EVALUATION OF ALTITUDE DECOMPRESSION PROCEDURES AND DEVELOPMENT OF NEW DECOMPRESSION STRATEGIES

by

SALİH MURAT EGİ

B.S. in Electrical Engineering, Boğaziçi University, 1989

M.S. in Biomedical Engineering, Boğaziçi University, 1992

Submitted to Institute of Biomedical Engineering
in partial fulfillment of the requirements
for the degree of
Doctor
of
Philosophy

Boğaziçi University

December, 1998

ACKNOWLEDGEMENTS

I am deeply grateful to my thesis supervisor, Prof. Dr. Yusuf P. Tan for his support. Very special thanks are to be extended to Prof. Dr. Yekta Ülgen, Dr. Yıldırım Bahadırlar and Fırat Yeşilleten for their collaboration during the bioimpedance project. I would like to express my sincere thanks to Prof. Dr. Yorgo İstefanopulos who supported the altitude diving project in every aspect. Without him, the altitude diving project would never be completed.

I deeply appreciate the invaluable medical assistance provided by Assoc. Dr. Salih Aydın and Assoc. Dr. Şamil Aktaş and Dr. Erdem Yavuz.

I wish express my gratitude to collaborators at SINTEF UNIMED, Section for Extreme Work Environment. I would like to thank Prof. Dr. Alf Brubakk for his notable suggestions and continuous scientific support and Olav Eftedal, friend and collaborator, who was always ready to answer questions about bubble detection.

I'm grateful to my family for their support and patience.

I am indebted to the friendly village people of Olgunlar and Kişgıllı who supported the Kaçkar and Süphan Expeditions, the team commander Ahmet Demir, his platoon and the armed volunteers so who provided close protection in hostile environment during the Süphan Expedition.

I wish to thank to all those brave ladies and gentlemen who participated in the Uludağ, Kaçkar and Süphan Expeditions, risked their lives, shared the difficulties and the knowledge. Namely: Nihat Gürmen, Umur Özkal, Mete Uz, Ahmet Özman, Murat Aydın, Baki Yokeş, Sertaç Kanan, Aydın Kandemir, Murat Yeşilleten, Aylin Özsoy, Zeynep Özsoy, Hakan Demirtürk, Zuhal Akan, Tolga Erkal, Samim Saner, Muhammet Uludağ, Emre Küçükçolak, Begüm Özkaynak, Fatih Hüseyinoğlu, Nilcan Kuleli, Cengiz Dinçoğlu, Esen B[illegible]yayla, Çiğdem Dindar, Burak Altınbaşak, Ahmet Şenoğlu, Deniz Şengün, Elvan Şengün, Oğuz Uzel, Lutfi Kolukırıkoğlu, Engin Aygün, Fehmi Şenok, Ali Bora İşbulan, Defne Erdur, Özlem Arıkan, Türker Tunalı, Didem Tünel, Derya Özkaya, Nevzat Aydın.

This thesis is dedicated to BÜSAS (Boğaziçi University Skin and SCUBA Diving Club), where I learned not only diving ...

EVALUATION OF ALTITUDE DECOMPRESSION PROCEDURES AND DEVELOPMENT OF NEW DECOMPRESSION STRATEGIES

ABSTRACT

Diving at altitude requires different tables than at sea level due to the reduction in surface ambient pressure. Several algorithms extrapolating the sea level diving experimental data have been put forward to construct altitude diving tables. The rationale for these algorithms is reviewed together with the conservatism of the resulting tables and decompression computer outputs. These are linear extrapolation (LEM); constant ratio translation (CRT) and constant ratio extrapolation (CRE) of maximum permissible tissue tensions (M values). Either new tables using the altitude-adapted M values were put forward or sea level tables are to be used through an operation called correction.

In this thesis, it is shown that for a given set of M values, CRT and CRE give the same result for no decompression stop dives; they always yield more conservative results than LEM. When decompression stops are used, then CRT is more conservative than CRE. When applied to different sets of M values, the conservatism becomes a function of bottom time, depth and altitude. Aviation altitude exposure decompression sickness (DCS) data is also addressed to compare different model outputs. Animal experiments performed within the scope of this thesis proved that precordial bubbles can form during the ascent from sea level to 2000 m. supporting a far lower threshold for altitude DCS then the model outputs.

In this work, a software package is developed to compare the output of the existing models related to the study of safe decompression profiles and compute new tables. Following three pioneering altitude diving expeditions to 2200, 3412 and 3980 m, a set of no-decompression stop (no-d) limits for 3500 m was calculated using linear extrapolation of US Navy M values decreased by 4 fsw (1 fsw = 3.063 kPa). This is a new method of altitude adaptation (NLHE, Nonlinear Hypobaric Extrapolation). The limits were tested during two expeditions to Kaçkar Great Sea Lake, 3412 m, Northeast of Turkey. At the end of five expeditions, 212 dives were achieved with a total bottom time of 4110 min. The no-decompression stop limits of 15,18,21,24,27 and 30 m. were tested by 10 man/dives per profile without any case of DCS. The mean DCS risk estimated according to precordial bubble scores (Spencer's Scale) ranges from 0.3% to 2.8% per profile. These results show that this method can be an alternative to the existing methods of hypobaric extrapolation of DCS boundary.

The last part of the thesis is devoted to the computation of decompression tables for 3500-m altitudes. This work suggests the use of a continuos variable for the compartment time constants, allowing the simulation of infinite number of compartments and reducing the discrepancy between different algorithms to a single M value expression.

Keywords: Algorithm, altitude, altitude sickness, aviation, decompression, decompression sickness, decompression tables, diving, dive computer, hypoxia, oxygen window

İRTİFA DEKOMPRESYON YÖNTEMLERİNİN DEĞERLENDİRİLMESİ VE YENİ DEKOMPRESYON STRATEJİLERİNİN GELİŞTİRİLMESİ

ÖZET

Yüzey seviyesindeki basıncın azalması nedeniyle irtifa dalışlarında kullanılan tablolar farklıdır. Deniz seviyesindeki dalışlardan elde edilen verilerin irtifaya uyarlanması için farklı bir kaç yöntem öne sürülmüştür. Bu tezde sözkonusu yöntemlerin altyapısı ile bunlara dayanılarak oluşturulan dalış tablolarının ve dalış bilgisayarlarının çıktılarının ne derece tutucu olacağı gözden geçirilmiştir. Bu yöntemler, izin verilebilecek en yüksek doku doygunluk seviyelerinin (M değerleri) doğrusal uzanım (LEM), sabit oran taşınması (CRT) ve sabit oran uzanım (CRE) yöntemleri ile irtifaya uyarlanmasını içerir. Tablolar ya uyarlanmış M değerlerine dayanılarak kullanılır ya da deniz seviyesi tabloları düzeltme işlemi sonrasında kullanılır.

Bu tezde, belirli bir M değerleri dizisi için, CRT ve CRE yöntemlerinin dekompresyon duraksız dalışlar için aynı sonuçlar vereceği ve bunların her zaman LEM yönteminden daha muhafazakar olacağı ispatlanmıştır. Dekompresyon durakları kullanıldığında ise, CRT yöntemi CRE'ye göre daha muhafazakar olacaktır. Bu yöntemler farklı M değeri dizilerine uyarlandığında ise muhafazakarlık derinlik, dip zamanı ve irtifanın bir fonksiyonu olacaktır. Farklı modeller, havacılıkta karşılaşılan dekompresyon hastalığı (DH) sınırına da uygulanarak karşılaştırma yapılmıştır. Bu tezin kapsamı dahilinde yapılan hayvan deneylerinde ise 2000 m yükseltide dahi prekordial kabarcık gözlenmesi bu sınırın çok daha alçak irtifalarda olabileceğini ortaya koymaktadır.

Bu çalışmada, yeni tabloların hesaplanabilmesi ve farklı model çıktılarının karşılaştırılması için bir yazılım paketi geliştirilmiştir. 2200, 3412 ve 3980 metreye yapılan üç ön araştırma gezisinden sonra, USN M değerlerinin 4 fsw (1 fsw = 3.063 kPa) azaltılması ile 3500 m için sıfır dekompresyon sınırları hesaplanmıştır. Bu irtifa dalış tablolarının hesaplanması için yeni bir yöntemdir (NHLE, Nonlinear Hyperbaric Extrapolation). Bu sınırlar Kaçkar Büyük Deniz Gölü'ne (3412 m.) yapılan iki araştırma gezisi ile sınanmıştır. Beş araştırma gezisinin sonunda 212 dalış tamamlanarak toplam 4110 dakika dip zamanına ulaşılmıştır. 15,18,21,24,27 ve 30 m sınırları profil başına 10 dalış düşecek şekilde hiç bir DH görülmeksizin sınanmıştır. Dalışlardan sonra yapılan precordial Doppler ultrason değerlendirmelerinden (Spencer Ölçeği) yola çıkarak yapılan kestirimde profil başına düşen ortalama DH riskinin 0.3% ile 2.8% arasında değiştiği hesaplanmıştır.

Tezin son kısmı 3500 m için dekompresyon tablolarının hesaplanmasına ayrılmıştır. Bu çalışmada ise doku yarı ömürleri için sürekli bir ifade kullanılarak sonsuz sayıda dokunun benzetişimi gerçekleştirilmiştir.

Anahtar Kelimeler: Algoritma, dağ hastalığı, dekompresyon, dekompresyon hastalığı, dekompresyon tablosu, dalış, dalış bilgisayarı, havacılık, hipoksi, irtifa, oksijen penceresi, vurgun

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

P_t	Inert gas tension in tissue
P_B	Ambient pressure (absolute)
s	Supersaturation ratio
s_m	Maximum allowable supersaturation ratio before any symptom of DCS occurs
D	Ambient pressure (gauge depth)
M(D)	Maximum allowable tissue tension before any symptom of DCS occurs
M_0	Sea level M value
a	Empirical constant corresponding to the slope of the M(D) versus D curve in the linear expression of M values
b,c	Empirical constants in Bühlmann expression of DCS boundary
M_b	Bühlmann M values
P_0	Sea level ambient pressure
h	Altitude
P_h	Ambient pressure at altitude h
$M_h(D)$	M value function extrapolated to hypobaric medium
M_{h0}	Surface level $M_h(D)$
$M_{XT}(D)$	M value function of a compartment. The half life of the compartment is X
P_c	Gauge depth of similar (equivalent) sea level dive
P	Gauge depth of actual dive
α	Correction factor
d_s	Sea level gauge depth of the decompression stop
d_a	Actual gauge depth of the decompression stop

$P_{hcritical}$	Pressure axis coordinate of the intersection point of two M(D) functions of the same tissue
$T_{1/2}$	Tissue half-life
T	Temperature
$\Pi_i(t)$	Inert gas exchange function
f	Fraction of N_2 in the alveoli
t	Bottom time
k	Tissue rate constant
Z(t)	Safety factor function while assuming that the diver is not equilibrated with the altitude, although he or she does
P_{hmax}	Ambient pressure of altitude threshold giving rise to DCS
P_X	Partial pressure of gas X.
V	Tissue volume
Q	Blood flow
sx	Solubility of gas in the compartment x
P_aX	Arterial tension of gas X
P_AX	Alveolar partial pressure of gas X
R	Respiratory quotient
F_iX	Fraction of inhaled gas X in dry air
P_{50}	Partial pressure of O_2 at which 50% of hemoglobin sites are filled
Y	Fractional saturation with oxygen
VO_2	The volume of oxygen in 100 ml of blood
C_{Hb}	Concentration of hemoglobin
γ	Volume of O_2 that combines to each gram of hemoglobin.
$VcapO_2$	Volume of O_2 in 100 ml of capillary blood

VvO_2	Volume of oxygen in 100 ml of venous blood
P_VX	Tension of gas X in venous blood
d	Rate of descent
δ	Deviation from linear extrapolation
fc	Characteristic frequency of the Cole-Cole plots

1. INTRODUCTION

Decompression sickness (DCS, Bends, Caisson Disease) is a result of inadequate decompression following exposure to increased pressure. It is encountered in aviation, space extravehicular activities (EVA), tunnel working and diving.

Metabolically inert gases such as Helium, Nitrogen, Hydrogen dissolve in body tissues under high pressure. Upon decrease of the ambient pressure, the gas(es) dissolved in the body fluids return to the gas phase, thereby forming bubbles. The bubbles in turn cause various symptoms, namely: chest or back pain, dizziness, extreme fatigue, headaches, malaise, numbness, pain at or near joints, tingling sensations, blotchy skin, confusion, convulsions, coughing, difficulty passing urine, hearing loss, incoordination, itch, loss of balance, loss of bladder/bowel control, nausea, paralysis, rash, ringing in ears, shortness of breath, unconsciousness, visual disturbances [1].

In order to avoid DCS in divers and tunnel workers, several ascent schedules showing safe pressure-time combinations were developed [2-7], whereas in aviation, much of the effort is devoted to establish a lower altitude limit not without any dispute [8-12], Although various decompression tables were proven to be quite satisfactory for relatively shallow and short duration sea level diving operations, they fail for saturation and deep sea diving. This is due to the empirical nature of these tables, whose underlying principles fail when the application domain is attempted to be extrapolated from the region of the supporting experimental data.

The conflict between different decompression algorithms is also enhanced when the altitude is increased [13]. For high altitude diving, i.e. above 3000 m, the number of the controlled experiments are not enough to exclude or accept any of the existing tables for diving at altitude.

1.1. Motivations

1.1.1. Evaluation of Opposing Decompression Theories and Development of New Theories

Different decompression tables are based on opposing theories of gas exchange, bubble formation, decompression sickness boundary, site or existence of critical tissues. However, through fitting of the theory into experimental data, these tables give quite similar results for shallow, short duration air diving. However, divergence is quite obvious when diving takes place in the hypobaric environment (Table 1.1).

Table 1.1

No-Decompression stop limits for diving at high altitude

Depth (m)	Bühlmann [4] (2500-3500m) (min)	Böni[a] [2] (2500-3200m) (min)	USAF [14] (10 000 ft) (min)	USC[b] (3500 m) (min)
12	76	30	51	60
15	55	10	37	40
18	38	5	27	26
21	25	--	19	18
24	20	--	13	12
27	17	--	10	9
30	15	--	8	7
33	12	--	6	6

[a]Each dive must include a decompression stop of 3 min at 2 m
[b]USC: USN no-d limits as modified by Cross Corrections [15,16]

This Ph.D. thesis is aimed to determine the validity of the underlying theories and establish a new model, through field tests. The purpose is to develop or synthesize somehow "more universal" safe decompression procedures.

1.1.2. Operational Concerns

Sportive activities, lymnological researches, underwater surveys, military operations and commercial activities motivate diving at altitude.

1.1.2.1. Sportive activities. Altitude diving is widely practiced in the mountain lakes of Switzerland, and Austria, since those countries do not possess seashore. The favorite decompression tables in these countries are Bühlmann Tables. These tables are accepted by CMAS (Confédération Mondiale des Activités Sub-Aquatiques, World Underwater Federation).

In the Transvaal, South Africa, all of the inland diving is carried out between 1300 and 1800 m [17]. In India, diving training is routinely carried out at 2134 m, in Lake Pykara [18]. Chili and Mexico are also among the countries where diving at altitude is quite common [19,20].

The training for high altitude diving is also within the curriculum of the recreational and technical diving activities, who offer air and nitrox tables up to 3900 m [21-25]. However, each organization adopts a different table (Table 1.2). None of these tables have been adequately tested above 3000 m. On the other hand, high altitude diving expeditions extends up to5928 m. [26-30].

Table 1.2

Altitude dive tables and corrections of recreational diving organization

ORGANIZATION	TABLE
CMAS	Bühlmann
IANTD (International Association of Nitrox and Technical Divers)	IANTD altitude diving tables
BSAC (British Sub-Aqua Club)	BSAC '88 Tables [25]
PADI (Professional Association of Diving Instructors)	Recreational Dive Planner/Cross Corrections
NAUI (National Association of Underwater Instructors)	NAUI Tables/ Corrections

1.1.2.2 Scientific Researches. Lake Tahoe (1860 m, CA) is one the favorite diving sites for lymnological researches. Possibly the earliest altitude decompression tables were developed by Dr. Jon Pegg in 1965 for such studies, but were never published [23]. In this lake, the University of California has conducted diver training and lymnological research for years. The investigation of endemic species was among the main purposes in two high altitude diving expeditions [19,30]. Archeological surveys were also included within the scope of the above expeditions. In fact, in Inca mythology, Manco Capac and Mama Ocllo, children of the Sun, emerged from the depths of Lake Titicaca (3810 m) to found their empire. Lake Titicaca has long been known to be not only the largest but also the most sacred lake in the Andes. Legends about the lake abound. They describe underwater cities, roads and treasures. The legends of treasures in Lake Titicaca began nearly as soon as the Spaniards, who entered Peru in 1532, became aware of it. In 1541 Almagro the Younger accused Hernando Pizarro of having sent men to search for treasure in the lake with the result that ten men drowned. With the development of underwater diving equipment, it was inevitable that investigations of the lake began to be undertaken. One of the first people to search it for artifacts and ruins was an American, William Mardoff. Unfortunately, he did not publish a report on his expedition. Mardoff is said to have dived twenty-five times at various places in the lake during 1956, but to have only found some pottery. He told of having seen a city 80 m. under water. Although never verified, this story (or ones similar) eventually led to other expeditions, including many unreported illegal dives for the quest of gold. An expedition was organized by Jacques Cousteau to investigate the lake in 1968. He reached the conclusion that the structures found by previous researchers were simply stones used to make walls to protect boats from the waves [30].

1.1.2.3. Military Operations. Altitude diving is also within the scope of military diving operations. The importance of altitude diving for the Swiss Army is emphasized by Bühlmann [31]. Conversion tables were developed by the Canadian Army to use the sea level dive tables at altitude [32]. The US Navy Diving Manual does not include altitude dive tables. Whenever required, they have to get them from the Operations Headquarters. A recent international exercise at Lake Titicaca involved hyperbaric exposures in open water and in hyperbaric chamber [29]. Since above 10500 ft US Navy does not have defined diving tables, Cross Corrected Böni 1976 Table 5 was used.

1.1.2.4. Commercial Operations. Commercial operations are quite common in reservoir lakes. In the case of commercial diving bottom time might be excessive, so does the decompression time. In the history of commercial applications of saturation diving was conducted by Marine Contracting of Southport, Connecticut, in 1965. The location was in Smith Mountain Dam, Virginia. Approximately two and a half years were spent filling the lake behind the dam, and construction costs approached $100 million. Trashracks were destroyed on two units located at 41.1 m and 62.5 m. The operation lasted 16 weeks and the project required 800 man hours bottom time [33].

Financial concerns and the operational difficulties associated with longer decompression times hinder the use of over safe decompression schedules. A commercial decompression procedure is developed by Stolt-COMEX, and is based on the correction of sea level tables and uses 6 m oxygen decompression stop (or altitude equivalent of that depth). No information is available on neither the development nor the testing stages of these tables. Considering the large number of dams built in Turkey, in future, commercial diving operations at altitude might be necessary in reservoir lakes.

A second commercial application of decompression at altitude is the tunnel work. An example of a construction technique using pressurized environment has already been applied in Mexico City, at 2286 m. [34].

1.2. Thesis Outline

The thesis is composed of twelve chapters. The first chapter outlines the motivations for carrying out altitude diving. The second chapter reviews the existing altitude decompression strategies and provides a method for comparing the conservativeness of different algorithms. The third chapter discusses the possible effects of hypoxia on DCS. The fourth chapter includes the estimation of oxygen window before and after altitude acclimatization. The fifth chapter is about the software library used to analyze the gas exchange and bubble formation as well as computation of decompression procedures. The sixth chapter describes the pioneering expeditions to Mt Uludağ (2200m), Mt Kaçkar (3412 m) and Mt Süphan (3980 m), the last one being the highest altitude dive in Turkey and may me cited among the highest altitude diving expeditions in the world. The seventh chapter includes animal experiments at simulated altitude. The testing of no-d limits calculated using an alternative method of altitude adaptation (Kaçkar '94 Expedition) is the topic of chapter eight. The effects of acclimatization are also described in this chapter. Chapter nine is the second phase of the tests of no-d limits (Kaçkar '97). Chapter ten concludes the operational problems of high altitude diving. Chapter eleven describes a new algorithm for modeling gas exchange and DCS boundary and the computation of decompression tables for 3500 m. Chapter twelve is reserved for the conclusions.

The thesis is a first attempt to define the effects of hypobaric hypoxia on diving. It also provides a method for comparison of different algorithms. The calculation of no-d limits is based on a novel concept of DCS boundary and the values presented in this thesis are the first field tested no-d limits for 3500 m. Animal experiments proved that the DCS may be encountered at very low altitudes. Finally, the continuous tissue model presented in Chapter twelve is a novel method in modeling DCS.

2. REVIEW OF DECOMPRESSION STRATEGIES

2.1. Introduction

Metabolically inert gases such as He, N_2 and H_2 dissolve in tissues at a rate that is a linear function of pressure. Upon reduction in pressure, the tension of the inert gas (P_t) may exceed the ambient pressure (P_B). The supersaturated state is defined as:

$$s = P_t / P_B \qquad (2.1)$$

Boycott et al. postulated that there exists an allowable supersaturation ratio (s_m) below which no symptoms of decompression sickness will occur. Based on the observation that goats can be decompressed to half of the saturation pressure without developing DCS, they concluded that the allowable supersaturation ratio is 1.58 [3]. Further experiments showed that the fixed ratio principle is too conservative for shallow dives but not conservative enough for deep dives. Hawkins et al. explained this by assuming the existence of multiple compartments in the body with different rates of gas exchange and supersaturation tolerances [5]. Moreover, Van Der Aue et al. observed that tolerable supersaturation ratio decreases with ambient pressure [6]. Thus, s_m will be a decreasing function of P_B (Figure 2.1b) and tissue rate constant.

