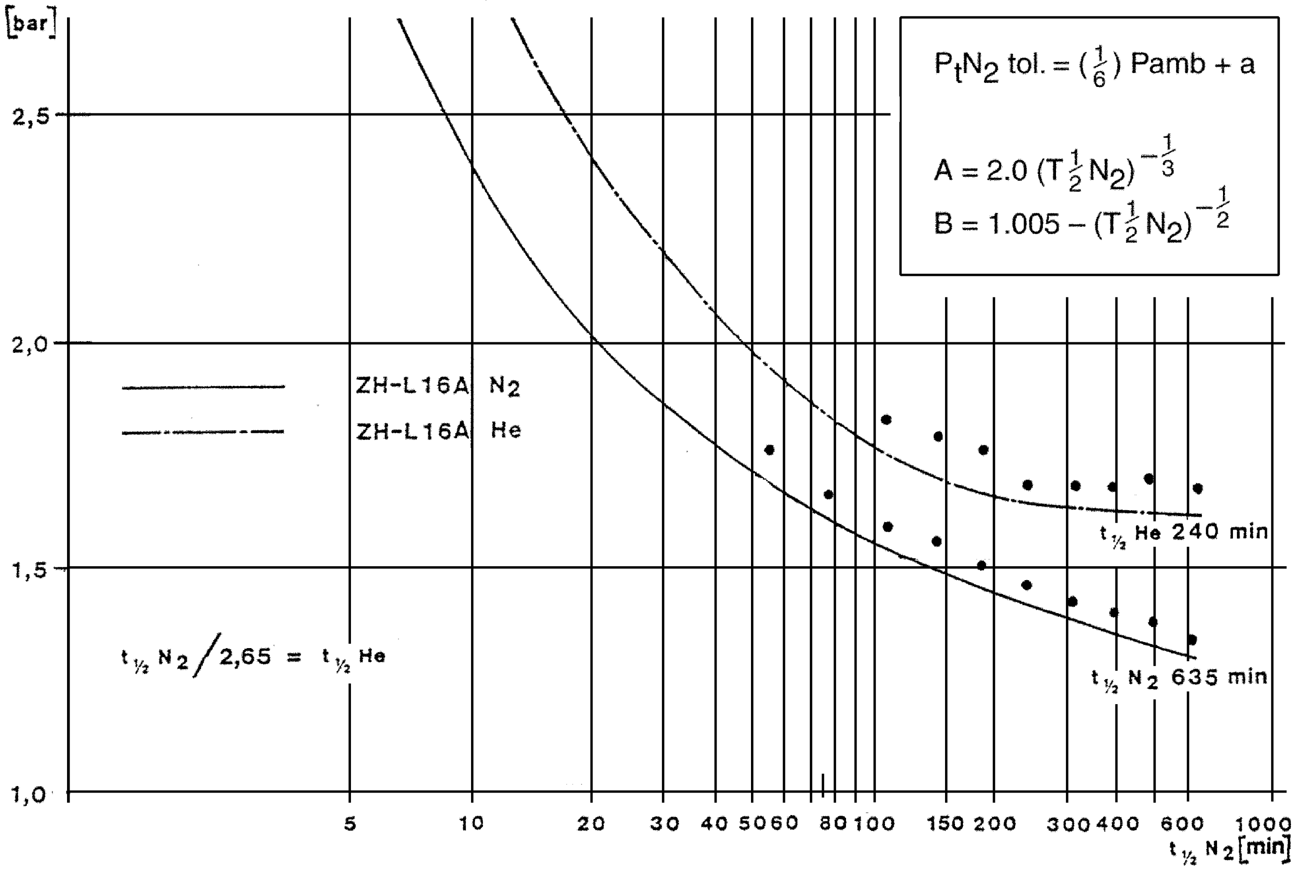


Figure 5. Bühlmann's theoretical maximum tolerable partial pressures, on returning to 1 bar after exposure to pressure, calculated for different tissue half times. The experimentally determined limits are shown by dots, each is the occurrence of decompression sickness symptoms (Redrawn from Bühlmann AA. Tauchmedizin (ISBN 3-540-58970-8) 1993).