For a given tissue and for each P_B there exists a unique s_m, therefore a unique P_t; so, for a given P_B, it is equally possible to express the symptomatic limit of DCS with the amount of dissolved (or supposed to be dissolved) gas. If the permissible amount of gas is expressed in terms of the gauge depth (D) instead of P_B, then this is called an M value of depth D [7]. The M values can be expressed in terms of the function:

$$M(D) = a \cdot D + M_0 \qquad (2.2)$$

where M_0 is the M value at surface and 'a' is an empirical constant. The transformation of the M values to s_m can be achieved by using:

$$s_m = (a \cdot D + M_0) / (D + P_0) \tag{2.3}$$

where P_0 is the sea level ambient pressure. For the sake of consistency, all DCS boundary expressions presented as a function of ambient pressure are termed as M values in this text. As an example, the original expression of Bühlmann DCS boundary is converted to M value function. Although the permissible tissue inert gas tension is expressed differently in Bühlmann tables, it is possible to write the corresponding M value function. The Bühlmann expression of DCS boundary is:

$$P_{tt} = P_B/b + c \tag{2.4}$$

where P_{tt} is the maximum nitrogen tension tolerated at the ambient pressure, b and c are empirical constants [4,9,31]. P_{tt} is the same identity as M values. $P_{tt} = M_b(D)$ and $P_B = D + P_0$ then:

$$M_b(D) = (D + P_0)/b + c \tag{2.5}$$

where M_b is the corresponding Bühlmann M values. Separating variables:

$$M_b(D) = D/b + P_0/b + c \tag{2.6}$$

then $P_0/b + c = M_{0b}$ and $1/b = a$ in Eq. 2.2. The concept of a straight DCS boundary is equally used in most decompression theories even if no tissue is assumed to be supersaturated [17,35-37]. It is thus always possible to convert them to the corresponding M values. The attempt to define a tolerable amount of gas phase coming out of solution before giving rise to DCS leads in the same way to a straight DCS boundary which defines the relationship between an allowable gas uptake and the ambient pressure [17,35-37]. So, for the sake of consistency with other non-neo-Haldanian theories, it is possible to redefine M values as the allowable gas content (dissolved + gas phase) above which symptoms of DCS will occur.

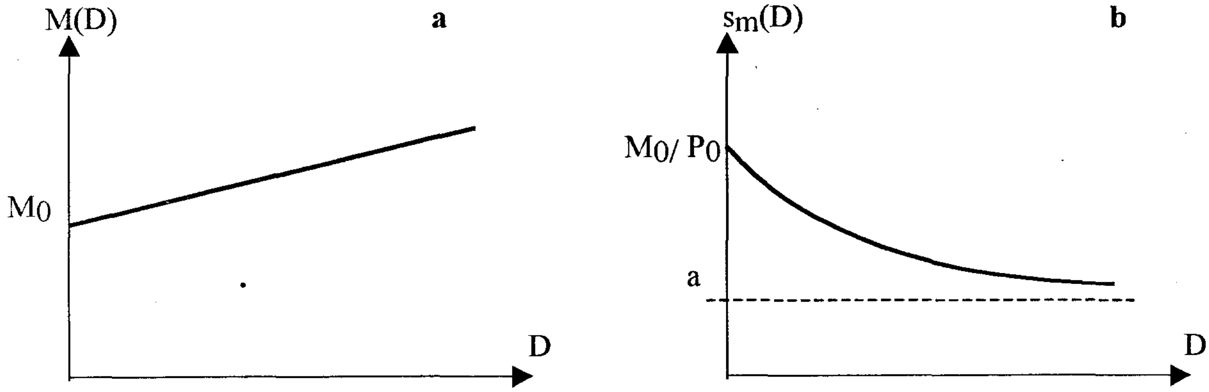


Figure 2.1. Typical M value and s_m value curves. Incrementally linear M(D) function (a) corresponds to a decreasing hyperbolic s_m (D) function (b).

2.2. Existing Algorithms of Altitude Diving Tables

Altitude dives require different tables than sea level tables because the surface level P_B diminishes with increasing elevation. The altitude P_B (P_h), if expressed in terms of gauge depth corresponds to the negative part of the x-axis in the M value and s_m value curves (Figure 2.1a, 2.1b). To define the critical tensions and tolerable supersaturation ratios in this part of the graph, either extrapolation or translation of the curves of sea level dives is performed. These algorithms do not take into account a possible change in the gas equations or DCS boundary due to the hypoxic response of the body above 2400 m. The time constants of the tissues are assumed to remain the same and the critical tensions or ratios are obtained through adaptation of sea level values. Few experiments have been carried out to confirm the predictions [2,4,9,17]. There are three different principles of adaptation:

A. Linear extrapolation of M values (LEM) (Figure 2.2a, 2b) [4,9,17,31]
B. Constant ratio translation (CRT) of M and s_m values (Fig. 2.3a, 2.3b) [15,16,34,38,39]
C. Constant ratio extrapolation (CRE) of s_m values (Figure 2.4a, 2.4b) [2]

These principles can be used to calculate new tables [2,4,9] or to use the existing ones through an operation called **correction** [15-17,34,38,39]

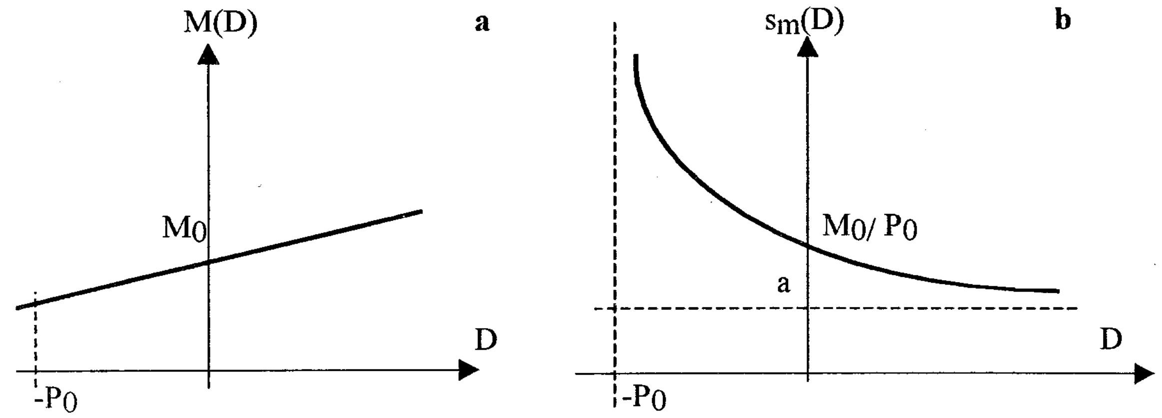


Figure 2.2. LEM algorithm. When linearly extrapolated (a), M values still give a positive tolerable tension at ideal vacuum ($-P_0$). This corresponds to an infinite tolerable supersaturation ratio at vacuum (b).

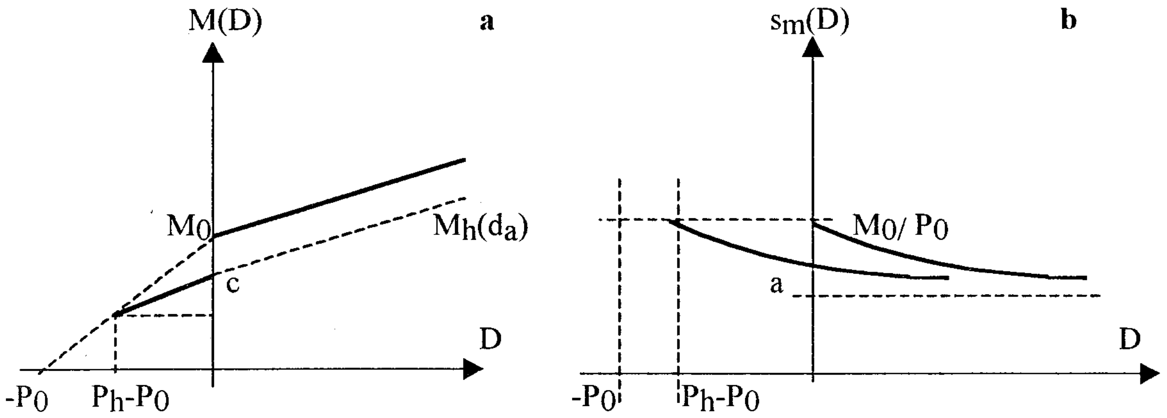


Figure 2.3. CRT algorithm. (a) CRT of M values. After intercepting Y axis at c, $M_h(d_a)$ line gives contradictory results (dashed). M_0 corresponds to sea level permissible tension; c is the M value of for a depth of (P_0- P_h) in altitude dives at P_h; (b) critical ratios corresponding to CRT.

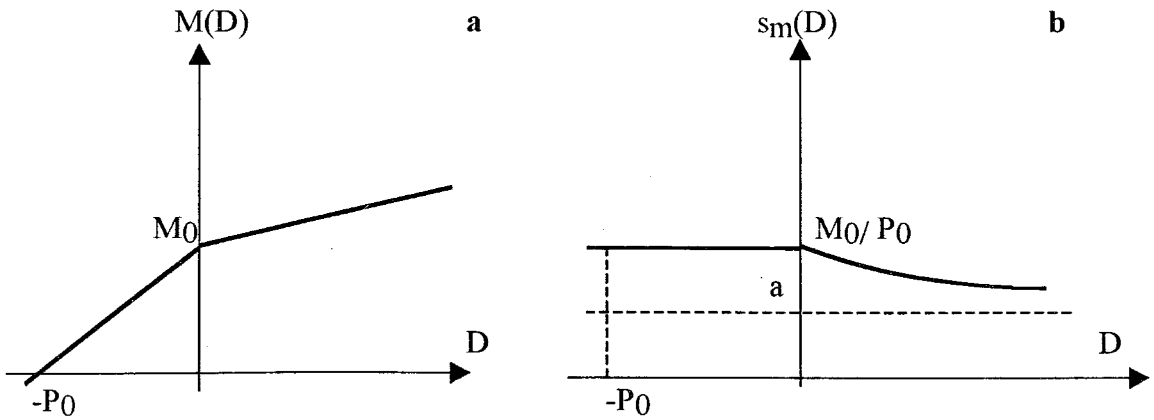


Figure 2.4. CRE algorithm. Extrapolation of M values (a) is done according to the sea level permissible ratio. This ratio is assumed to be constant for all altitudes (b)

2.2.1. LEM Algorithms

To find the safe surfacing value at the altitude it is sufficient to extrapolate the M versus D curve linearly (Figure 2.2a). The gauge depth of the altitude surface value will be P_h-P_0 where P_h is the surface level ambient pressure corresponding to the given altitude. Using Eq. 2.2, the M_0 value at a given altitude (M_{h0}) will be:

$$M_{h0} = M_0 + a \cdot (P_h - P_0) \tag{2.7}$$

It is equally possible to calculate the M value of any depth by substituting D with the ambient pressure at the decompression stop expressed as gauge depth relative to sea level pressure (Figure 2.2a).

This principle is used by Bühlmann to device altitude diving tables [4], and by Hennessy to calculate corrections for standard sea level tables [17]. To introduce a safety factor, Bühlmann tables assume that the diver is not equilibrated with the ambient pressure. These tables were tested by 573 simulated dives in the chamber and 544 mountain dives [9]. However, limited data is available about the profiles of the test dives. On the other hand, Hennessy introduced two separate correction formulas for sea level and altitude equilibrated divers. Some of the decompression computers such as Decobrain, Aladin [40] and Scubapro DC-12 (personal communication) with altitude diving option use LEM to calculate decompression procedures. They also compute the nitrogen elimination during altitude residence.

Note that this type of extrapolation will imply greater tolerance to higher supersaturation ratios for increasing altitude, asymptotically approaching infinity at zero absolute pressure (Figure 2.2b). Bell [34] points out that the region of extrapolation of s_m values is located in a region of greatest curvature, and it may be hazardous to extrapolate. In contrast, M values are located on a straight line providing no obvious hazard to extrapolate. The method seems to underestimate the altitude DCS limit compared to the aviation literature (to be discussed separately).

When applied to US Navy M values, this method gives ambiguous results. The multiple compartment principle of US Navy M values is based on the principle that tissues with longer half times have less supersaturation tolerances. The linear formulation of M values implies decreasing critical tensions in the hypobaric range. Above a given altitude, compartments with longer half-life will have higher supersaturation using this procedure, contradictory to the multiple compartment concept.

For instance, solving $M_{40T}(D) = M_{200T}(D)$ yields 5602 m altitude. Above this altitude, 200T compartment will give larger supersaturation ratios than 40T. This situation is totally contradictory to the multiple compartment concept. In fact, LEM of US Navy M values has been tested and found inadequate for flying after diving [14].

2.2.2. Constant Ratio Translation (CRT)

Correction terms are used to specify that the sea level tables will be used after converting the depth of the actual dive to a **similar dive** at the sea level. The original similarity criterion is published in Skin Diver 1967 and refined in 1970 by E.R. Cross and recognized thereby as Cross Corrections [15-16]. The same philosophy of using the sea-level tables after converting the actual depth of a dive performed at the altitude is therefore grouped under the name of "correction". In the original Cross Corrections the gauge depth of the similar dive (P_c) is given by:

$$P_c = P \cdot P_0 / P_h \tag{2.8}$$

where P is the gauge depth of the actual dive. The similarity requires that the diver is totally equilibrated with P_h. The term P_0/P_h is also known as correction factor (α). After calculating the depth of the similar dive, the standard sea level diving tables can be used but the decompression stops should also be corrected as:

$$d_a = d_s / \alpha \tag{2.9}$$

where d_s is the sea level decompression stops and d_a is the actual stop for the altitude dive. This implies that the corresponding permissible tensions for the altitude dives should also be divided by α:

$$M_h(d_a) = M(d_s) / \alpha \tag{2.10}$$

Substituting D by d_s in Eq. 2.2 and combining Eq. 2.9 and 2.10 we find:

$$M_h(d_a) = M_0 / \alpha + a \cdot d_a \tag{2.11}$$

This is a translation of the M(D) curve along the M_0/α line with $d_a = D - (P_h - P_0)$ (Fig. 2.3a)

Another simple way of using Cross Corrections, which gives exactly the same result above is to use simply a capillary gauge and enter the readings of the capillary gauge directly into the sea level tables [39].

It is somehow contradictory to adopt the old fixed ratio principle of Boycott et al. for adaptation of a table that uses a depth dependent ratio model. As a result, Cross Corrections (CRT) are self-contradictory, as they result in multiple M values corresponding to the same ambient pressure. For example, the M value of a 2 meter decompression stop of an altitude dive at 81.06 kPa is different from the surfacing value (M_0) of the sea level dive although the ambient pressure at the 2m stop at 81.06 kPa (101.325 kPa absolute) is the same as sea level surface pressure. It is possible to ensure the consistency in the graph by defining $0 < d_a < (P_0 - P_h)$. Then M(D) will be a discontinuous function defined for all D.

Dacor Omni Pro and Oceanic DataMax Pro use this algorithm (personal communication). Both of the computers follow the decompression procedures based on the CRT corrections of Bell and Borgward [34]. These corrections are defined only for altitude equilibrated divers. Unfortunately, there is no warning in the user manual of these decompression computers that, before any altitude dive, the user should wait until all the tissues equilibrate with altitude ambient pressure.

2.2.3. Constant Ratio Extrapolation (CRE)

The CRT correction strategy (see 2.2.2, above) which is practiced by many of the diving organizations (NAUI, COMEX, RN, DCIEM) is termed as "Haldane altitude conversion" by Hennessy [17] indicating that the conversion criterion is based on one single allowable decompression ratio independent of ambient pressure. In fact, this is quite misleading as the definition of similar dives itself and the concept of CRE should be distinguished from Cross Corrections. The difference of the CRE and CRT algorithm is the calculation of decompression stops. The contradiction resulting from the correction of decompression stops is also recognized by Bell and Borgward [34]. As they found out that Cross Corrections lead to more conservative results, they concluded that Cross Corrections could still be used. They pointed out that the ascent rate should also be corrected.

If the s_m (D) curve is assumed to be continuous then for all altitude exposures s_m is equal to the surfacing value at sea level. The neo-Haldanian postulates should be changed with the postulates below:

s_m is

a decreasing function of P_B for all P_B >101.325 kPa

constant for all P_B < 101.325 kPa

a function of tissue half time

In fact:

$$s_m(D) = M_0/P_0 \quad \text{for all } D < 0 \tag{2.12}$$

For an altitude exposure the constant ratio principle implies:

$$s_m(D) = M_h(D)/P_h = M_0/P_0 \tag{2.13}$$

Substituting P_h using $D = P_h - P_0$ and rearranging:

$$M_h(D) = M_0 + D \cdot M_0/P_0 \qquad \text{for } D < 0 \tag{2.14}$$

Therefore constant ratio extrapolation will give a straight DCS boundary with a slope of M_0/P_0 and resulting in zero tolerated tension at zero ambient pressure (at $D = -P_0$, Figure 2.4a). This principle is used by Böni et al. to device a new set of altitude diving tables [2]. Checking the $M_h(d_a)$ function for $d_a = 0$, CRT algorithms give the same result for no decompression stop dives. They diverge in dives that involve decompression stops, CRT yielding always more conservative results. The authors did not specify the reason for using the old Haldanian fixed ratio principle for only altitude dives whereas they accept a diminishing ratio principle for sea level dives. It is somehow contradictory to discard one part of the theoretical basis of a table then after some manipulations referring back to the same table. In addition to this, the physiological basis of the abrupt change in the slope of the M value curve (Figure 2.4a) or the discontinuities in the curve itself (Figure 2.3a) remains unexplained. In addition to that, none of the experimental dives performed to test CRE algorithm of Böni et al. were performed at the limits of the table. The bottom times of their altitude diving tables are always longer than those of the test dives.

On the other side, in his recent work, Wienke used a modified version of the varying permeability and reduced gradient bubble model (RGBM) to prove that s_m is nearly constant for altitude exposures [24,41,42]. This can partly justify the use of fixed s_m values in the correction algorithms. In that case, M(D) function will have a more complex expression without any discontinuity in the slope and the CRE curve will represent the asymptote of the M(D) curve for high altitudes (Figure 2.5). The resulting permissible tissue tension function is an exponential extrapolation of M values. Unfortunately, the curve fitting to find the bubble constants in the hypobaric region is accomplished using only one data point that is the DCS threshold in aviation. When used together with the critical tensions in the hyperbaric range, altitude decompression sickness limit gives an M value graph that is quite linear in the altitude diving range. For instance, the RGBM M_{h0} value (Figure 2.5) for 3000 m is 38.5 fsw. For the same altitude LEM and CRE give 40.5 and 23.6 fsw. of M_{h0} respectively. Despite this fact, Wienke supports the use of Cross Corrections for altitude diving.

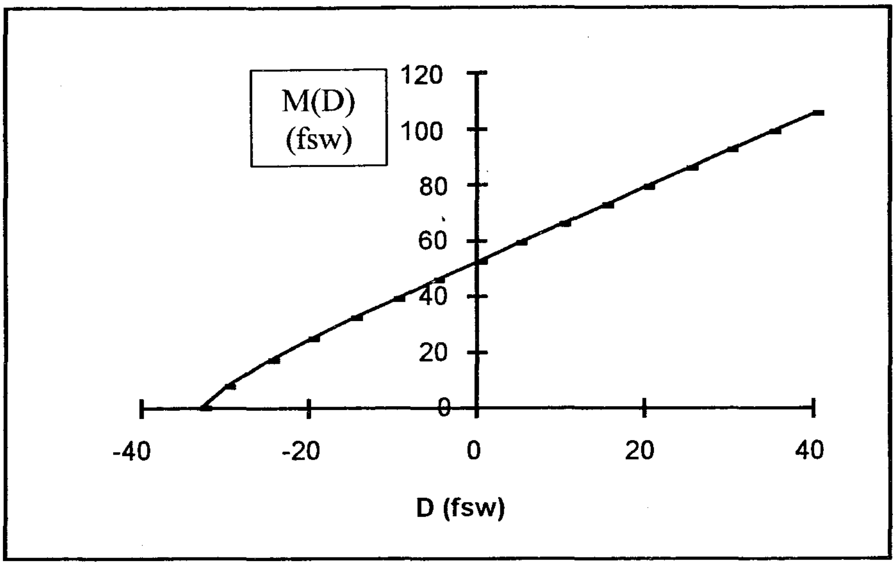


Figure 2.5. Permissible tissue tensions of RGBM model. Although M values are extrapolated exponentially, the curve preserves its incrementally linear value for moderate altitudes.

2.3. Comparison of the "Conservativeness" of the Resulting Tables

In the preceding section, three different principles of altitude adaptation algorithm are reviewed. Altitude similarity criteria are used by most of the authors to transform the dive to an equivalent sea level dive to allow readily computed ascent schedules based on sea level M and s_m values. We proceeded backwards in order to calculate the equivalent M and s_m values at the altitude for the sake of comparison of conservatism of the resulting tables. In fact, if two algorithms give different sets of M values for a given altitude, the one which gives lower allowable supersaturation tensions will suggest shorter no-decompression stop times.

2.3.1. Different Adaptation Algorithms Applied to the Same Model

Different algorithms applied to the same sea level model are depicted in Figure 2.6. For all depth and bottom time combinations CRT and CRE algorithms result in more conservative dives then LEM and the difference increases with increasing altitude (Figure 2.6). For no decompression dives CRT and CRE algorithms yield the same result, whereas if decompression stops are involved, the CRT results are more conservative.

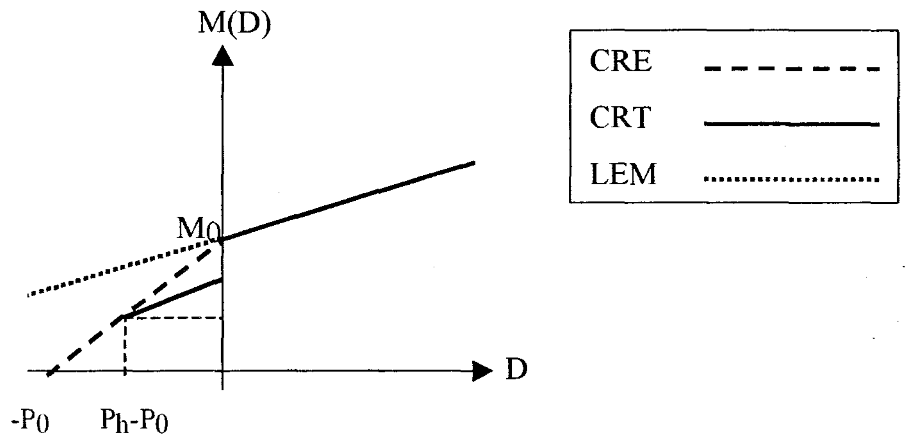


Figure 2.6. Different altitude adaptation algorithms applied to the same model

2.3.2. Different Algorithms, Different Models

For the sake of simplicity the comparison is done only for zero decompression times. In this case, M_{h0} values of CRT and CRE algorithms are located on the same line. There exist four possible combinations for M_0 and 'a' values of each tissue of two different models as depicted in Figures 2.7a, 2.7b, 2.7c, 2.7d.

2.3.2.1 Böni et al. versus Bühlmann Tables. Although the experimental basis of CRE tables of Böni et al. [2] is often used as reference for Bühlmann LEM tables [4,9,31], they give quite different results (Table 2.1a, 2.1c). As both of them share identical tissue half times and same safety factor of assuming sea level saturation at the beginning of the dive, it is trivial to compare them in the basis of individual tissues (Table 2.2). Given the M_0 and 'a' values, the intersection point ($P_{hcritical}$) of the line equations of CRE and LEM methods is computed using simple analytical geometry.

To calculate the Tables 2.2 and 2.3, first the constants in Eq. 2.4 are calculated for the tissues of interest using the empirical equation proposed by Bühlmann [9]:

$$c = 2 \cdot (T_{1/2})^{-1/3} \qquad \text{(in bars, 1 bar = 100 kPa)} \qquad (2.15)$$

$$b = 1.0005 - (T_{1/2})^{-1/2} \qquad \text{(unitless)} \qquad (2.16)$$

Bühlmann DCS boundary expression is converted to M value format using Eq 2.6 The M value expression corresponding to CRE algorithm is calculated for Böni et al. and US Navy tables using Eq. 2.14. Then the M values are plotted on the same graph. For the case depicted in Figure 2.7c M values of CRE are always smaller than LEM. For the case corresponding to Figure 2.7b, the intersection point ($P_{hcritical}$) is calculated by equating Eq. 2.2 to Eq. 2.14. Then $P_{hcritical}$ is converted to elevation using the following formula.

$$P_h = P_0 \cdot \exp\left((-29 \cdot h) / (831.4 \cdot T) \right) \qquad (2.17)$$

where T and h are respectively the temperature (Kelvin) and elevation (m).

The M value plots of both algorithms on the same graph give the combination depicted in Figures 2.7c and 2.7b for faster (5, 15, 25, 40) and slower tissues respectively. Thus, for fast tissues M values by CRE will be smaller than LEM values for all altitudes (Table 2.2). Observe that for slower tissues, LEM gives more conservative results for altitudes with ambient pressure higher than $P_{hcritical}$ (Figure 2.7b). Thereby for a given dive Böni et al. tables will be more conservative for increasing altitude. From Table 2.2, it can be seen that $P_{hcritical}$ decreases with increasing tissue half time. For a given altitude, the shallower the dive the more conservative LEM is, because slower tissues which control zero decompression times at shallower depths have lower $P_{hcritical}$ (Table 2.2) whereas faster tissues do not have $P_{hcritical}$ at all (Figure 2.7c). To conclude CRE Böni et al. tables give more conservative results than Bühlmann tables for higher altitudes, longer bottom times and deeper dives. Note that this comparison does not include the computers that use the Bühlmann LEM, because they calculate the offgasing at altitude. Thereby their $Ph_{critical}$ will be higher; giving less conservative results than the Bühlmann tables itself (Table 2.1c).

Table 2.1
No-d limits for altitude dives

a. Zero decompression limits of Bühlmann tables (LEM) [4]

Altitude (m) \ Depth (m)	9	12	15	18	21	24	27	30	33	36	39	42
0	300	120	75	53	35	25	22	20	17	15	12	10
1500	180	90	63	43	30	25	18	16	14	11	10	--
2500	135	82	55	40	30	23	17	15	12	10	9	--
3500	125	76	55	38	25	20	17	15	12	10	8	--

b. Zero decompression limits of US Navy tables as modified by Cross Corrections[a]

Altitude (m) \ Depth (m)	9	12	15	18	21	24	27	30	33	36	39	42
0	∞	200	100	60	50	40	30	25	20	15	**10**	10
1500	272	104	63	46	33	**24**	**17**	**12**	**10**	**8**	7	6
2500	185	**77**	**51**	**35**	**24**	**17**	**12**	**9**	**8**	7	**6**	5
3500	**117**	**60**	**40**	**26**	**18**	**12**	**9**	7	**6**	**5**	--	--

c. Zero decompression limits of Böni et al. tables (CRE) (11)

Altitude (m) \ Depth (m)	9	12	15	18	20	25	30	35	40
0	--	200	75	**50**	30	25	20	15	**10**
1500	720	90	**30**	**20**	**15**	**10**	**5**	**4**	--
2500	240	**40**	**15**	7	**5**	--	--	--	--
3200	150	**30**	**10**	5	--	--	--	--	--

Highlighted numbers indicate shorter bottom times compared to Bühlmann tables.
[a]These limits are in fact not from US Navy Diving Manual. They are calculated using CRT of US Navy M values. Offgasing during ascent is neglected.

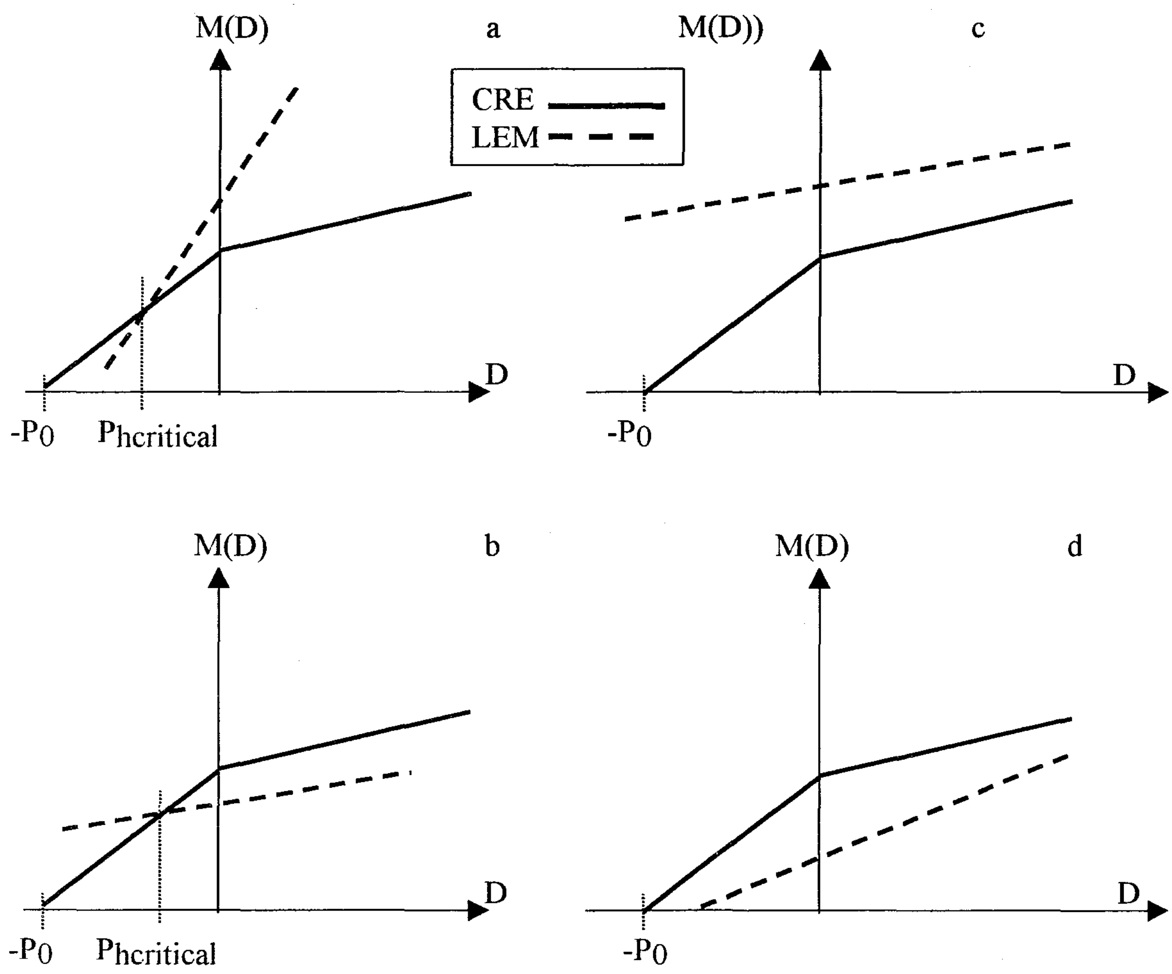


Figure 2.7. Possible combinations of CRE and LEM algorithms applied to M values of two different models. LEM is more conservative for all ambient pressures lower than Phcritical (a), higher than Phcritical (b), for all altitudes (d); in c CRE is always more conservative.

2.3.2.2. CRT US Navy Standard Air Diving Tables versus Bühlmann tables and Computers which Use this Algorithm. Two different altitude diving table applications are popular in practice: linearly extrapolated Bühlmann tables together with decompression computers using that algorithm (Decobrain, Aladin, Scubapro DC-12) and corrections using CRT principle (COMEX, RN, DCIEM, NAUI, Dacor Omni Pro, Oceanic DataMax Pro). Different decompression models use different sets of M values and tissue rate constants. In fact, it is possible to use empirically derived equations to express critical tensions as a function of tissue rate constants [4,42].

Table 2.2
Conservative altitude range of CRE of Böni et al. compared to LEM of Bühlmann tables

Half time of the controlling tissue (min.)	$Ph_{critical}$ (kPa)	Dives where CRE tables are more conservative than Bühlmann tables
5[a]	---	All altitude dives
15[a]	---	All altitude dives
25[a]	---	All altitude dives
40[a]	---	All altitude dives
53	93.32	At altitudes higher than 657 m
79	86.02	At altitudes higher than 1307 m
146	90.58	At altitudes higher than 896 m
185	90.58	At altitudes higher than 896 m
238	74.17	At altitudes higher than 2499 m
304	56.54	At altitudes higher than 4681 m
395	56.54	At altitudes higher than 4681 m
503	56.54	At altitudes higher than 4681 m
635	56.54	At altitudes higher than 4681 m

[a] These tissues do not exist in the original Bühlmann altitude diving tables. Instead 2.65, 7.94, 12.2, 18.5, 26.5, 37 min. tissues were used. For the sake of comparison it is possible to obtain the M_0 and a values of any tissue using the empirical equation derived by Bühlmann [9].

The equivalent M values corresponding to the original Bühlmann tables are different from LEM for the reason that all tissues are assumed to be sea level equilibrated in order to introduce a safety factor [4,31]. It is possible to calculate the magnitude of this safety factor in the case of altitude equilibrated diver. The nitrogen gas exchange equation used in these models is defined as:

$$\Pi_1(t) = f \cdot P_0 + f \cdot (P_B - P_0) \cdot (\, 1 - \exp(-k \cdot t)\,) \qquad (2.18)$$

where $\Pi_1(t)$ is the tension of inert gas for a given tissue, f is the fraction of N_2 in the alveoli, P_B is the ambient pressure of the depth, t is the bottom time and k is the tissue rate constant. For an altitude equilibrated diver the surface level is P_h. Substituting P_0 by P_h:

$$\Pi_2(t) = f \cdot P_h + f \cdot (P_B - P_h) \cdot (\, 1 - \exp(-k \cdot t)\,) \qquad (2.19)$$

If the diver is assumed to be sea level equilibrated although he is altitude equilibrated, subtracting Eq. 2.19 from Eq. 2.18 the safety factor Z(t) is calculated:

$$Z(t) = f \cdot (P_0 - P_h) \cdot (\exp(-k \cdot t)) \tag{2.20}$$

Thus, for the same fraction composition of inert gas (f), the safety factor Z(t) depends on height (P_h), tissue (k) and bottom time (t). To find the graphical representation of this safety factor, Eq. 2.18 will be equated to Eq. 2.2, $\Pi_1(t)$ will be substituted by $\Pi_2(t) + Z(t)$ and $(P_h - P_0)$ by D:

$$M_0 + a \cdot D = \Pi_2(t) + Z(t) \tag{2.21}$$

Thus:

$$M(D) = M_0 + (a + f \cdot \exp(-k \cdot t)) \cdot D \tag{2.22}$$

This means that the slope of the M value line will increase with bottom time (Figure 2.8). For a given level of supersaturation of tissue the increase of the slope of M(D) by $f \cdot \exp(-k \cdot t)$ has more impact on the slow tissues. This is shown in the Table 2.3 for $t = 1.25/k$, as this is a proven criterion for the tissue to control the zero decompression procedure of the dive [42]. Then we find:

$$M(D) = M_0 + (a + 0.2263) \cdot D \tag{2.23}$$

As the decompression computers using the Bühlmann model calculate the offgasing of N_2 for the altitude-equilibrated diver, their M(D) function will not include this safety factor. The M value plots of both algorithms on the same graph give the combination depicted in Figure 2.7b for all tissues. Again with increasing altitude, CRE modification of US Navy tables becomes more conservative.

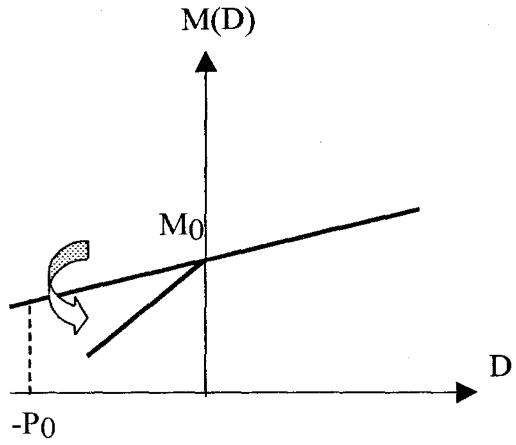


Figure 2.8. Change in the slope of M(D) function as bottom time is increased. The safety factor of assuming that all tissues are sea level equilibrated for an altitude-equilibrated diver is equivalent to introducing a new set of M values.

Table 2.3

Conservative altitude range of CRE of US Navy tables compared to Bühlmann tables

	US Navy versus Decompression Computers using LEM of Bühlmann M values		US Navy versus Bühlmann Altitude Dive Tables	
Half time of the controlling tissue (min.)	Phcritical (kPa)	Dives where CRE tables are more conservative than Bühlmann tables	Phcritical (kPa)[a]	Dives where CRE tables are more conservative than Bühlmann tables[a]
5	85.01	h > 1406 m	81.76	h > 1720 m
10	75.38	h > 2365 m	69.51	h > 3021 m
20	80.45	h > 1844 m	73.56	h > 2571 m
40	99.6	h > 132 m	98.59	h > 219 m
80	99.6	h > 132 m	97.88	h > 273 m
120	87.74	h > 1153 m	74.07	h > 2512 m

[a]LEM is computed taking into account the safety factor Z(t) of assuming the diver is sea level equilibrated.

2.4. Altitude Diving Tables and Aviation DCS Data

The linear extrapolation of some of the tables is criticized by Conkin et al. (RN tables) and Basset (US Navy tables) for the reason that they do not fit the altitude exposure data of aviation and space activities [10,43], while some of the extrapolated tables are in close agreement with some of the thresholds cited in aviation literature (see below).

Elaborate test procedures can be applied using various data from EVA and aviators DCS with different O_2 pre-breathing mixtures and different pressure profiles [10]. This, in fact, introduces an additional calculation step. The simplest way to test the performance of altitude decompression tables is just to compare their model output for the threshold altitude giving rise to DCS when exposure from sea level is performed (Table 2.4). In each of the following models the ambient pressure (P_{hmax}) of this altitude threshold is calculated for a sea level equilibrated man. For CRE algorithm P_{hmax} can be found using:

$$s_m = M_0/P_0 = f \cdot P_0/P_{hmax} \tag{2.24}$$

For LEM algorithms we have:

$$f \cdot P_0 = M_0 + a \cdot (P_{hmax} - P_0) \tag{2.25}$$

The above equations are applied to the slowest tissue of the models to find P_{hmax} which is then converted to altitude DCS height limit. In fact, the altitude DCS boundary is determined in the aviation literature with no less inconsistency: 3900 m Conkin et al. [10], 3950 m Ryder et al. [44], 5486 m Heimbach and Sheffield [11], 6096 m Behnke et al. (8), 7550 m Gray [45].

Table 2.4

Altitude limit giving rise to DCS

as predicted by different algorithms applied to different models

Algorithm	Model	Hmax (m)
CRE	Haldane [3]	5524
CRE	US Navy [7]	5193
CRE	Böni et al. [2]	5120
LEM	US Navy [7]	8581
LEM	Bühlmann [4]	5332
LEM	Yount [37]	5784
LEM	RN [10]	8977
LEM	Hennessy [17]	5784
RGBM*	Wienke [41]	6838

*RGBM equation [41] solved for a sea level equilibrated tissue.

There are also cases in literature in which DCS has been encountered at far less altitudes: 3049 m, 3659 m Allan [46], 3353 m Rayman et al. [47], 4269 m Voge [48], 4877 m Houston [49]. In some of these cases the DCS was attributed to the presence of a recent injury and it was stressed that this has the bends threshold lowering effect.

The comparison given above may reflect the conservatism of the relative models; but in reality, the concept of a threshold is misleading, in the sense that it points at the spontaneous occurrence of DCS above the given altitude, whereas the dynamics of bubble growth, and the development of symptoms are time dependent (Yount, Van Liew [37,50] for bubble growth, Kumar et al. [12] for development of symptoms). So the attempt of determining a time independent height limit is illogical. This subject is treated comprehensively in Kumar et al. [12]. The time dependent DCS limits are:

3353 m for 6 hour simulated EVA (without O_2 pre-breathing)

7925 m for 2 hour simulated EVA (without O_2 pre-breathing)

2.5. Discussion

The common practice of divers is to use Cross Corrections together with their favorite sea level diving tables, unless they use the Bühlmann Altitude Diving Tables. Some of the decompression computers use the linear extrapolation. Thereby the altitude diver who uses his dive computer as a back up for his dive that he has planned according to corrections of sea level tables may be surprised with the large discrepancy of the results even for non multilevel dives. For high altitude diving, the decompression computers with LEM algorithm give less conservative results.

It is shown in this review that the Cross Corrections of US Navy tables will lead to less conservative results at low altitudes compared to Bühlmann altitude diving tables. But in practical applications, this depends on the interpretation of the table. For example, if the diver cannot calculate the exact depth of the similar dive, he will refer to conversion tables. For a 31 feet dive at 1000 feet, the diver will complete the depth to the next highest depth that is 40 feet, if he uses for instance Bell Correction Table [34]. But the situation will be different if he, for example, uses COMEX corrections that tabulate equivalent depths with 1 m increments [38]. With Bell corrections the corresponding similar depth will be 41 feet, which in turn will be converted to 50 feet while using the Standard US Navy Tables; with so much rounding-offs the Bell corrections give a more conservative result even at low altitude compared to the linear extrapolated alternative in which only 31 to 40 rounding-off can be done.

The philosophy of the comparisons is similar to the comparison of physical and chemical properties of the elements in the periodic table: that is, with some intuitive deductions along with some inconsistency arising from the switch over points between discrete identities.

As the rate constants are different in both tables, exact comparison cannot be made for the actual tables. The switchover points between different tissues may lead to some inconsistencies and in addition to this we are still faced with the problem of the 10 by 10 incremental nature in the presentation of the tables. Still, the table 2.1, 2.2, 2.3 and the corresponding graphical interpretations (Fig 2.7a, 2.7b, 2.7c, 2.7d) allow comparison of the different tables. Instead of claiming that one table is less conservative than others are, it is more logical to define the specific conditions in which the algorithm itself is more or less conservative. The comparisons given above will hold only in the case of the no-decompression stop time calculated exactly for the depth without any rounding-off. The advantage of such comparison is that it will determine the relative performance of the decompression computers with altitude dive option. In this case depths and time will not be rounded-off and it makes an exact comparison between different algorithms possible.