Figure 6. W Keusen during an altitude dive at 4,780 m (Mt Kenya).

3,800 m (Lake Titicaca) and at 4,780 m (Mount Kenya, see Fig 6) proved the acceptable safety limits at these particular conditions.[4,5]

The results confirmed the calculated safety limits and gave further support to the general model. Bühlmann's hypothesis was that the algorithm had universal validity because it had been shown to be consistently successful with diving procedures when using helium, air, mixed gases for deep bounce dives as well as saturation dives.

Sports divers have successfully used the tables in various forms and in Switzerland the decompression of tunnel workers, using tables calculated for the particular altitude of the working site, has been successful.

Supporting development of dive-computers (1983-93)

When the first dive computers appeared, Bühlmann was asked to help develop a program containing the Zurich algorithm. He had never dived and considered recreational divers as foolhardy. At first he refused because he could not understand the enthusiasm of sports divers to be diving, when there was an increasing number of diving accidents in Swiss lakes.

He finally accepted the invitation having recognised that divers would use computers anyway so they might as well use his algorithm with its increased safety. He even found recreational divers interesting as research subjects for real time simulation of the tissue partial pressure of gases to get further validation of his algorithm.

For computers the tables were adapted to the specific characteristics of the hardware and software, adding the appropriate correction factors to the coefficients. Dive computers are now very popular in Europe and the DAN accident statistics do not show any increase of DCS incidence for computer users.

The next step was to study the cumulative effects of yo-yo and multi-level diving and flying after diving. Bühlmann supported the ideas of Ernst Voellm, a software-specialist and diving instructor, who wanted to modify the dive computer into an interactive monitor of various environmental and physiological parameters. The adaptive ZH16 model was born. It is influenced by the work-load of the diver, the (supposed) number of arterial bubbles and the temperature during the dive. Muscular work temporarily changes the halftime of that "tissue" resulting in a higher gas load. Bubbles slow down the elimination of nitrogen in the lungs. This is taken into account by assuming the start of bubble production when the supersaturation ratio is more than the threshold level. The correction applied is not changing the half-time coefficient, but temporarily adding a retardation factor according to the assumed quantity of bubbles as a function of time. The profiles can be downloaded into the PC and can be analysed by the divers immediately. (Fig 7)

The physiological parameters are taken by a sensor at the regulator valve and emitted to the dive computer through a radio-signal. In the same way the actual oxygen percentage will be monitored from mixed-gas rebreathers and then computed in a way to get a real time calculation of the theoretical gas tensions even during a Nitrox dive with semi-closed or closed systems.

The fact that 90% of Swiss divers and more than 80% of European divers use dive-computers, mostly with Bühlmann algorithms, without producing more accidents is an indirect validation of the algorithms used. In the future, prospective studies of the safety limits of the various Bühlmann algorithms, comparing the older ones with the most up-to-date modification, which certainly has more redundancy and would certainly allow shorter decompressions, should be performed. This project however is not financially viable if it is not sponsored by a Health and Safety Department or other interested organisation. A single individual would certainly not take the risk to reduce the coefficients.