The theoretical basis of CRT is contradictory, while CRE can be explained by RGBM. A decompression computer using CRT algorithm will be definitely more conservative. It might be useful to suggest that such conservatism should be adopted, in cases where the implication of the high altitude changes of the body parameters on DCS is not determined.

3. DIVING AND HYPOBARIC HYPOXIA

3.1 Introduction

As the range of existing altitude dive tables and decompression computers extends up to 4000 m (Table 3.1) the effects of hypoxia need to be considered. With increasing altitude, the pressure of inhaled O_2 decreases. It is followed by a cascade of drops in alveolar, arterial, capillary levels of O_2. Due to the sigmoidal shape of the O_2 dissociation curve, up to 1000 m, the effect of low P_{O2} is only felt at maximal exercise level. To maintain the critical O_2 pressure at which cells may function normally above 2000 m, a series of adaptations is needed to occur in the body. This has two consequences for the high altitude diving: limitations on the ascent rate to altitude and possible effects of acclimatization on DCS incidence.

Table 3.1

Altitude limit of dive computers

Dive Computer	Altitude limit
Aladin Pro	4000 m
DC-12	2500 m
Omni Pro	3000 m
Monitor	3960 m
Suunto Solution	2400 m
DataMax Pro	4267 m

3.2. Ascent Rules

If the body fails to adapt then the subject will suffer from a number of diseases namely acute mountain sickness (AMS), high altitude pulmonary edema (HAPE), high altitude cerebral edema (HACE) or retinopathy [51-55]. The altitude diver, like any other altitude sojourner, should follow a number of rules to adapt properly so as to avoid these diseases. There are a number of rules of thumb compiled from different authorities. The diver can disregard any of them at his own risk:

Acclimatization is best ensured by slow ascent. It is a good rule to ascent no more than 600 m. a day when above 2100 m. If the symptoms become prominent descend a few hundred meters at night. The altitude at which one sleeps is more important than the altitude reached during the day. It is also necessary to drink more water at altitude than at sea level to compensate for the fluid loss through hyperventilation [52]. Avoiding strenuous exercise for the first two day is helpful [54]. Taking more salt than necessary causes fluid retention, perhaps enough to trigger altitude sickness [52].

Above 3000 m, an average gain of less than 500m/day is recommended to avoid AMS [56].

Above 3000 m a rate of ascent of 300 m/day for two days followed by 150 m/day thereafter is recommended, but such a practice is not popular since it requires much more time for adaptation [57].

AMS is prevented in most of the cases by slow ascent. "Slow ascent" is hard to define. The speed of ascent that is perfectly tolerable for one individual may cause HAPE in another. Above 2500-3000 m, the sleeping altitude should not be increased by more than 300 m per day. Adequate fluid intake must be maintained, resulting in the production of at least 1 liter of clear urine per day [55].

Above 3500 m a rate of ascent of 300 m/day or 500 m/day as an average of two consecutive days should be maximum speed [58].

Note that these rules do not claim to protect each climber. The susceptibility of the individual plays an important role. Bartsch et al. [59] found out that the slow ascent with an average gain of 500 m of altitude per day is associated with the absence of AMS and or HAPE in non susceptible mountaineers, but **cannot** prevent these illnesses in susceptible subjects. As a consequence, even if the ascent rules are followed, the climber should not forget the phrase "if in doubt go down" [57].

3.3. Altitude Acclimatization and DCS

There exist significant changes in body parameters in order to adapt to low partial pressure of inhaled O_2. Some of these are expected to change both the time constants of tissue compartments and the threshold of DCS.

3.3.1. Changes in Regional Blood Flow Distribution

Cerebral blood flow to brain increases to compensate for the hypoxemia [60-63]. Experiments on rats have shown that the blood flow to brain, respiratory muscles, and liver increases both in absolute value and as a fraction of aortic flow, while the total aortic blood flow increases. Fractional blood flow to the gastrointestinal tract, spleen, pancreas, skin, fat and hind limb bones decreases in hypoxia; blood flow decreases in absolute values only in stomach and fat [64]. In case of the alteration of the regional blood flow, corresponding change is expected to occur in the time constants of the relative tissues. In a perfusion limited gas exchange model the half time of the tissue is given as:

$$T_{1/2} = (0.693 \cdot s2 \cdot V) / (s1 \cdot Q) \qquad 3.1$$

where V is the tissue volume, Q is the blood flow, s1 and s2 are the solubility of the gas in blood and in the tissue respectively. The s2/s1 is also termed as partition coefficient. The decrease in regional blood flow will result in an increase in $T_{1/2}$. As an example, a 50% percent reduction in blood flow to fat compartments will double the corresponding $T_{1/2}$. This will imply:

a) As the surface interval is calculated with respect to slower tissues including fat compartments, the tables need to be revised for hypoxic exposures, together with the surface gas exchange calculation of decompression computers.

b) The time of altitude equilibration. This is essentially important for the conversion of sea level tables using Cross Corrections [15,16] since the conversion can only be applied after all the tissues are equilibrated with the ambient pressure. For example, the 12 hours rule of US Navy tables, should be changed to 24 hours assuming a 50% reduction in the blood flow to the 120 min. half time tissue since the half time will be changed to 240 min.

However, the time course of the flow changes is complex, because the stimulating effect of hypoxemia may be opposed by the flow depressant effect of hypocapnia caused by the hyperventilation at high altitude.

3.3.2. Changes in Blood Composition

Ordinarily, at full acclimatization to low O_2, the hematocrit rises from a normal value of 40 to 45% to an average value of 60 to 65%, with an average increase in hemoglobin concentration from a normal of 15 g/dl to about 22 g/dl [51]. An increase in viscosity [65-67] and facilitation of coagulation are reported [52,58,68]. Hemorrhages, especially (retinal) are common in high altitude climbers.

The time course of the changes in hemorheology and hemology is studied by several authors for different altitudes. For some altitude-residence time combination, the differences in the composition of blood are slight: 3800 m/2 week, [69], 4500 m/12 day [70], 2700 m/17 days [65]. On the other side, no change has been reported upon immediate exposure to hypoxia. In fact, the erythropoietic system is activated within hours after hypoxic exposure in man, but the steady state increase in the number of circulating red blood cells is reached after several weeks [71]. An increase in blood and plasma viscosity is encountered even for moderately high altitude [65]. It is certain that the increase of coagulation is a potential risk for the fully acclimatized altitude diver. In addition to this, the above-cited changes (viscosity, hematocrit, hemorrhages, thrombosis) occur in response to the existence of bubbles resulting from inadequate decompression of the diver and they are among the key factors leading to symptoms of DCS [72]. Wienke stated that the dehydration increases the disposition to DCS, and this is physically linked to low surface tension of blood serum that does not inhibit bubble growth optimally [73]. In fact, Le Péchon et al. suggested that the consequences of ischemia associated with circulating bubbles and the perfusion restriction that they may induce may dramatically increase the risk of DCS because of the hypoxic condition following decompression at altitude. Therefore, they have pointed out that more conservative safety factors should be used in the calculation of decompression schedules [19].

3.3.3. Changes in Body Composition

Both acclimatization and altitude related illnesses cause a change in the body composition [74-77]. Weight loss is common among high altitude climbers. Anorexia, nausea and vomiting which are within the frequently encountered symptoms of AMS have negative effect on food intake. At moderate altitudes, once the symptoms of AMS disappear, caloric intake and energy balance is usually resumed and the body weight can stabilize. Hypoxia induced hyperventilation causes water loss by respiration. A problem of high altitude is the progressive dehydration. In addition to the changes in ion balance, water and food intake is diminished as a result of unknown central anorexic mechanisms. A marked diuresis at the beginning of a high altitude climb is considered by mountaineers as a sign of good adaptation, whereas subjects showing antidiuresis are considered as being susceptible to AMS. It has been suggested that this effect results from the hypoxic stimulation of the peripheral chemoreceptors that inhibit Na^+ reabsorbtion via a decrease in the tubular effect of aldosteron. Salt and water intake is also diminished and a decrease in ECF might be expected [78]. On the other hand, hypoxia may cause failure of energy dependent Na^+/K^+ pumps. As a result the K^+ will leak out and disturb the water balance [52]. Unlike hemorrhage and dehydration where the fluid is lost from all compartments, long term exposure to high altitude appears to result in losses from both intracellular and plasma compartments with concomitant increase in the interstitial compartment [75].

The measurement of resulting changes in body composition is presented in several articles [74-78]. The question is whether these changes are big enough to effect the inert gas solubility and thereby induce changes in the time constants of the corresponding gas exchange equations or the dynamics of decompression bubbles.

3.3.4. Changes in Ventilation

Upon exposure to hypoxia, ventilation will increase so as to defend alveolar P_{O2}. The respiratory alkalosis that develops inhibits the ventilatory response to some extent [79-81]. Both the changes in blood flow and ventilation will cause subsequent changes in the oxygen window that is the driving force for inert gas elimination from bubbles and determines the degree of supersaturation [35,36]. The oxygen window decreases with increasing altitude up to 4000 m altitude and decrease furthermore with acclimatization (to be discussed in Chapter 4).

3.4. Recommendations

Knowing that the physiological changes involved in acclimatization follow a time course; the utopic altitude dive table would have an altitude residence time entry. At least, a coarse division between short time (up to 3 days) and long time residence (e.g. after 10 days) should be possible following the acclimatization phases. In fact, it is equally possible to restrict the use of the tables after the acclimatization phase where the related parameters will settle down to a greater extent, and thereby getting rid of the complex dynamics of the first 3 days. Some of the altitude diving tables are restricted for use 12 to 48 hours after arrival, but the reason is just simply to equilibrate the nitrogen in the tissues with the ambient pressure.

The argument supporting the immediate diving upon arrival is that the subject will be symptom free from AMS upon arrival till 4 to 6 hours at altitude. So, if the appropriate table takes into account the residual N_2 from the sea level, immediate diving followed by immediate descent to lower altitudes, if possible to sea level, may be encouraged for altitudes up to 3000 m. Higher altitudes will have too high DCS stress, since exposure to 3300 m (Kumar) and 3900 m (Conkin et al.) from sea level is defined as altitude DCS limit by some sources [10,12]. In the case of immediate diving, the ascent rate for the last few meters of water should be extremely slow so as to avoid fast exposure to hypoxia. Long distance surface swimming is to be avoided to prevent depletion after relatively fast transition to hypoxic medium. Safety decompression stops are advised.

Diving after full acclimatization at high altitudes (e.g. after 10 days at higher than 3000 m) should be avoided until controlled experiments are carried out about the DCS stress induced by subclinical development of HAPE and the changes in blood parameters. The decrease in the oxygen window through acclimatization is also to be considered.

Even if an altitude dive table is devised so as to take into account the above cited changes together with the correct DCS boundary, for dives above 2400 m the diver should use them with the same conservatism as in dives which involves heavy work, cold environments or personal fitness problems. Because even though the diver does not suffer from the symptoms of AMS, HAPE and other altitude related diseases, subclinical development is possible; in addition to this, the decrease in both physical and mental performance associated to altitude is reported by many sources [51-53]. The increased blood flow to the brain creates an accumulation of fluid; the resulting fluid pressure can lead to headache and can impede judgment [52] that will affect the performance of the diver.

4. ESTIMATION OF THE OXYGEN WINDOW

4.1. Arterial N_2 Tension

In some tables, the tension of inert gas in the arterial blood is assumed to be equilibrated with the fraction of the inhaled inert gas, without taking into account the presence of alveolar H_2O and CO_2. In extrapolating the sea level DCS limits to altitude, this will in fact create a problem. While calculating the gas uptakes, this error is not too large since the difference is negligible compared to the applied pressure. More important, errors will occur during calculation of surface washouts. For altitudes above 3000 m, calculation of arterial N_2 (P_aN_2) as a fraction of air introduces a considerable overestimation of the N_2 tension during surface washouts (Table 4.1). Note that the theoretical basis of Cross Corrections is also based on a fixed mole fraction of N_2 in the alveoli; which is not correct when the altitude changes. In Bühlmann tables and decompression computers using that algorithm only the presence of water vapor in the alveoli is taken into account, which is true for a respiratory quotient of 1. A more realistic formula taking the presence of CO_2 and H_2O into account is computed as follows:

Arterial N_2 tension (P_aN_2) is equal to alveolar partial pressure of N_2 (P_AN_2). The partial pressures of alveolar H_2O, CO_2 and O_2 are metabolically controlled. N_2 fills the vacancy to complete the sum of the gases to ambient pressure. Thus:

$$P_AN_2 = P_B - (P_ACO_2 + P_AO_2 + P_{H_2O}) \qquad (4.1)$$

where P_ACO_2, P_AO_2, P_{H_2O} are the alveolar partial pressures of CO_2, O_2 and H_2O respectively. P_{H_2O} is constant (6.266 kPa). P_ACO_2 and P_AO_2 are dependent variables. P_ACO_2 is constant up to 3000 m (5.333 kPa) At 3000, 3500, 4000 m. the P_ACO_2 is taken as 5.2, 4.8, 4.66 kPa respectively. For a given P_ACO_2, P_AO_2 is found using:

$$P_AO_2 = P_iO_2 - P_ACO_2/R + P_ACO_2 \cdot F_iO_2 \cdot (1 - R)/R \qquad (4.2)$$

where P_{iO2} is the partial pressure of inhaled gas in kPa, R is the respiratory quotient and F_{iO2} is the fraction of O_2 in the dry air [82]. In turn:

$$P_{iO2} = F_{iO2} \cdot (P_B - P_{H2O}) \tag{4.3}$$

Combining Eq. 4.3, 4.2 and 4.1 one can find:

$$P_{aN2} = F_{iN2} \cdot (P_{ACO2} \cdot (1 - R)/R + P_B - P_{H2O}) \tag{4.4}$$

where F_{iN2} (or $1-F_{iO2}$) is the fraction of inhaled N_2 in dry air. Schreiner and Kelly also proposed that the above equation (with constant P_{ACO2}) should be used in altitude diving [83]. Note that P_{ACO2} values given above will decrease through acclimatization, but the sum of P_{ACO2} and P_{AO2} will only decrease by a negligible amount to yield 0.2-0.4 kPa higher P_{aN2} than the above equation.

Table 4.1

Overestimation of arterial N_2 tension at different altitudes

Altitude (m)	P_B (kPa)	P_{aN2} calculated as %79 of air (kPa)	P_{aN2} calculated From Eq 4.4 (kPa)	% error
0	101.325	79.993	76.127	5.11
500	95.192	75.193	71.327	5.46
1000	89.459	70.661	66.794	5.83
1500	83.993	66.394	62.528	6.23
2000	78.926	63.461	58.528	6.66
2500	74.26	58.528	54.795	7.12
3000	69.727	55.062	51.195	7.67
3500	65.461	51.729	47.729	8.39
4000	61.595	48.662	44.663	9.03

4.2. Estimation of the Oxygen Window

The oxygen window is defined to be the driving force for inert gas elimination from bubbles and determines the degree of supersaturation [35,36]. The ideal bubble free decompression model would use this vacancy to eliminate the inert gas without exceeding the saturation limit. The oxygen window decreases with altitude (Table 4.2), because while alveolar partial pressure of O_2 decreases dramatically, the partial pressure of alveolar CO_2 and H_2O remain almost the same. Through acclimatization the O_2 carrying capacity of the blood increases [71], thereby arterial and venous level of O_2 also increase. This is due to the increase in the hemoglobin concentration and the P_{50} values (partial pressure of O_2 at which 50% of hemoglobin sites are filled). Because of the sigmoidal shape of the O_2 dissociation curve, this has more impact on the venous O_2 levels. Therefore, the oxygen window will decrease still more with acclimatization. Another implication of this hypothesis is the reduced oxygen window for the case of an altitude-acclimatized individual upon coming back to sea level (Table 4.2, altitude 0). The quantitative estimation of the oxygen window for various altitudes before and after acclimatization is as follows [84]:

The ambient pressure is first calculated using eq. 2.17. P_{AO2} is calculated using eq. 4.2. P_{AO2} is equilibrated with pulmonary capillaries. In the case of acclimatization P_{ACO2} values are read from CO_2-O_2 diagram [85]. Then the fractional saturation of hemoglobin in the pulmonary capillaries is calculated using the Hill equation [86]:

$$\log \left(Y/(1-Y) \right) = n \cdot \log \left(P_{O2}/P_{50} \right) \tag{4.5}$$

where Y indicates fractional saturation with oxygen, P_{50} is the P_{O2} for half of the hemoglobin to be saturated and n is an empirical constant. n is taken as 2.8, and values of P_{50} before and after full acclimatization are accepted as 26.5 and 30.6 respectively [71]. The volume of oxygen in 100 ml of blood (VO_2) can be found using:

$$VO_2 = C_{Hb} \cdot \gamma \cdot Y \tag{4.6}$$

where C_{Hb} is the concentration of hemoglobin (g/dl), and γ is the volume of O_2 that combines to each gram of hemoglobin. The hemoglobin concentration is taken as 15 g/dl before acclimatization and 22 g/dl after acclimatization [51] and γ is equal to 1.34 ml/g. $VcapO_2$ (volume of O_2 in 100 ml of capillary blood) is calculated from eq. 4.6; assuming a constant expenditure of 5 ml of oxygen per 100 ml of blood, and %5 shunt fraction, the volume of oxygen carried by 100 ml of venous blood is found by:

$$VvO_2 = (0.95 \cdot VcapO_2 - 5) / 0.95 \tag{4.7}$$

where VvO_2 is the volume of oxygen in 100 ml of venous blood. Knowing VvO_2, venous hemoglobin saturation (Y) is found using Eq. 4.6. Finally the hemoglobin saturation is converted to venous level of O_2 (P_{VO_2}) using the Hill equation (Eq. 4.5). The oxygen window for an altitude-equilibrated diver is found using:

$$\text{Oxygen window} = P_B - (P_{VO_2} + P_{VCO_2} + P_{H_2O} + P_{VN_2}) \tag{4.8}$$

where P_{VCO_2} and P_{VN_2} are the venous levels of CO_2 and N_2 respectively. A constant arterio-venous difference is assumed while calculating P_{VCO_2} values. P_{VN_2} is calculated for an altitude equilibrated diver using the procedure given in Section 4.1, and assuming $P_{VN_2} = P_{AN_2}$.

4.3. Discussion

The oxygen window is found to decrease with altitude for both post and pre acclimatization periods. The results for the preacclimatization period are in close agreement with the estimations of Van Liew et al. [87]. Given the decrease in oxygen window, for the same level of inert gas uptake, altitude dives will result in higher supersaturation level. Since the supersaturation level determines the number of bubbles generated, this will imply higher risk of DCS.

For a given size of bubble, the driving force for the elimination of inert gas decreases at altitude. This suggests a higher lifetime for a bubble. Therefore, the altitude diver with the same number of bubbles as compared to a sea level diver, is under a higher risk of DCS.

The oxygen window is found to decrease furthermore with acclimatization. Although acclimatization is necessary for the body to get ready to use its maximum energy, the change in blood parameters causes a decrease in oxygen window. Not only the altitude diver should consider these, divers, who also practice high altitude mountaineering, should be conservative while planning their dives upon return from high altitude climbing.

Table 4.2

Estimation of oxygen window before and after full acclimatization

Altitude (m)	Oxygen window (kPa) (Before acclimatization)	Oxygen window (kPa) (After acclimatization)
0	7.997	6.388
500	6.772	5.242
1000	5.644	4.21
1500	4.613	3.296
2000	3.683	2.503
2500	2.859	2.36
3000	2.263	2.262
3500	1.975	1.789
4000	1.535	1.394

5. DEVELOPMENT OF A SOFTWARE LIBRARY FOR COMPARATIVE STUDIES OF DCS: "UNVDECO"

5.1 Introduction

The aim of this study is to develop a software package to compare the output of the existing models related to the study of safe decompression profiles and develop new tables. The existing algorithms are related to the three different stages of DCS:

a. Inert gas exchange
b. Bubble dynamics
c. DCS boundary

Starting with Haldane, the conventional and yet practical approach to design decompression schedules combines a and c [2-7,35,83,88]. The empirical nature of such a strategy suggests a trial and error type of testing and modification of the model parameters through experimental dives: the body is divided into compartments or tissues with a given time constant. The time constants of the **tissues** are determined by physiological data [4]. On the other hand, the time constants of the **compartments** are arbitrarily chosen [2,3,5-7,35,83,88]. Each compartment or tissue has an experimentally justified DCS boundary expressed as a ratio, gradient or gas tension. Although, the experimental outcome is sometimes validated by the measurement of intravascular bubbles [89], the design of above cited models do not incorporate the modeling of bubbles induced by decompression. However, analysis of decompression profiles using simulation of gas bubbles dynamics has been attempted [50]. The UNVDECO software is aimed also to be a review of the above modeling works.

5.2. Program Structure

The UNVDECO package consists of a source code written in C language (unvdec.c), an object code (unvdec.exe), and configuration files (mapleson.cts, mapleson.hdr, config.dec). The program structure is divided into two parts: the input/output (I/O) and modeling subroutines.

5.2.1. I/O Subroutines

The I/O functions includes interactive routines which enable the user to define:

- Source of the profile (keyboard or data file)
- Type of ascent (staged, linear, omitted decompression stops i.e. forced ascents)
- Breathing gas (air, nitrox, heliox)
- Saturation level (hypobaric, hyperbaric, sea-level)
- Model and related parameters (gas exchange and DCS boundary)

I/O subroutines also include graphical modules for drawing the profile, the compartment gas tensions as well as bubble radius. Another alternative is to use the data file output of a depth recorder.

5.2.2. Gas Exchange Models

Three perfusion-limited models are selected: Bühlmann, US Navy and a general perfusion limited model. The general perfusion limited model allows user to enter tissue volume, tissue to blood partition coefficient, blood flow to the tissue and the blood volume in equilibrium with the tissue. Fourteen tissues are used. The halftimes are determined using Eq. 3.1. The mixed venous blood inert gas tension is calculated assuming that it is equal to the weighted mean of the inert gas content of the blood draining each tissue [90]. For each tissue and mixed venous blood, maximum amount of gas tension before giving rise to supersaturation (vacancy) is superimposed on the gas exchange graph. The vacancy is defined as:

$$\text{vacancy} = P_B - P_{H_2O} - P_{VCO_2} - P_{VO_2} \quad (5.1)$$

where P_{VCO_2} and P_{VO_2} are the venous tensions of P_{VCO_2} and P_{VO_2} respectively. The P_{aN_2}, the oxygen window are computed using the Eq 4.4 and 4.8. The gas exchange is computed using [83]:

$$\Pi(t) = f \cdot P_B + f \cdot c \cdot (t - k^{-1}) - f \cdot [P_B - P_0 - d] \cdot e^{-k \cdot t} \quad (5.2)$$

where d is the rate of descent.

The following parameters can only be modified at the source code. The default values are as follows:

- Time discretisation for calculations: 0.1 min
- Metabolic rate corresponding to 5 ml/dl O_2 extraction, a respiratory quotient of 0.8 and a constant arterio-venous difference of CO_2 (5 mm Hg) are assumed.
- Hemoglobin concentration = 15 mg/dl
- Non-linearity coefficient in the Hill O_2 dissociation curve = 2.8
- P_{50} = 26.5 mm hg
- P_{H20} = 47 mm Hg
- Shunt fraction = 5%
- P_{ACO_2} for different altitudes:

Sea level:	40 mm Hg
3000 m:	39 mm Hg
3500 m:	36 mm Hg
4000 m:	35 mm Hg

5.2.3. Bubble Dynamics

To simulate the dynamics of bubble growth in mixed venous blood, the system of equations introduced by Van Liew [50] is simplified based on the assumption that the amount of gas trapped in the bubbles does not affect the dynamics of mixed venous gas exchange [91].

5.2.4. DCS Boundary

For sea level and saturation dives linear DCS boundary of Bühlmann and US Navy are used [7]. If the DCS boundary is to be coupled with a different gas exchange model, i.e. general perfusion model coupled with US Navy DCS boundary, recent formulations of Bühlmann and Wienke are used [9,73]. For altitude dives, the user can choose either LEM or CRT of DCS boundary.

5.3. Results

5.3.1. Computation of no-d Limits for Altitude Dives at 3500 m

Different combinations of gas exchange and DCS boundary are used to derive no-d limits for altitude diving at 3500 m (Table 5.2). The model parameters for the general perfusion case are listed in Table 5.1. [92].

5.3.2. Simulation of Bubble Dynamics for Altitude Dives

It is known that performing a given depth bottom time combination at altitude increases the risk of DCS, but the difference is not clearly defined in terms of bubble dynamics. Several authors attempted to simulate bubble dynamics for sea level dives [36,37,50]. In this thesis, UNVDECO software is used to compare the bubble dynamics of a sea level dive with an altitude dive at 3500 m. Bubble dynamics during and after a 42 m. dive is simulated for sea level (Figure 5.1 and 5.2) and for altitude (Figure 5.3 and 5.4). The descent is assumed to last 3 min. The time spent at the bottom is 3 min. Clearly the bubble radius grows larger at the altitude dive and the decay of the bubble lasts longer. The effect of increasing the ascent speed has more dramatic effects. Doubling the ascent speed at 3500 m altitude dive causes an almost stable bubble (Figure 5.3). Moreover, repetitive deep dive at altitude results in explosive decompression causing a very fast growing bubble (Figure 5.5).

Table 5.1
General perfusion model parameters

Tissue	Volume (ml)	Partition Coefficient*	Blood Flow(ml/min)	Blood Volume (ml)
Adrenals	20	1	100	62
Kidneys	300	1	1240	765
Thyroid	20	1	80	49
Gray matter	750	1	600	371
Heart	300	1	240	148
Small organs	160	1	80	50
Liver	3900	1	1580	976
White matter	750	1	160	100
Red marrow	1400	1	120	74
Muscle	30000	1	600	370
Skin	3000	1	60	37
Non fat (subcutaneous)	4800	1	70	43
Fatty marrow	2200	5	60	37
Fat	10000	5	200	123

Table 5.2

No-d limits of different model combinations for diving at 3500 m

Depth(m)	9	12	15	18	21	24	27	30	33	36	39
GPB	418	150	85	39	31	20	16	13	11	9	8
GPL	288	159	88	52	35	23	18	14	11	9	7
USL	207	75	50	38	31	26	21	17	13	10	9
USC	117	60	40	26	18	12	9	7	6	5	-
M3	107	58	41	32	26	22	18	15	11	9	8
M4	93	53	38	29	24	21	17	14	11	9	7

GPB: General perfusion model coupled with Bühlmann DCS boundary
GPL: General perfusion model coupled with US Navy linear extrapolated DCS boundary
USL: Linear extrapolated US Navy M values
USC: US Navy Tables as modified by Cross Corrections
M3: Linear extrapolated M values, with M_0 values decreased by 3 fsw
M4: Linear extrapolated M values, with M_0 values decreased by 4 fsw

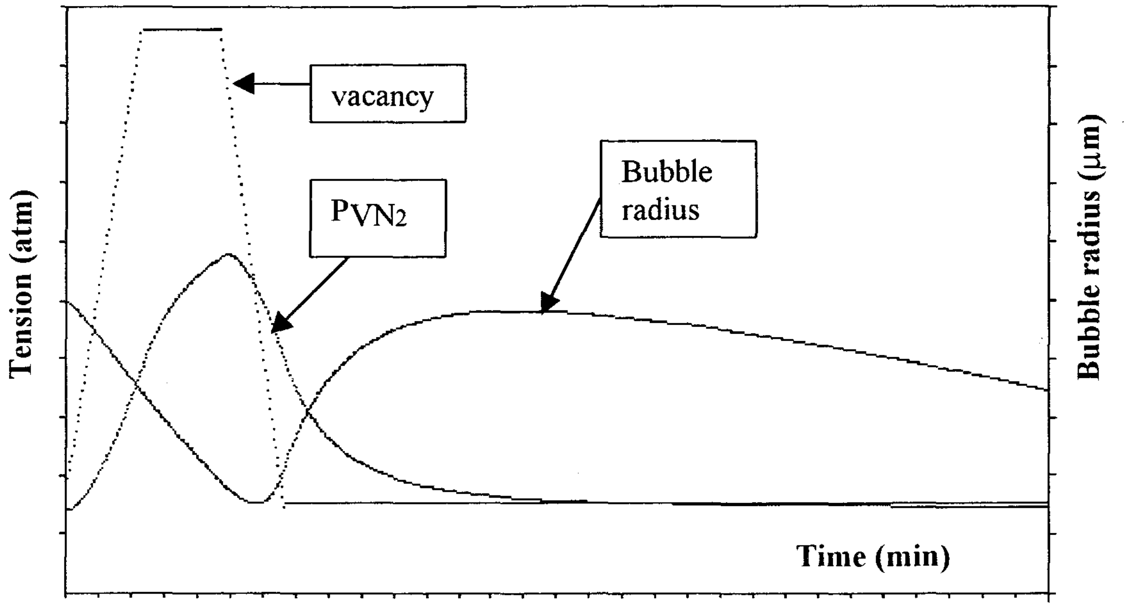


Figure 5.1. Simulation of a 42m/6 min dive at sea level. The ascent time = 2.5 min. Vertical axis scale = 0.5 atm/division for the vacancy and tissue tension, 5 µm/div for the bubble radius. Horizontal axis represents the time (1.283 min/div). At 30th min following surfacing the bubble radius drops to 17 µm.

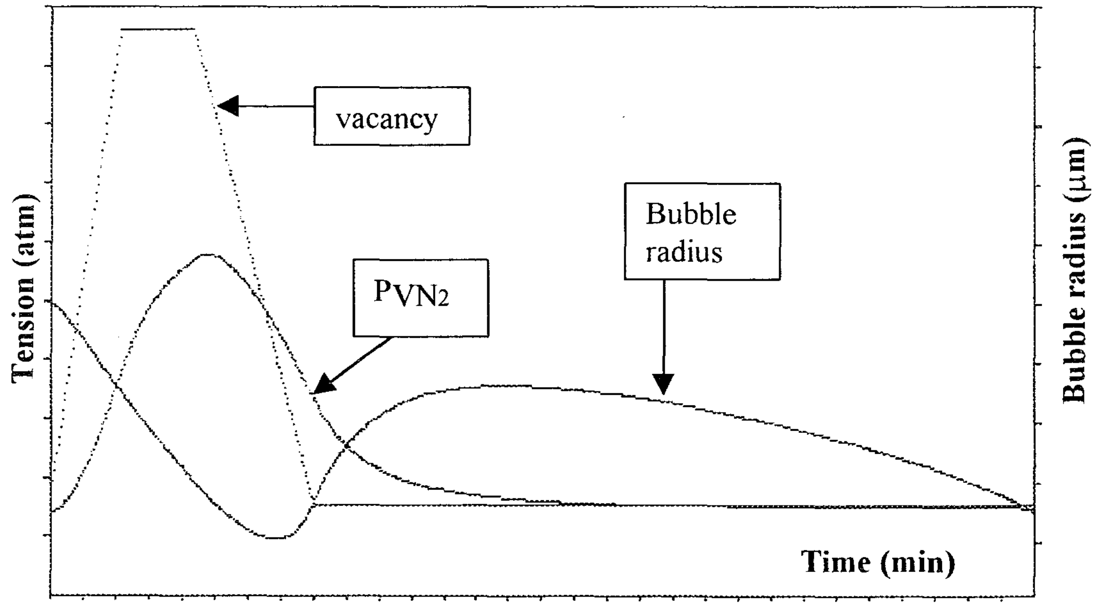


Figure 5.2. Simulation of a 42m/6 min dive at sea level. The ascent time = 5 min. The vertical axis scales are the same as in Fig 5.1. Time axis scale = 1.366 min/div. At 30th min following surfacing the bubble radius drops to 7 µm.

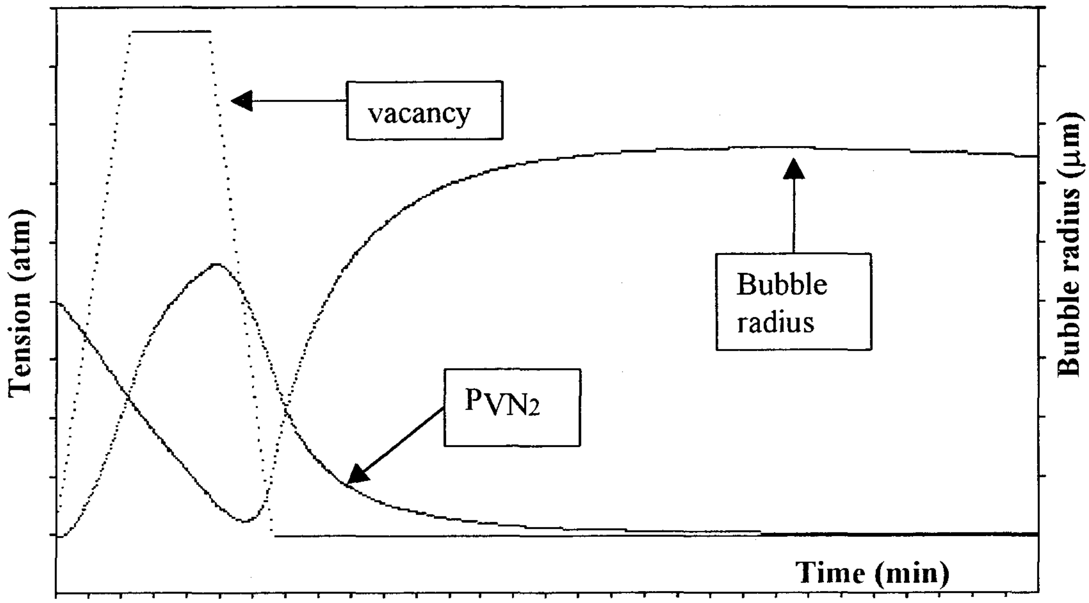


Figure 5.3. Simulation of a 42m/6 min dive at 3500 m. altitude. The ascent time = 2.5 min. Vertical axis scale = 0.484 atm/division for the vacancy and tissue tension, 5 µm/div for the bubble radius. Time axis scale = 1.283 min/div. At 30th min following surfacing the bubble radius is almost stable (38 µm).

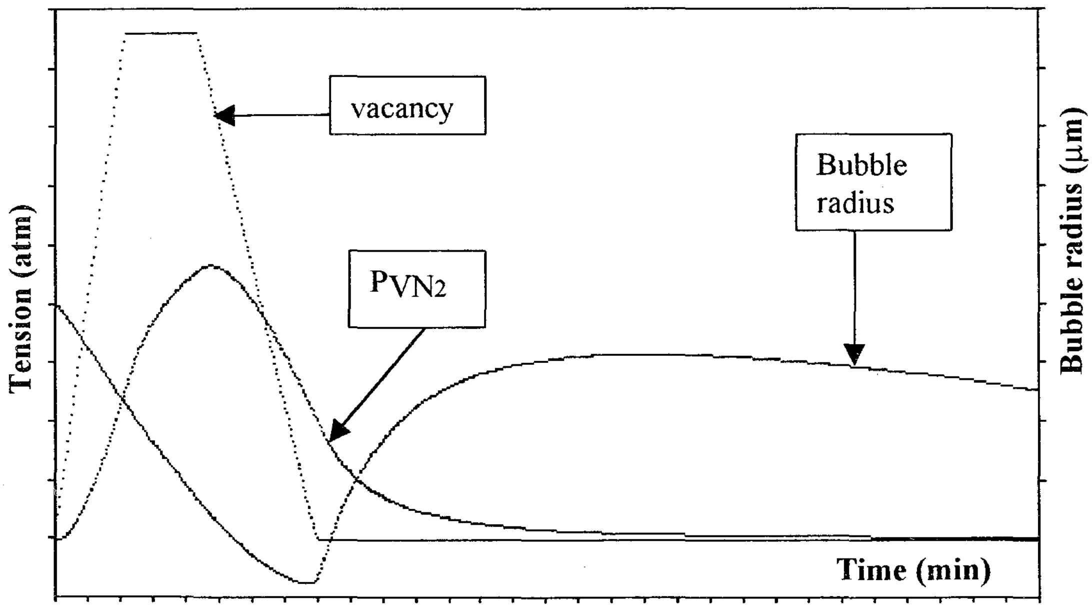


Figure 5.4. Simulation of a 42m/6 min dive at 3500 m. altitude. The ascent time = 5 min. The vertical axis scales are the same as in Figure 5.3. Time axis scale = 1.366 min/div. At 30th min following surfacing the bubble radius drops to 17 µm.

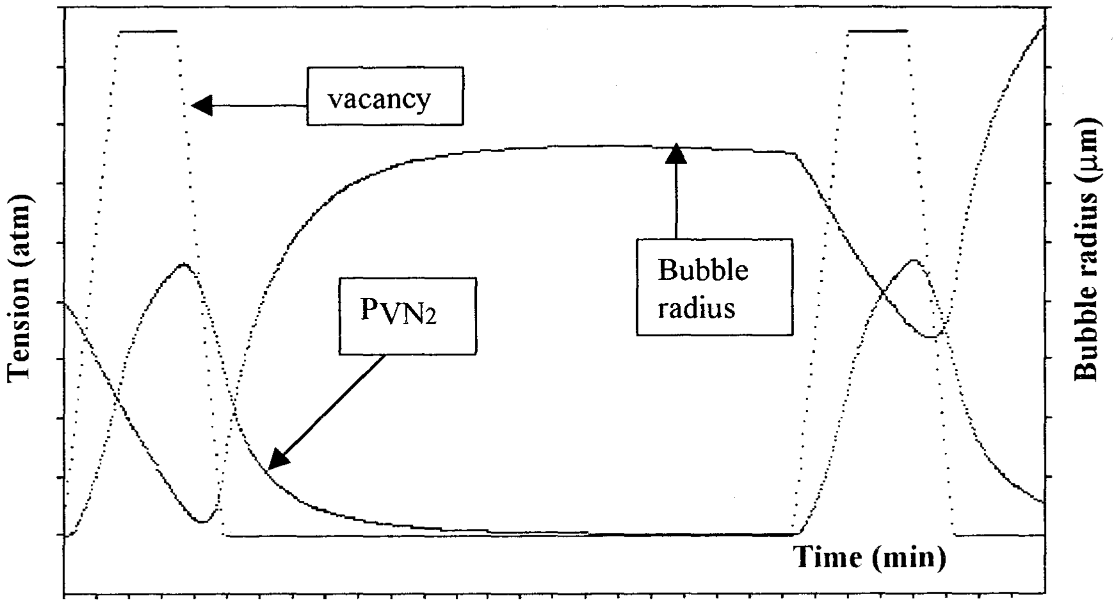


Figure 5.8. Simulation of a repetitive deep diving at altitude (42 m/6 min followed by 30 min surface interval, ascent time = 2.5 min). Vertical axis scale = 0.484 atm/division for the vacancy and tissue tension, 5 μm/div for the bubble radius. Time axis scale = 1.73 min/div. Within 5 minutes following surfacing, the bubble radius grows to 49 μm. resulting in explosive decompression.

5.4 Discussion

Through combinations of different modules of UNVDECO, it is possible to design new decompression procedures. If the general perfusion model is chosen for the gas exchange simulation module, then the user can simulate the effect of temperature or exercise by changing the blood flow to organs. Further refinements can be accomplished at the source code to simulate the effect of O_2 extraction, respiratory quotient, arterio-venous CO_2 difference, hemoglobin concentration, P_{50}, P_{H_2O}, shunt fraction, P_{ACO_2}, initial bubble radius, surface tension of bubbles, diffusivity of inert gas in body fluids.

Through simulations of an isolated bubble, the effect of altitude on the bubble dynamics is shown. A single isolated bubble collapses within 30 min after a 42 m/6 min dive at sea level; but it is almost stable after the same dive accomplished at altitude. The site of the simulation is chosen as mixed venous blood that can equally represent a bubble trapped in the lungs. The deep repetitive dives are associated with a very higher risk of DCS, since the bubbles will grow with a very high rate radius. However, the quantization of such a risk is not possible because of the ill-defined isolated bubble-DCS risk relation [93]. On the other hand, the assumption that the bubble stays isolated inside a given compartment may not be valid [94]; bubbles may collide, divide or migrate.

Lastly, the boundary conditions that define a single isolated bubble are arbitrary [95], and the results of bubble dynamics depend to a great extent to the initial size of the bubble [94]. Thus, these problems of the simulation motivated the author for a collaboration to model a population of bubbles [96].

6. PIONNERING EXPEDITIONS

In 1990, Boğaziçi University launched an altitude diving program to develop diving techniques and safe decompression profiles for altitude. Three expeditions to Uludağ Ice Lake and Black Lake (2200 m, 1990), Kaçkar Great Sea Lake (3412 m, 1991) and Süphan Crater Lake (3980 m, 1992) were performed.

6.1. Uludağ 1990 (2200 m)

The aim of the expedition was to get proficiency in altitude and ice diving techniques. No-d limits for 2200 m were calculated using LEM of US Navy M values [7]. Gas uptake of nine compartments was calculated using Eq. 2.18. Descent time and off gassing during the ascent were neglected.

Team members (male, aged between 20-25) were certified SCUBA divers of the Boğaziçi University Diving Club (BÜSAS) with 1 to 6 years of diving experience. Five of them were instructors and one was a 1 Star CMAS diver. The team left Istanbul (sea level) on day 1 (15^{th} of July). They traveled by bus for 4 hours to reach the city of Bursa (150 m), change the bus and traveled for one more hour to reach Alaçam, a village on the way to Mt. Uludağ. A truck transported the team, camping and diving equipment up to the lake. The trip took 3 hours. Approximately 16 hours after arrival, the first dives were performed in the ice-covered lake. The depth of the dives was limited to 5 m; the maximum bottom time was 50 minutes. 6 man dives were completed on day 2. The following day, 6 man dives were performed on Black Lake (day 3). The maximum depth reached was 15 m, with a bottom time of 20 min. All of the dives were below LEM no-d limits calculated for 2200 m. (Table 6.1). No DCS case has been encountered.

Table 6.1

Dive log of Uludağ '90 Expedition

Diver	Lake	Depth	Bottom Time
S Saner	Buzlugöl	5	8
S Saner	Karagöl	14	35
U Özkal	Buzlugöl	5	25
U Özkal	Karagöl	14	35
M Uz	Buzlugöl	5	50
M Uz	Karagöl	15	20
M Egi	Buzlugöl	5	50
M Egi	Karagöl	15	20
A Özman	Buzlugöl	5	25
A Özman	Buzlugöl	5	8
A Özman	Karagöl	14	20
A Kandemir	Karagöl	14	20

6.2. Kaçkar 1991 (3412 m) [97]

6.2.1. Theoretical Background

A probable deviation from linear extrapolation which is an alternative of the three methods of altitude adaptation of DCS boundary presented in Chapter 2, was put forward by Conkin et al [9] for aviators' altitude exposure and simulated extravehicular activities (EVA) and have been tested by USAF in flying after diving experiments [14]. The theoretical basis of this nonlinear hypobaric extrapolation (NLHE) uses phase volume constraints that impose linear M value curves in the hyperbaric range, gradually deviating from linearity in the hypobaric domain (Figure 6.1) [41]. Because of the lack of field-tested altitude tables above 3000 m, the experimental data supporting NLHE is limited to the aviation literature.