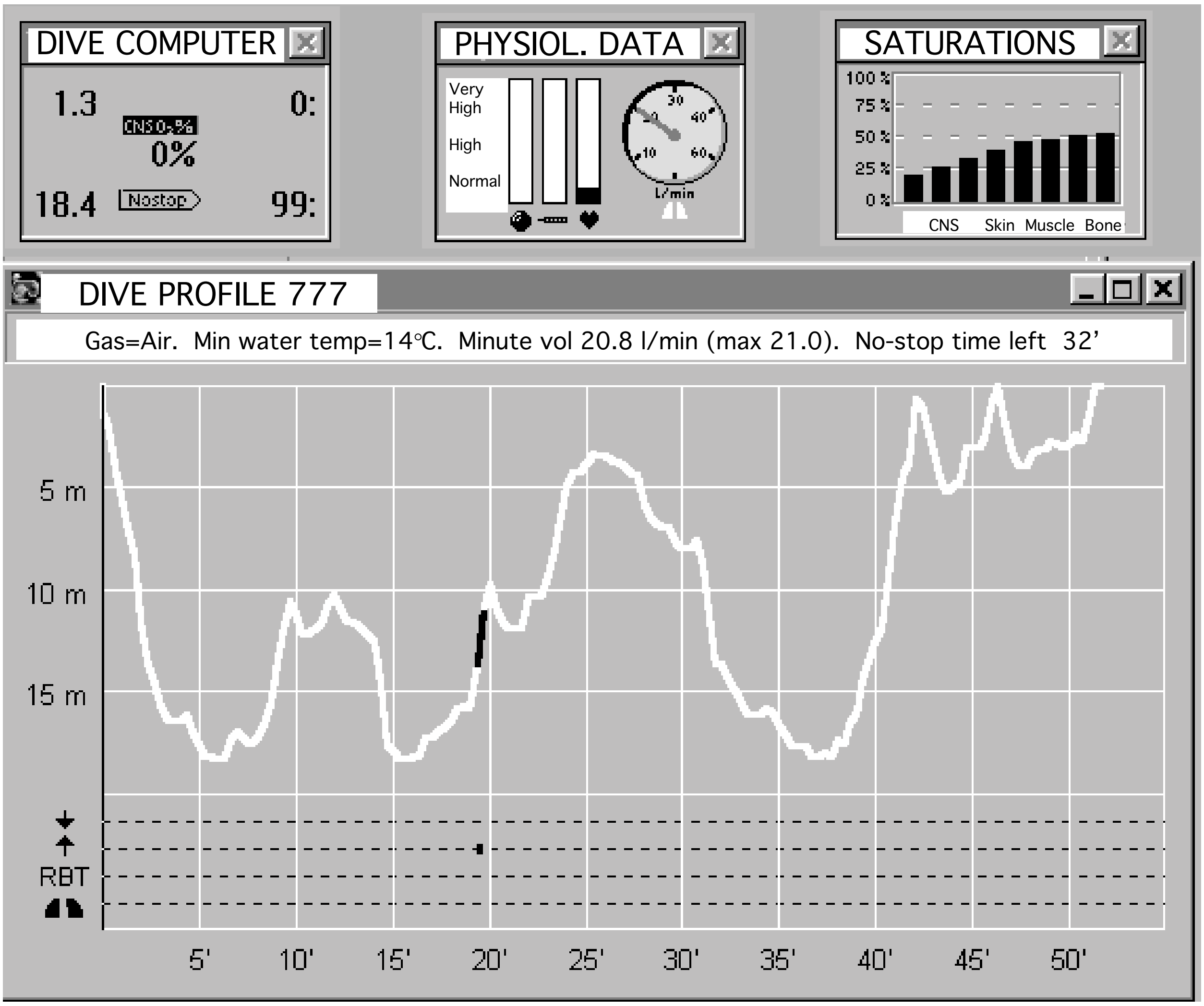


Fig 7. The graph, a screen capture, shows the time/depth profile of dive 777 taken from an Aladin-airX dive computer used by a diver. The black portion of the dive was when the diver ascended above the decompression stop requirement of the computer and the insufficient depth warning was sounded. Below the graph are four dotted lines. They are, from the top, the rapid ascent warning (arrow down), the too shallow warning (arrow up) with a black dot at the time it was activated, the alarm for insufficient remaining air to allow adequate decompression (RBT) and the hyperventilation alarm (outline of heart and lungs). The three small boxes across the top show the dive computer's calculations at the position of the cursor on the profile. In the first, at the top on the left, the maximum oxygen partial pressure attained, CNS O_2% as oxygen toxicity units and the dive time remaining. At the bottom the maximum depth and the no-stop time remaining. In the second box the first column, with a symbolic bubble below it, shows the estimated change in tissue perfusion by arterial bubbles of pulmonary (venous bubble passage), intra-arterial or tissue origin, the second column, with a symbolic thermometer under it, shows the expected temperature induced augmentation of the half times and the third column, over a symbolic heart, shows the estimated change in tissue perfusion due to increased cardiac output (calculated for the respiratory rate and minute volume). The dial, with symbolic lungs under it, shows the actual minute volume. The third box shows the saturation of eight theoretical tissues, defined by their half times, at the moment corresponding to the position of the screen cursor on the profile. In this case the CNS saturation is 25%, the skin is 40%, muscle is about 48% and bone is 50% of the tolerated supersaturation. (Redrawn from Bühlmann AA. Tauchmedizin (ISBN 3-540-58970-8) 1993)