An expedition to Kaçkar Great Sea Lake was planned to test different sets of no d limits derived from NLHE of US Navy, starting from the more conservative one. Three set of no-d limits for 3500 m were calculated using LEM of US Navy [7], NLHE of US Navy with δ=2 fsw and δ=3 fsw. (Table 6.2). Offgasing during the ascent was neglected.

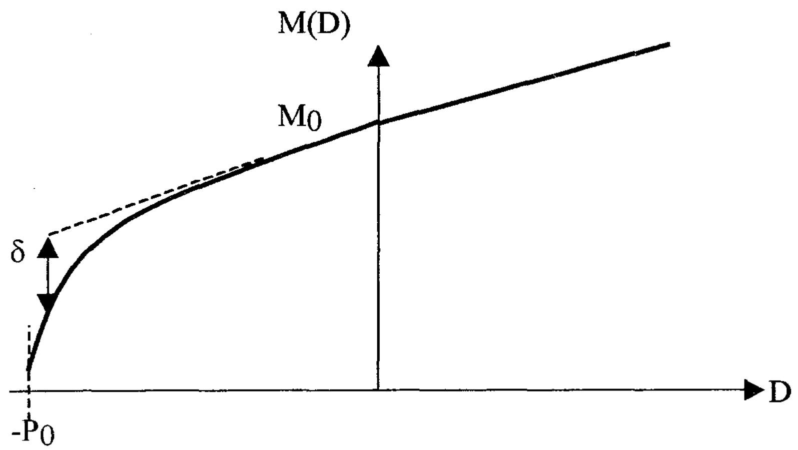


Figure 6.1. NLHE, Non linear hypobaric extrapolation of M values. The amount of deviation from linear extrapolation is noted as δ.

Table 6.2

No-d limits calculated for 3500 m

Depth (m)	15	18	21	24	27	30
LEM	57	42	32	25	19	13
NLHE, δ = 2 fsw	49	37	29	23	17	12
NLHE, δ = 3 fsw	46	35	28	22	16	12

6.2.2. Material and Methods

Nine male divers aged between 20-26 year gave informed consent to join the trip. All members were instructors of the university diving club, with 7 to 3 years of diving experience. Before departure, all participants had a detailed medical examination to check their fitness to dive. The tests included: audiometry, pulmonary function tests, chest x-ray, paranasal sinus x-rays, red and white blood cell counts, bleeding and clotting times, platelet count, erythrocyte sedimentation rate, hematocrit, hemoglobin, SGOT, SGPT, triglyceride, cholesterol, blood glucose, uric acid. The team left Istanbul (sea level) on day 1 (14^{th} of July) and traveled 23 hours by bus before reaching Yusufeli at 560 m on day 2. They spent the night at Yusufeli and traveled for 3 hours by bus to the last village Olgunlar (2200 m) on the way to Kaçkar Mountain on day 3. The team reached the lake at 3412 m by walking 6-10 hours. 1.2 ton of equipment had to be carried up through a trackless mountain terrain by seventeen mules. Above 3200 m., in parts where the route was too difficult even for the mules, the members of the research team and volunteers from the village had to carry it on their back.

The Lake is located in a bowl-shaped basin; at that time of the year the surrounding slopes and surface were still covered with ice and snow. The daily weather temperature varied between 10-15^{0}C while it dropped to –5 during the night. The water temperature was 0 ^{0}C. The team members started diving on day 4, approximately 16 hours after arrival. The first 3 dives were reserved to survey, calibration of depth gauges and video recording. One man dive was accomplished using a semi closed circuit UBA (60% O_2, 40% N_2, FGT-1/D). For the test dives, the subjects were requested to descend to the target depth as soon as possible, keep the dive depth constant and swim around. The ascent rate was 6 m/min. to ensure a slow transition to hypoxia. Aladin Pro dive computer was used to measure the depth as a backup device for the Bourdon type depth gauges calibrated for altitude. Divers wore neoprene or vulcanized dry suits if they had adequate diving experience. Less experienced divers used 5-7 mm semi-dry neoprene suits. 29 man dives, including a night dive, were performed until day 7.

Following decompression, divers were monitored for VGE (venous gas embolism) using a continuous Doppler ultrasound device (5 MHz, Remote 1, Model 4-400, Birtcher, CA) by one of the investigators who was trained in grading Doppler signals. Precordial measurements were carried out, within 10 and 50 min following surfacing, both at rest, after knee or arm bends. The signal was graded according to Spencer Scale [98].

6.2.3. Results

One diver suffered from acute mountain sickness. He complained of a strong headache and had high pulse rate and hypertension. This diver did not participate in the dives. He recovered upon coming back to Yusufeli village.

Divers NG and MA did their first dive with inefficient thermal protection. Towards the end of the dive they experienced extreme shivering. MA's BCD exhaust valve o-ring malfunctioned and had a constant leak. NG had to lower the reserve mechanism manually, which was missed in the buddy check. In their hypothermic state they did not manage to lower the reserve manifold. So NG had to make an emergency ascent. MA surfaced with the help of guideline since the BCD was not operable. The divers did not have any health problems due to this incident.

One diver got entangled to the cable of the surface supplied camera, lost control of his buoyancy and hit the ice. His regulator fell off and his buddy gave him his alternative second stage, they both surfaced safely.

During a test dive originally planned as to 24 m/22 min, divers went down to 28 m at the beginning of the dive. They kept this level, and used the information provided by Aladin Pro dive computer to surface. At 18th min. of the dive, before leaving the bottom the dive computer was still giving 2 min to no-d limit, and gave no decompression during any instant of the ascent. After this dive, grade II-III precordial bubbles were observed in one of the divers, both at 10th and 50th min recordings. This diver showed neurological symptoms of central nervous system DCS, including a pathological Babinski on the right side and no plantar response on the left. Divers were treated by pure oxygen, 250 mg aspirin was given and 8 mg Dexamethazone was injected intramuscularly. Both the dive computer, the LEM and NLHE, $\delta = 2$ fsw. no-d limits were proven to be unsafe for diving at 3412 m. Because of this incident, in the following expeditions the test dives were decided to be concentrated on NLHE, $\delta = 4$ fsw.

6.3. Süphan 1992 (3980 m)

The aim of the expedition was to achieve the highest altitude dive in Turkey. The team consisted of nine male divers (eight instructors and one CMAS 2 star diver) aged between 20 to 27. Their diving experience ranged from 2 to 8 years. All had an up to date medical certificate for fitness to dive. They traveled by plane from Istanbul to Van (1646 m) and took a bus to reach Adilcevaz (1700 m), spending the night there (12th of August). On day 2, they reached the village Kışgıllı (2200 m) by car and started walking. Because of the political situation in the region, the expedition was aimed to be completed with a minimum delay. Thus, no time for acclimatization was planned. It took 4 hours for the team to reach a plateau at 3700 m. where two members suffered from vomiting and strong headache. They were treated with pure oxygen and 8 mg intramuscular Dexamethazone injection. The team spent the night at 3700 m. The symptoms disappeared on the morning of day 3 and the team started climbing a steep rocky hill. One of the team members injured his leg during climbing. The lake was totally covered with ice. The diving operation started at noon, approximately 1 hour after arrival. Scubapro DC-11 dive computer, planned for measuring the depth as the back up, did not function. Only Bourdon type of depth gauges corrected for altitude were used. The first dive was aborted at 3 m after 4 min due to a leak in the dry suit. Only 6 man dives could be achieved with a maximum depth of 11 m and a bottom time of 18 min. The team returned back to Adilcevaz the same day.

Table 6.3

Dive log of Süphan '92 Expedition

Diver	Depth	Bottom Time
U Özkal	5	5
M Uz	11	18
M Egi	5	5
A Özman	5	5
A Kandemir	5	5
M Aydın	3	4

7. ANIMAL EXPERIMENTS

7.1. Introduction

A series of pig experiment was planned to test the validity of similarity criterion described Section 2.2.2. It was also aimed to observe the occurrence of intravascular gas bubbles at altitude exposures and the effect of simulated altitude on cardiopulmonary parameter of pigs. The theoretical basis for these two topics was described in section 2.4 and 3.3 respectively.

7.2. Material and Methods

7.2.1. Selection of Altitude, Depth and Bottom Time

The differences between altitude adaptation of dive tables are enhanced as altitude, depth and bottom time is increased [13]. Therefore a relatively deep air dive (40 m/42 min) was selected from the sea level experimental data performed at SINTEF UNIMED [99]. The corresponding equivalent altitude diving depth calculated for 3500 m. altitude is 25.8 m. That altitude was chosen to provide data for further human experiment on Mt Kaçkar (3412 m). To preserve the similarity criterion of Bell and Borgward [34] the compression-decompression time of the altitude dive was selected to be the same as the 40 m. sea level dive.

7.2.2. Selection of Ascent Rate to Altitude.

Conkin et al. estimated 3900 m as the altitude threshold of DCS for a 1500m/min ascent rate [10]. However, the data about the hypoxic response of pigs is not available for moderate altitude. Thus a moderately low ascent rate was chosen. The ascent was decided to be split into 2 phases to allow time for adaptation to low partial pressure of oxygen.

Beside this, emergency back-up plans were prepared in case of severe manifestation of hypoxia. The decision whether to switch to another profile was decided to be judged according to cardiopulmonary measurements. The duration of anesthesia limited the predive altitude equilibration period. This duration was arbitrarily chosen as 240 min.

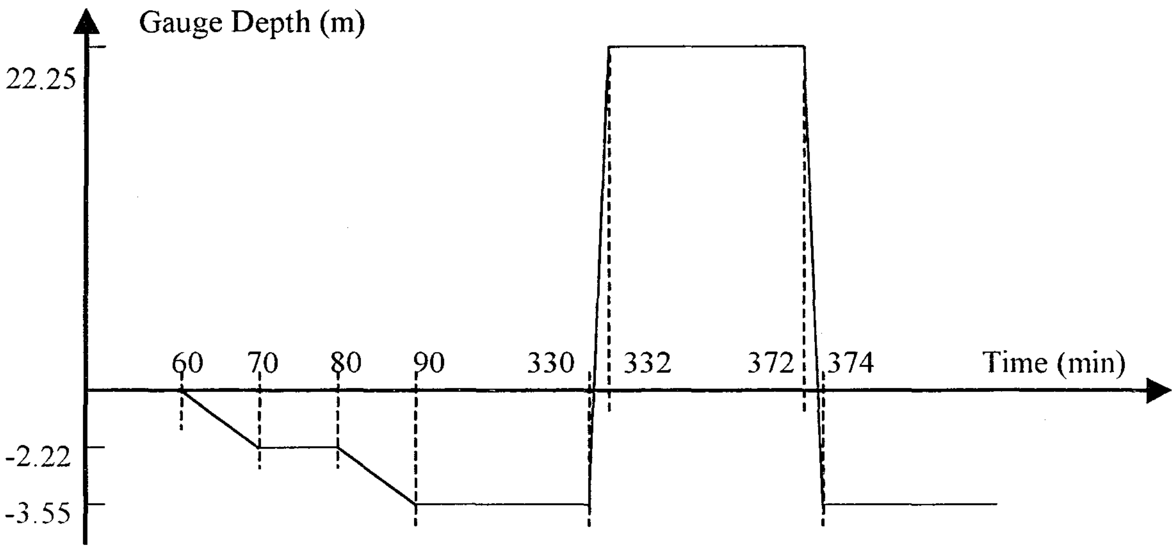


Figure 7.1. The profile of the altitude diving experiment.

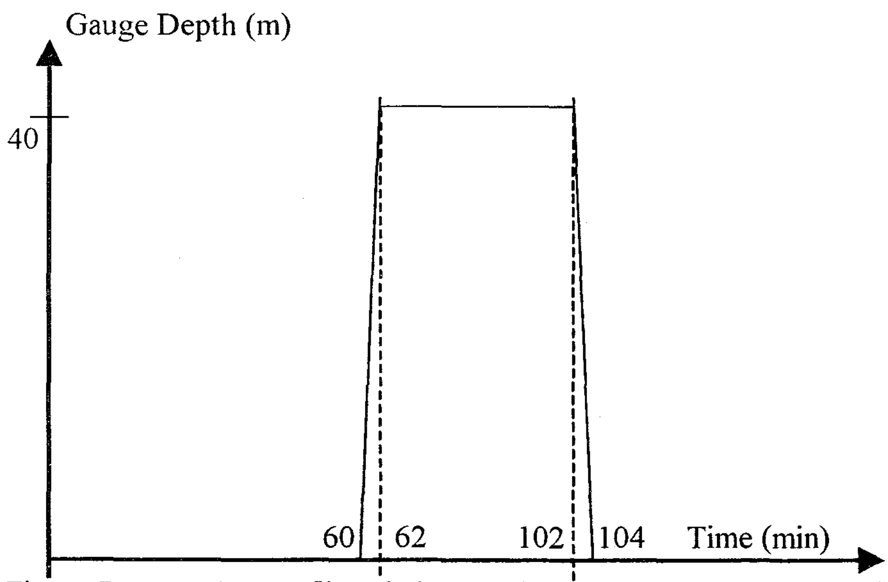


Figure 7.2. The profile of the sea level experiment suggested 'equivalent' to above altitude dive [15,16,34].

7.2.3. Experimental Set-up and Procedure

The profile were simulated in UNVDECO software using the general perfusion model with parameters listed in Table 5.1 to observe gas exchange and the vacancy during the ascent.

The experimental set-up and procedure of the sea level experiments are described elsewhere [99]. The altitude simulation experiments were carried out on 7-8 years old pigs weighting 22, 23,5 and 25 kg. (n=3). They were premedicated, and then anaesthetized for preparatory surgery with Atropine, Thiopentone and Ketalar. Maintenance anesthesia was with Ketalar and α-Chloralose and was adjusted to maintain normal respiratory and cardiovascular levels as judged by arterial blood gases. Arterial and venous blood samples were taken at regular intervals to measure the partial pressures of oxygen and carbon dioxide. Following tracheotomy, an airway was inserted allowing the use of a two way breathing valve and measurement of ventilation by a Fleich V pneumotachograph. The pigs breathed spontaneously in supine position during the experiments. Surgery was carried out to allow the insertion of the catheters for measurements of pulmonary artery, central venous and arterial pressures. The pigs were allowed to stabilize for one hour before decompression to altitude. The control of the pressure chamber, measurements of blood pressures and breathing gases were accomplished by Chamber Guard software [99]. The recording was not possible due to software problem that occurred during the 2nd experiment.

To evaluate the mixed venous levels of nitrogen, 1 ml. blood samples were taken through a catheter placed into the pulmonary artery. The samples were drawn into gas tight syringes. The samples were analyzed for nitrogen content using the gas extraction technique [100]. This technique has been shown to perform well in gas exchange studies [91]. However, during the first experiment the catheter was blocked, and the scatter in the measured levels made impossible to draw and conclusion.

A transoesopagal echocardiographic transducer (TEE-probe, 7.5 MHz, CFM 750, Vingmed A/S, Horten, Norway) was used to detect arterial and venous gas bubbles. The probe was inserted ~35 cm into the esophagus providing a 2D image of the right ventricle, the main pulmonary artery and aorta. The air bubbles were observed as intense spots in the blood (Figure 7.15) [101]. A system for real time detection and quantification of the bubbles was used [102] (Figure 7.3). The result is presented as number of bubbles per cm^2. During experiment with the first pig, it was not possible to get the images due to a hardware problem.

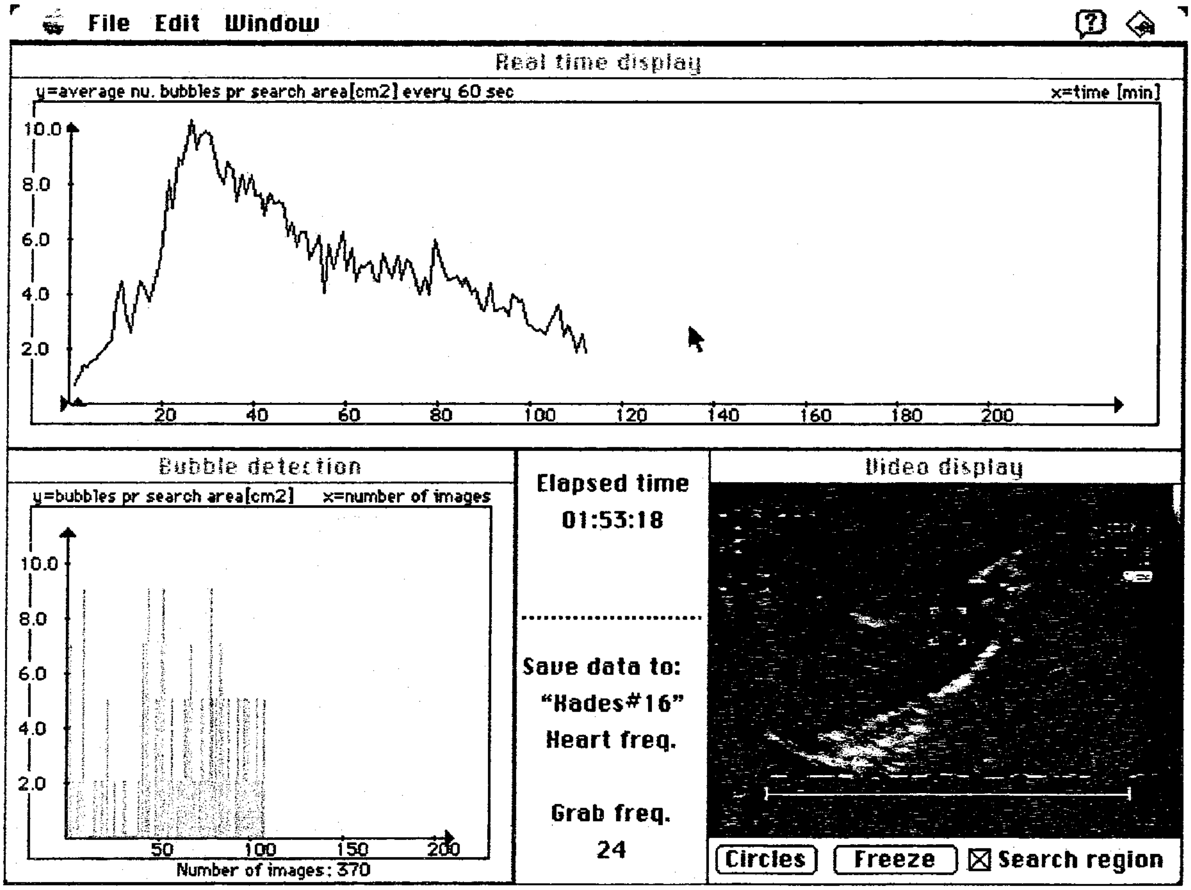


Figure 7.3. Sample output of the automatic bubble counting system.

7.3. Results

7.3.1. Hypoxic Response of Pigs to Simulated Altitude

The pigs tolerated well the ascent profile. The end expiratory partial pressure of oxygen followed the ambient pressure. In fact, the end expiratory P_{O2} decreased from 10,4±3.61 (mean±SD of 4 measurements) to 5.28±0.36 (mean±SD of 9 measurements) and from 11,16±3.85 to 5.7±0.28 for pig 1 and 3 respectively (Figure 7.4). The P_{CO2} remained constant before, during and after the ascent (Figure 7.5).

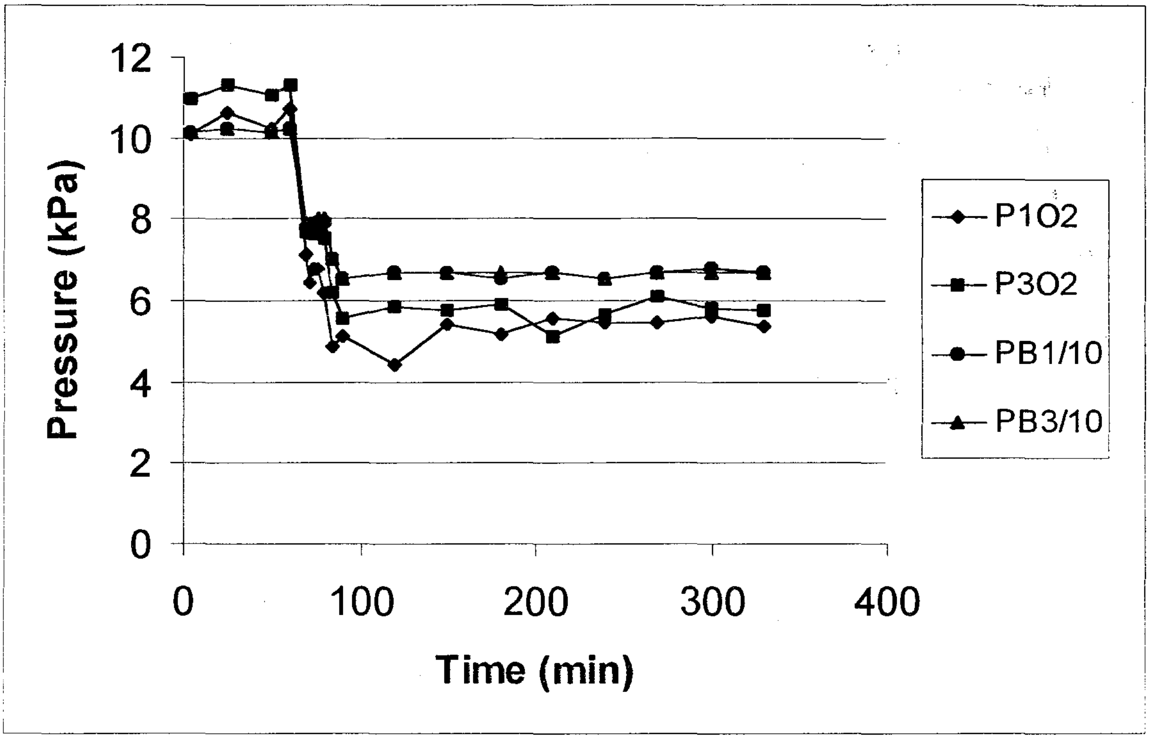


Figure 7.4. The chamber ambient pressure and partial pressure of end expiratory O_2. The P_{O2} level of pig1 decreases significantly down to 4.44 kPa 30 min following the ascent but gradually recovers.

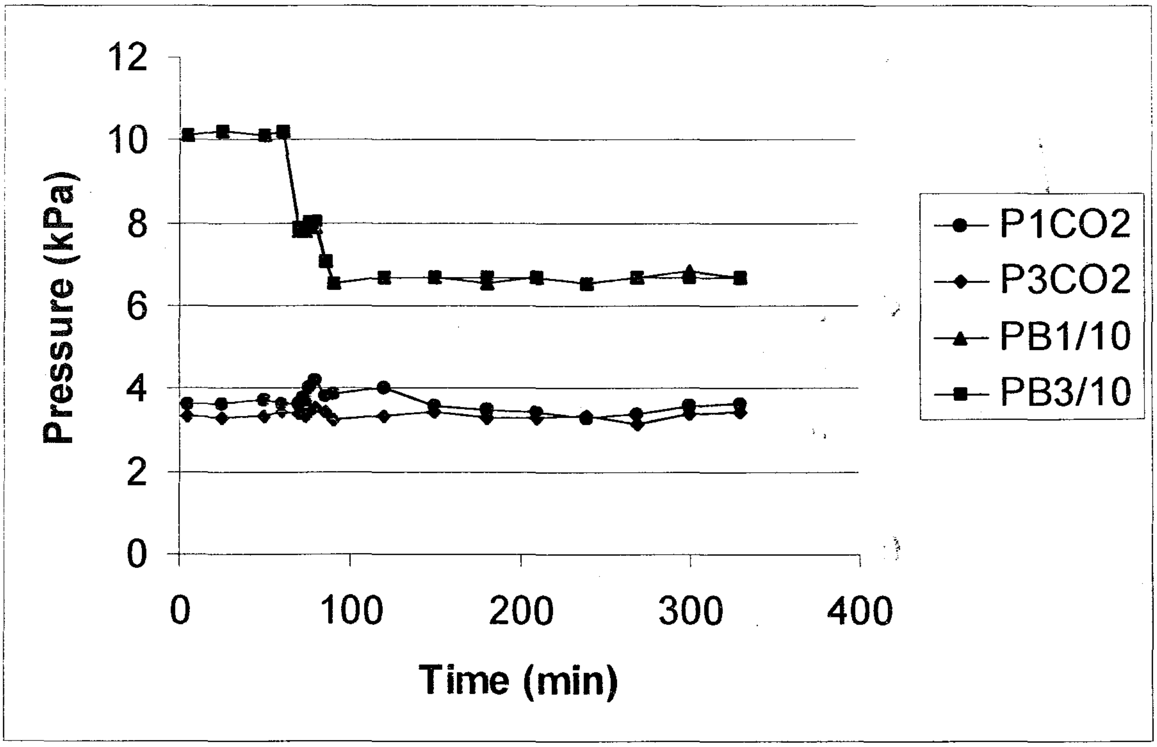


Figure 7.5. The chamber ambient pressure and partial pressure of end expiratory CO_2. The end expiratory P_{CO2} remained constant.

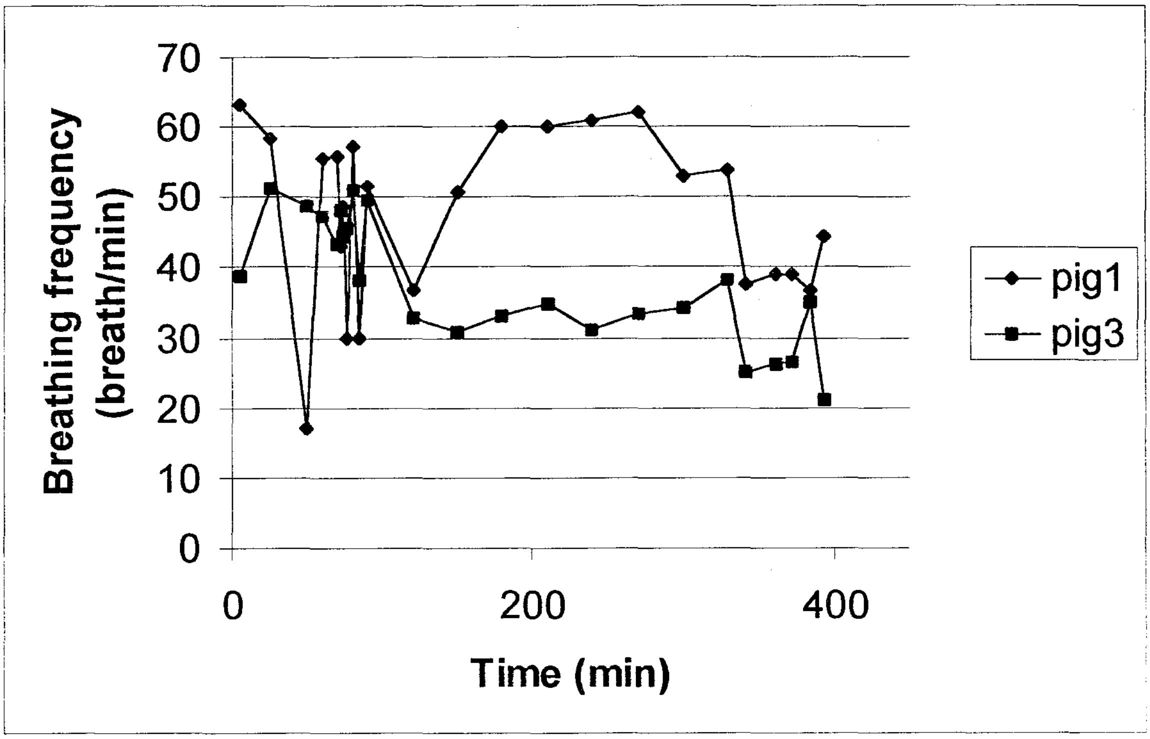


Figure 7.6. Breathing frequency of the pigs during the experiment.

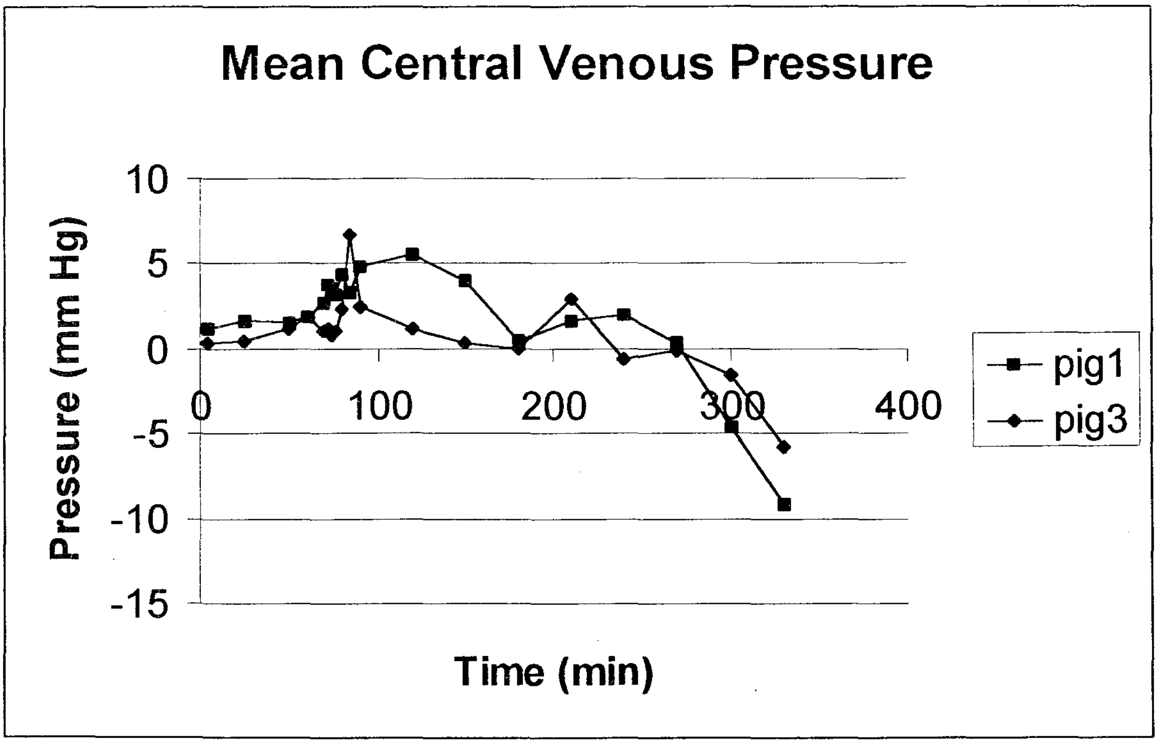


Figure 7.7. The central venous pressure of the pigs. It was almost stable during the altitude exposure, but started to decrease at 300th and 330th min readings.

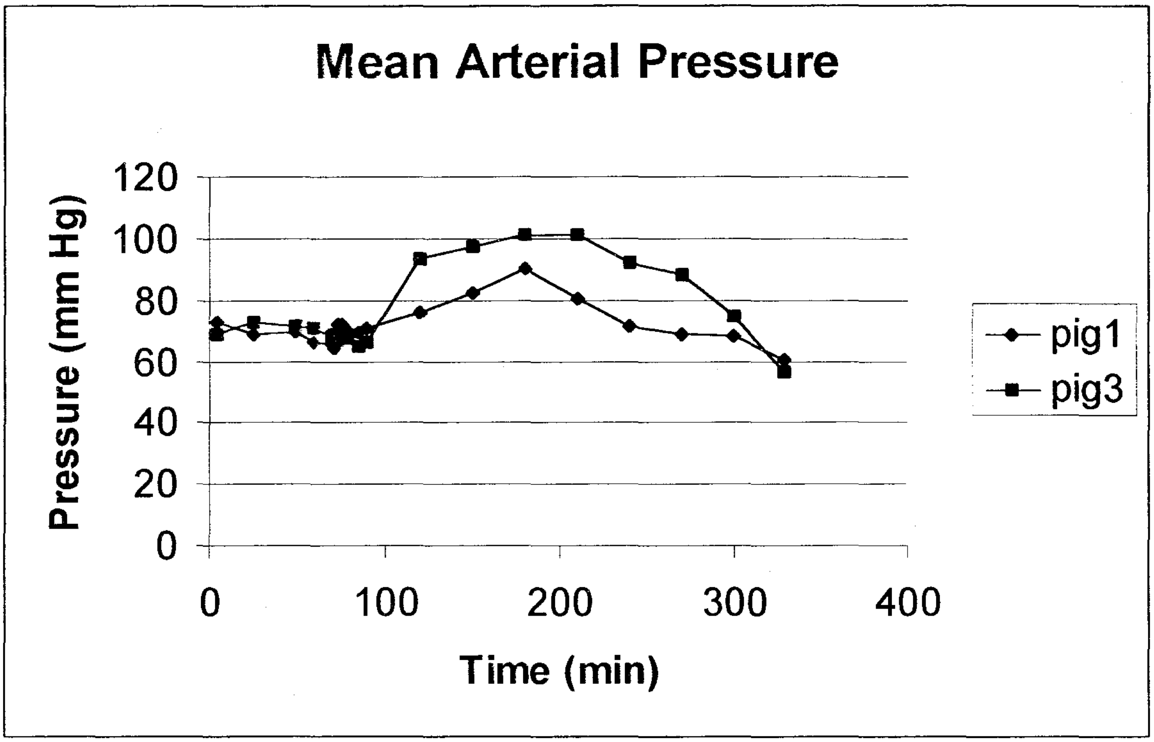


Figure 7.8. Mean arterial pressure starts to increase following ascent, but gradually recovers.

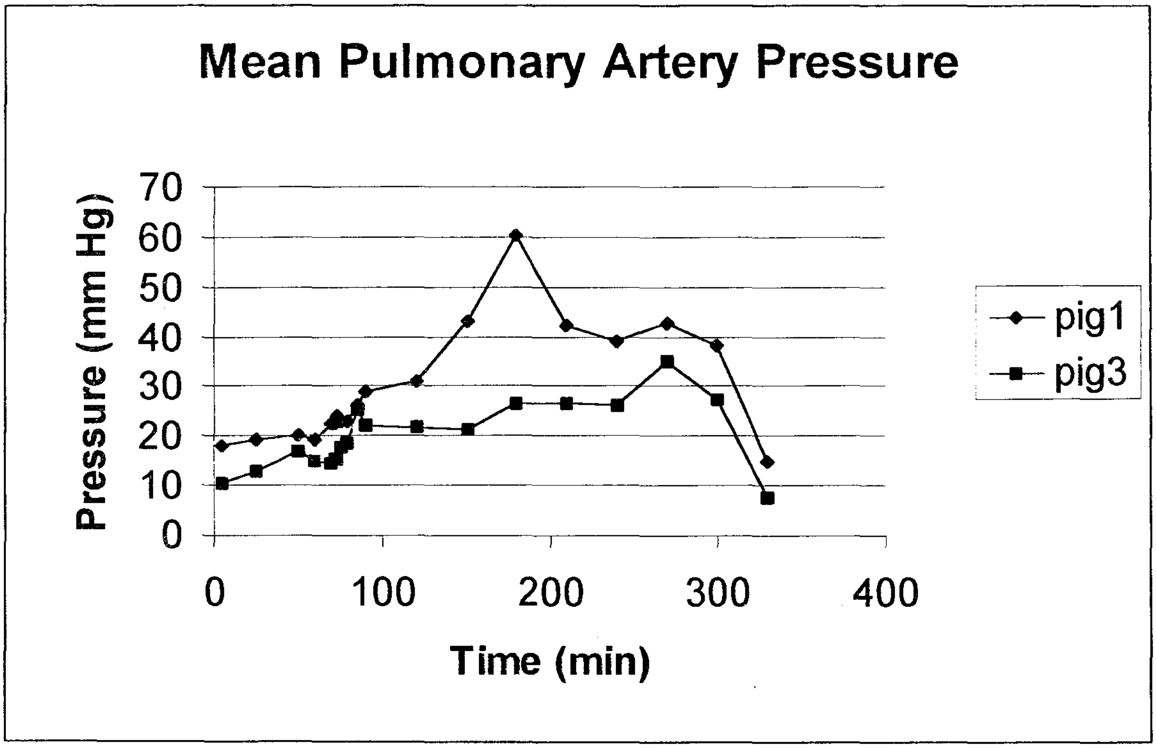


Figure 7.9. Mean pulmonary artery pressure follows the same trend as the arterial pressure.

The systemic pressures of both pigs showed similar trends (Figures 7.7, 7.8, 7.9), but the breathing frequency of pig3 is significantly lower than pig1 until the start of the dive (Figure 7.6, 330th min). Arterial pressure and pulmonary artery pressure increased from mean pre-ascent values (69,18 mm Hg and 19.13 mm Hg for pig1, 70,92 mm Hg and 13.05 mm Hg for pig3) to compensate for hypoxia, but gradually fell back. (pig1: 90.34 Hg maximum arterial pressure reached at 180th min; pig3: 101.21 mm Hg maximum arterial pressure at 210th min; pig1: 60.5 mm Hg maximum pulmonary artery pressure at 180th min.; pig3: maximum pulmonary artery pressure 34.96 mm Hg at 270th min).

7.3.2. Observation of pulmonary artery bubbles during ascent to 2000 and 3500 m

The UNVDECO simulation of the profile suggests a supersaturation in some tissues as well as mixed venous blood (Figure 7.10-13). This experiment proved that such a supersaturation is enough to yield intravascular bubbles (Figure 7.14, 7.15). The amount of bubbles corresponds approximately to a Grade 1 Doppler ultrasound observation. According to the data compiled by Nishi, Grade 1 bubble observation is associated with 1.2% of DCS incident [89]. This finding explains the "rare" cases of DCS encountered in aviation [46-49]. Conkin et al. and Kumar et al [10,12] also suggested altitude thresholds far below the "conventional" DCS limit of 6096 m [8]. In operation Everest II Malconian et al. observed much higher incidence of DCS below 6096 m [103]. Their observations are also consistent with NASA reports [104]. They concluded that in operational aviation medical environment, the threat of potential grounding discourages aviators from reporting minor symptoms. The situation is even worse in civil aviation, in which DCS is not an appreciated hazard at all. Several airplanes are capable of cruising above 6000 m without cabin pressure. In addition to these, there is no information in owner manuals of these planes about this issue [105].

Detection of intravascular bubbles at low supersaturation levels has also been reported by Eckenhoff et al. [106]. Based on their observation from shallow saturation diving, they have pointed out that similar bubble observation would be possible at altitude exposures, and have suggested that the complications induced by these bubbles may cause acute mountain sickness.

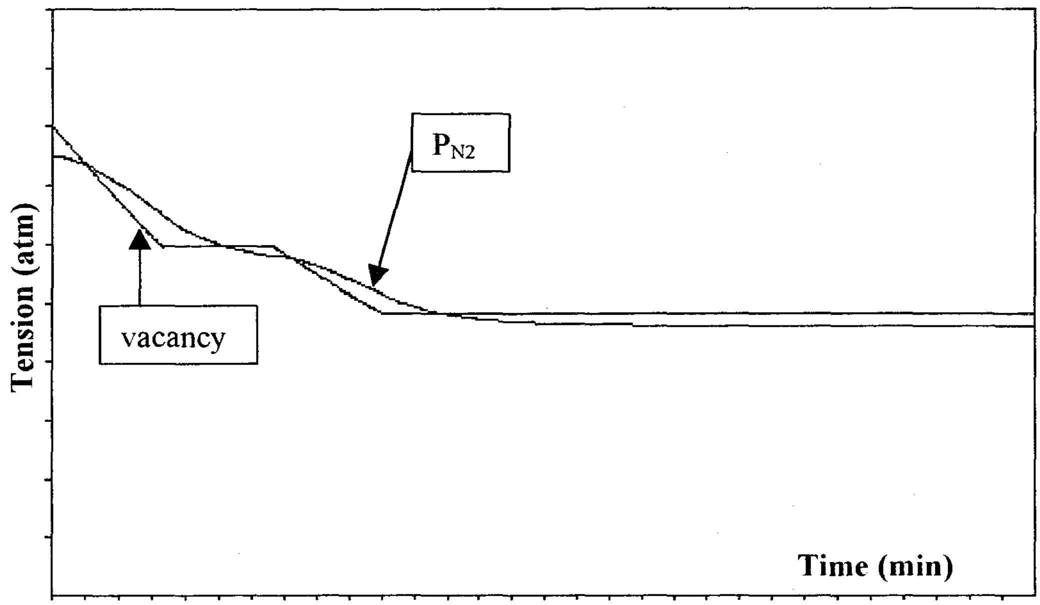


Figure 7.10. Gas exchange and vacancy graph of the white matter during ascent to 3500 m. Vertical axis scale = 0.1 atm/div, horizontal axis scale = 3 min/div.

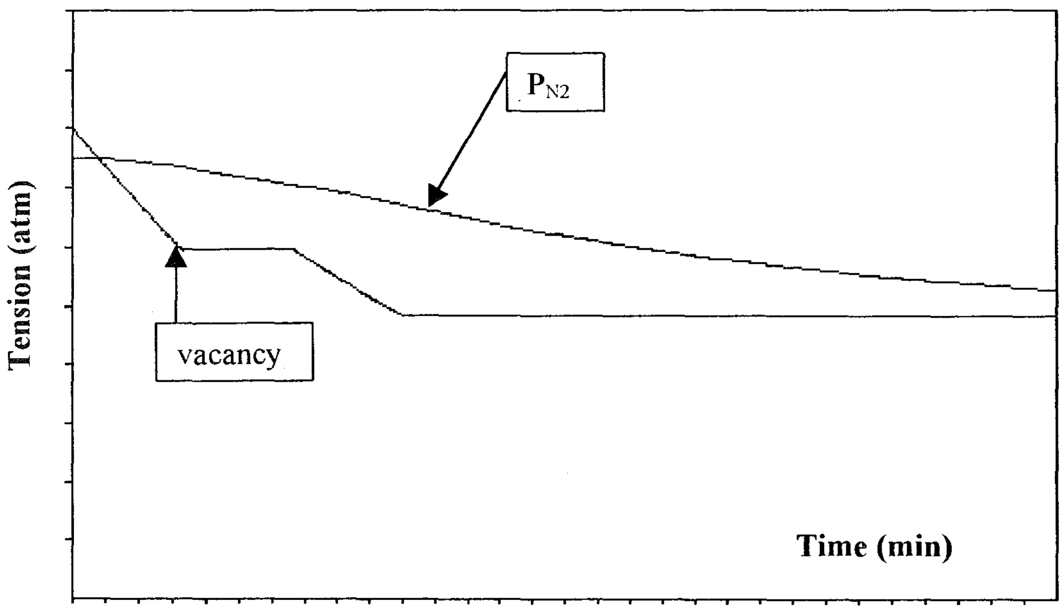


Figure 7.11. Gas exchange and vacancy graph of the muscle tissue during ascent to 3500 m. The scales are the same as in Figure 7.10.