Conclusions

The Zurich research group has now become history. Professor Bühlmann died in 1994, Hannes Keller has stopped diving and become a software-specialist and Benno Schenk will retire soon. The chamber is still used as a HBO facility and fights, as many others do, with financial problems. The University no longer finances it and it is not very practical, and too expensive, for efficient clinical use.

Research is being continued with the development of a deep dive breathing apparatus (Schenk) which facilitates breathing at greater depths, up to 700 m, by high frequency jet ventilation and airway pressure assistance.

The Zurich group was never in the main stream but nevertheless was successful in stimulating others to think over current concepts and define new ones (open bell bounce diving techniques, Workman M-values, Lambertsen counter diffusion principle).

The tables are the official dive tables of numerous sports diving associations, the CMAS affiliated diving federations in Germany, Switzerland, Austria, Ireland and Portugal, the British Subaqua Association (BSA) in England and are officially endorsed by NAUI International. The altitude adapted tables for tunnel workers are still often requested. Dive computer development benefits more and more from the "untrue", but very handy, algorithm that continues to be safe in spite of the opinions of many experts.

Acknowledgements

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References

1 Keller H and Bühlmann AA. Deep diving and short decompression by breathing mixed gases. *J Appl Physiol* 1965; 20 (6): 1267-1270
2 Bühlmann AA., Frei P and Keller H. Saturation and desaturation with N_2 and He at 4 atm. *J Appl Physiol* 1967; 23 (4): 458-462
3 Bühlmann AA. Die Berechnung der risikoarmen Dekompression. *Schweiz med Wschr* 1988; 118 (6): 185-197
4 Böni M, Schibli R, Nussberger P and Bühlmann AA. Diving at diminished atmospheric pressure: air decompression tables for different altitudes. *Undersea Biomed Res* 1976; 3 (3): 189-193
5 Moody M. *Report on Exercise Paddington Diamond, Lake Titicaca, Bolivia.* 1987

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A BRIEF HISTORY OF DIVING AND DECOMPRESSION ILLNESS

Chris Acott

Key Words

Decompression illness, history, occupational diving.

Abstract

The significant events in the history of diving and decompression illness (decompression sickness and cerebral arterial gas embolism) are listed in chronological order.

The early history of diving

4,500-3,200 BC

Archaeological evidence shows that breathhold divers harvested sponges, food, mother of pearl and coral.[1,2]

1,194-1,184 BC

Breathhold divers were used in the Trojan wars to sabotage ships. Counter measures were introduced.[1]

900 BC An Assyrian bas-relief that showed a swimmer using an air filled balloon was part of King Assur-Nasir-Pal's palace at Nineveh. This balloon was probably not an air reserve but an early buoyancy device. This bas-relief is displayed now at the British museum.[3]

460 BC Herodotus described a Greek diver, Scyllis, also called Syllias or Scyllos, salvaging treasure for the Persian king, Xexres. He was so successful that Xexres held him captive to continue diving. Scyllis escaped by swimming 9 miles to shore during a storm (probably not underwater as it was reported!). He sabotaged the salvage fleet by cutting its moorings.[4]

332 BC Alexander the Great used divers for underwater demolition during the Siege of Tyre. He was supposed to have dived in a diving bell named "Colimphax". This event was recorded in a French manuscript in 1,250 AD.[1-5]

384-322 BC Aristotle described the use of the snorkel. He also described tympanic membrane perforation in divers and the use of the diving bell by Alexander the Great.[3,5] Reed snorkels have been used throughout history even recently