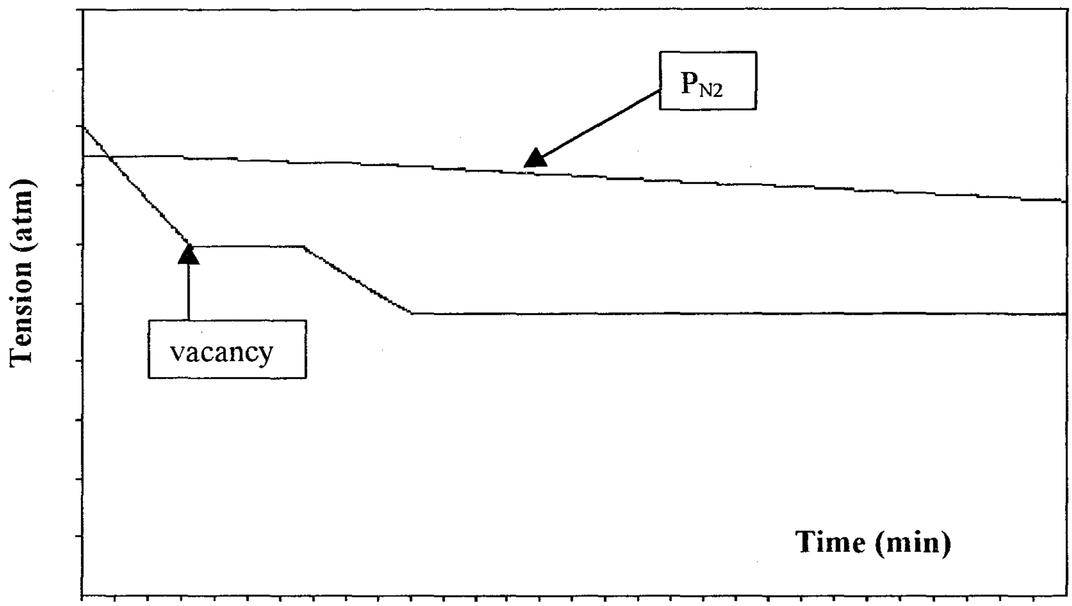


Figure 7.12. Gas exchange and vacancy graph of the fat tissue during ascent to 3500 m. The scales are the same as in Figure 7.10.

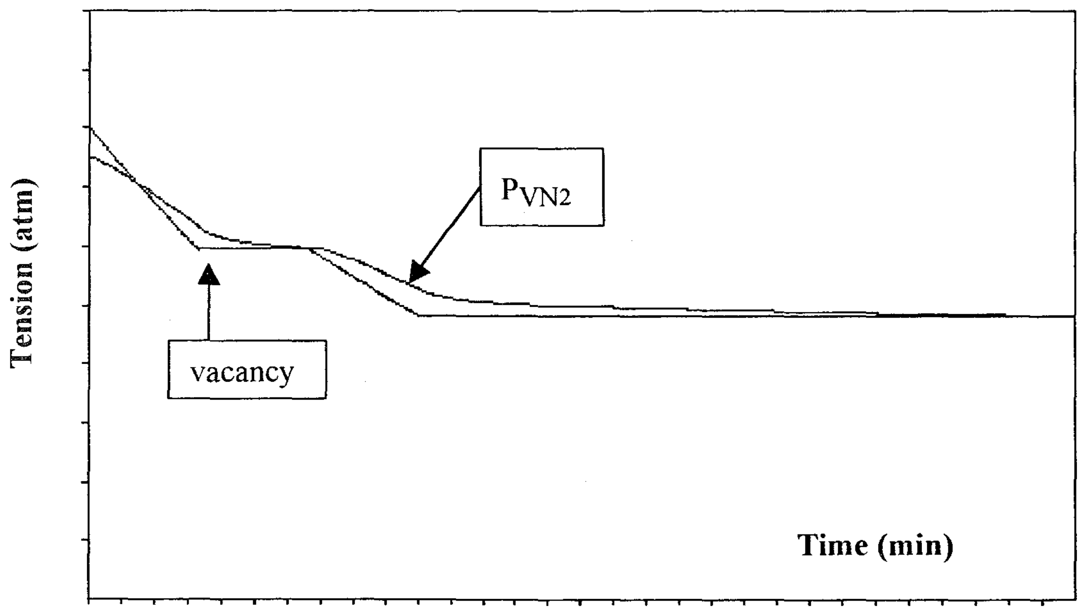


Figure 7.13. The gas exchange and vacancy graph of the mixed venous blood during the ascent to 3500 m. The scales are the same as in Figure 7.10.

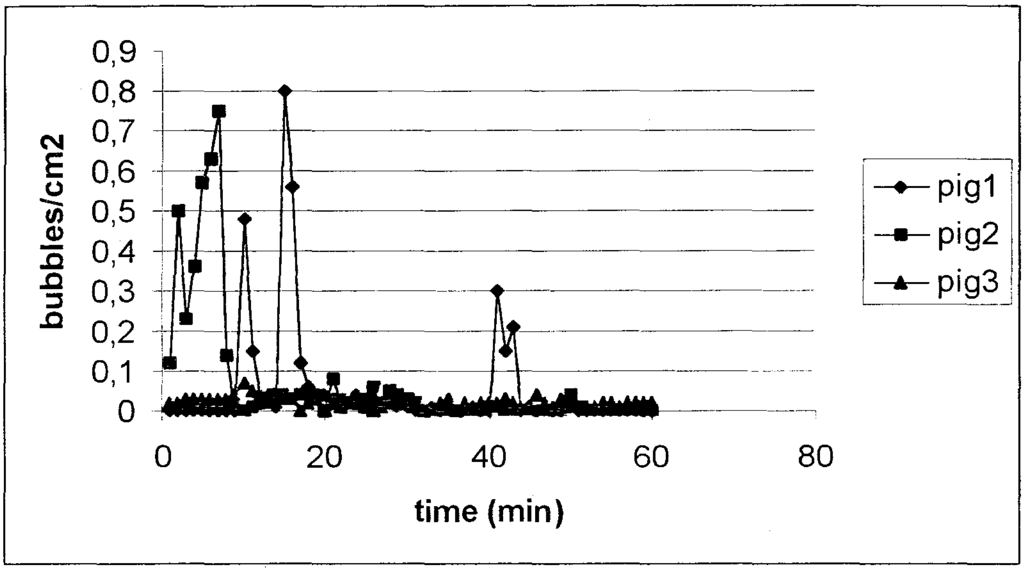


Figure 7.14. Bubble counts during and after the ascent to 3500 m simulated altitude.

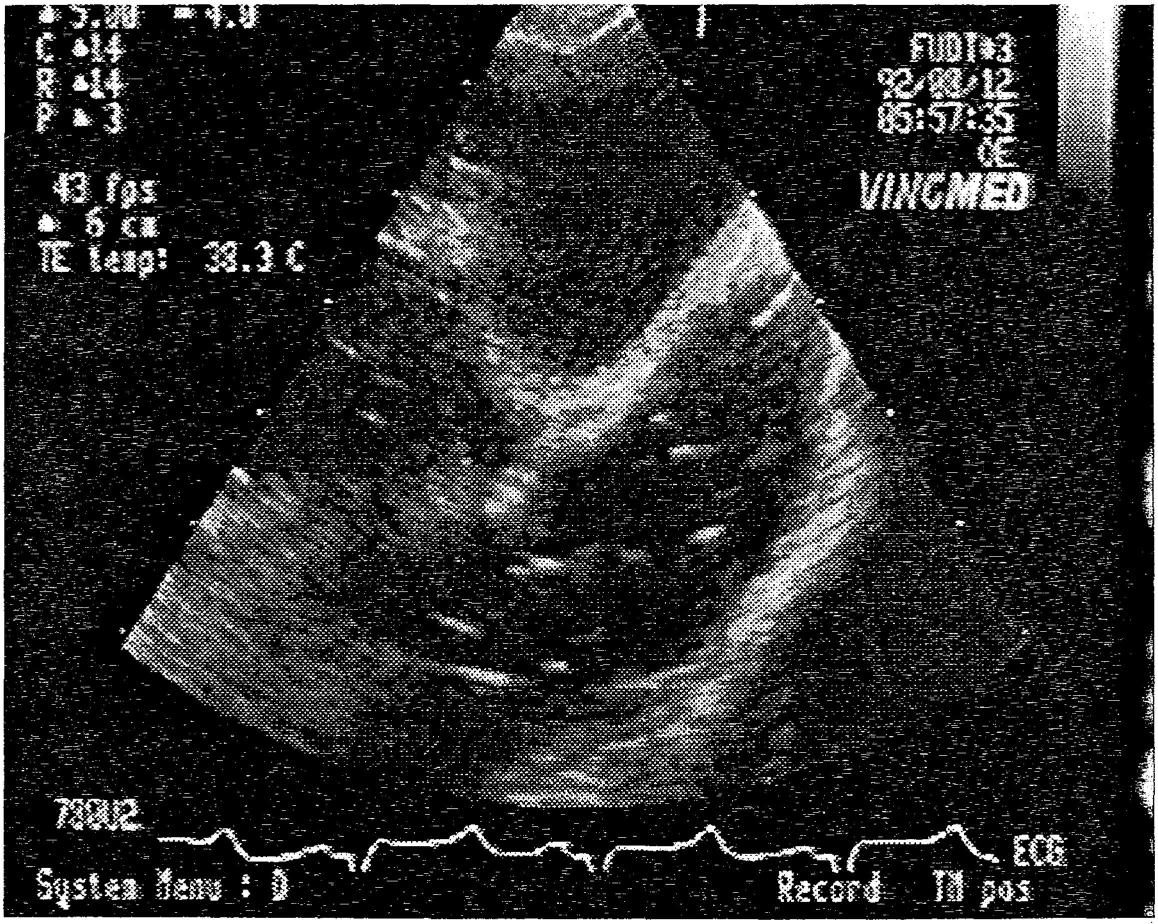


Figure 7.15. Ultrasonic scan of pulmonary artery. Bright spots are gas bubbles.

7.3.3. Failure of the Similarity Criterion

During sea level experiments, a high number of bubbles follow surfacing, decreasing soon after, but giving rise to a second peak around 45-60 min (Figure 7.16). On the other hand, at altitude, pigs had a very low level of bubble counts following surfacing, gradually increasing towards the 60th min. In fact, one of the pigs in the altitude diving experiments died with a very large number of bubbles (up to 22 bubbles/cm^2). To conclude, the bubble counts of sea level and altitude series shows different characteristics, in terms of maximum counts, peak time and duration, indicating that these dives do not have the same DCS stress However, the number of experiments is not enough to establish a risk of DCS associated with each dive series.

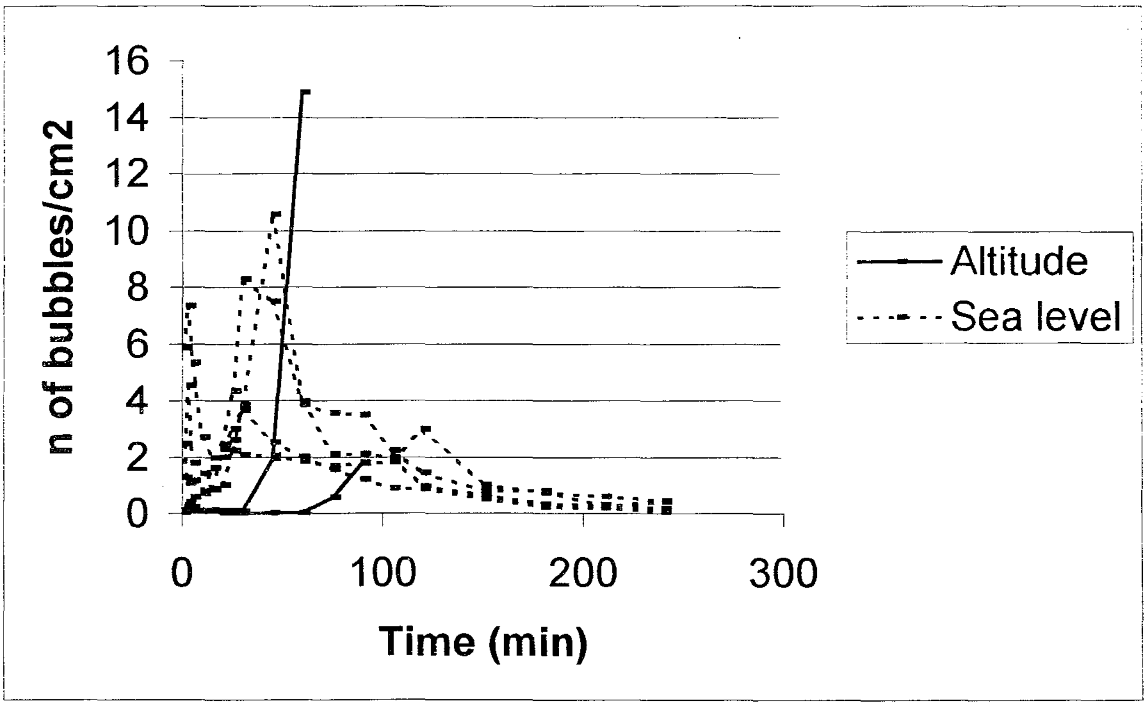


Figure 7.16. Bubble counts of simulated altitude dives and equivalent sea level dives. Time origin corresponds to the end of decompression.

7.4. Discussion

The hardware and software problems encountered during the experiments limited the amount of data. Even if the number of experiments have been increased, the following artifacts hinders the projection of the animal experiments into practical decompression schedule computations:

There is not enough time for equilibration of the tissues with ambient pressure at altitude. In 240 min, only tissues with half times less then 35 min will get rid of the excess dissolved gas remaining from sea level. The period of altitude equilibration cannot be increased furthermore, because it would be a problem to sustain the anesthesia.

The surgical operation on the animals will cause induction of bubble nuclei that will increase the number of bubbles [107]. This is enhanced by the tribonucleation caused during the blood sampling. In fact, a large number of bubbles (up to 2 bubbles/cm^2) were observed before the start of simulated diving in pig3 and after decompression this animal died with a very high number of bubbles (up to 22 bubbles/cm^2).

An important conclusion of the experiments was the observation of intravascular bubbles during ascent to 2000 m simulated altitude.

8. EXPEDITION KAÇKAR '94

8.1. Introduction

An expedition was carried out to Kaçkar Great Sea Lake (3412 m) in 1994 [108-111]. The objectives of the expedition were to study:

- No-d limits calculated using an alternative method of extrapolation of DCS boundary.
- The magnitude and the time course of some of the adaptational changes that might effect the occurrence of DCS or VGE.
- The correlation of VGE with these changes (if any) and with the duration of stay at the altitude

8.2. Material and Methods

During Kaçkar 91 expedition, one diver had showed neurological DCS symptoms, including pathological Babinski on the right side and no plantar response on the left after a 28 m/18 min. dive. Therefore, δ of NLHE is decided to be increased to 4 fsw. The gas exchanges during the descent and ascent was calculated using Eq. 5.2. An arbitrary ascent rate of 18 m/min. was used in the calculations to account for a possible emergency ascent. The descent to target depth is assumed to take 1 min. The computation was performed using UNVDECO Software [112].

Twenty-nine divers (24 male, 5 female, aged between 20 to 29, height 1.77 ± 0.077, weight 71.5 ± 11.2 mean ± S.D.) gave written informed consent to join the '94 expedition. The team was composed of fifteen instructors, five Two Star and nine One Star CMAS divers. Their diving experiences ranged from 1 to 10 years. None of the divers had a

DCS history except one who had mild neurological symptoms in one of the preceding expedition (1991). This diver did not participate to the test dives in 1994. One of them had AMS symptoms at 3412 m in the 1991 and two other had minor symptoms of AMS at 3700 m (1992). Before departure all participants had the same detailed medical examination as in 1991 expedition. None of the divers had been above 2400 m in the two months period preceding the expedition. The divers were encouraged to attend a six-week physical training program, mainly designed to increase the oxygen utilization and transportation. They attended a course on high altitude diving and were encouraged to report any symptoms of AMS and DCS.

Because of the limitation of the camping area around the Lake and to minimize logistic problems the team was divided into three groups. The first team left Istanbul (sea level) on day 1. After a 27 hours bus trip, they arrived in the village of Yaylalar (2200 m); they spent the night at 2200 m. to reduce the susceptibility of AMS. On day 3, the team reached 3412 m by walking 6-10 hours. The weight of diving, camping and laboratory equipment was two tons. It took 2 days for the mules to carry the equipment up to 3200 m. The tents had to be put up under heavy rain. The other groups also followed the same ascent schedule. The stay of each group at 3412 m was limited to 5 days in order to focus the measurements on short time acclimatization. Two researchers and two divers stayed at 3412 m. for 17 and 11 days respectively.

16 hours elapsed before the first dives. Two blood samples were taken from the fingertip of each diver before each dive and hematocrit measurements were carried out. To reduce the susceptibility of DCS, divers with mean hematocrit levels higher than 49 were not allowed to dive. All team members were encouraged to drink water, soup and soft drinks to prevent dehydration.

Heavy rain and hail was common during the expedition. The temperature in the lake varied between 0-7^{O}C. Divers were encouraged to abort the dive in case of extreme shivering. A guideline with 15, 18, 21, 24 and 27 m tags was placed to facilitate the descent and the ascent and to reduce the additional buoyancy problems caused by altitude and the use of dry suits. Bourdon type of depth gauges were used by adding 4 m. to the actual reading to compensate for decreasing ambient pressure. Aladin Pro Dive Computer was also used for depth measurements. The bottom of the lake was covered by a silt and mud layer. Divers were advised to fin just above the bottom to avoid stirring up of the sediment.

One set of dives was reserved for underwater photography and training. The depth of these dives was limited to 12 m. Some of those dives were multilevel and repetitive. The ascent rate was arbitrarily set as 6 m/min. Doppler measurements were carried out only if the diver had made an emergency ascent with a faster rate then 6 m/min.

Another set of dive profiles was run to test the no-decompression stop limits of 15, 18, 21, 24 and 27 m. Divers were requested to reach the target depth within 2 minutes after leaving the surface, keep the dive depth constant and swim. A standby diver was ready during the test dives. Following decompression, divers were monitored for VGE using a continuous Doppler ultrasound device (2-5 MHz Mini Dopplex, Huntleigh Healthcare Ltd., UK) by two of the investigators who were trained in grading Doppler signals. Femoral, precordial and subclavian measurements were carried out, both at rest, after knee or arm bends. The first measurement was taken within 15 minutes following surfacing. If no bubbles were detected the measurement sequence was 15, 30, 45, 75, 105, 180 minutes following the first one. If bubbles were detected, the measurements were extended up to 6 hours and the sequence was scheduled to 15, 30, 45, 60, 75, 90, 105, 120, 180, 240, 300, 360 minutes following the first measurement. The signal was graded according to the Spencer Scale.

A monoplace telescopic pressure chamber and pure oxygen were available at the diving site.

Near arterial O_2 and CO_2 levels were monitored using transcutaneous recordings ($TcPO_2$ and $TcPCO_2$) from left second intercostal space while the subjects lying in the supine position for 30 min. (TINA TCM3, Radiometer Copenhagen, Denmark). The electrodes were calibrated for ambient pressure using a 20% O_2 5% CO_2 gas mixture supplied by the manufacturer. The electrode temperature was 45^oC. The measurements were taken before departure (day 0), day 3, 8 and after coming back to sea level (day 12) for the third group and day 0, 4, 6, 8 for the second group. On the 8th day, measurements were repeated for the third group members while the subjects were breathing pure oxygen.

Electrical bio-impedance measurements were carried out to assess the body composition in the first (sea level only) and third group (day 0, 4, 6, 8, 12) using a custom made portable four probe impedance meter. Seven male and three female volunteers (mean age 22.9±2.132 S.D.) gave informed written consent to join these experiments. The average height and weight are 173.7±7.273 S.D. and 67.875±8.79 S.D. respectively. The device was calibrated with hp 4284A LCR Meter (Hewlett Packard) and has been found to be inadequate for carrying out measurements above 800 kHz. The measurements were done while the subjects lay in supine position, with limbs abducted from the body. The disposable ECG electrodes were placed on the dorsal surfaces of the hands (wrist and distal metacarpals) and feet (ankle and distal metatarsals). Tetrapolar measurement sites were left side (L.S: from left arm to left leg), right side (R.S: from right arm to right leg), cross sides (L-R: from left arm to right leg and R-L: from right arm to left leg), arms (from right arm to left arm), trunk, left leg (L.L), right leg (R.L.), left arm (L.A.) and right arm (R.A). Thus, the electrode combinations were arranged to measure whole body (four different combinations of extremities), from arm to arm, trunk, each arm and leg. For 50 kHz, whole body impedances were calculated using the average of left side, right side, from left hand to right leg and from right hand to left leg combinations. The sea level measurements were performed after overnight fasting. However, due to severe operational difficulties this could not be realized for the measurements at the diving site. The fat free mass (FFM) and %fat were calculated using different equations compiled from the literature [113-119]. Beside the conventional 50 kHz measurements, 5 kHz, 200 kHz and 500 kHz measurements were taken to investigate the changes in the volume of extracellular fluid (ECF). Multiple frequency data is used to draw the Cole-Cole plots. The data which does not converge is eliminated. Statistical analysis to compute the significance of the changes in body composition is performed using paired Student's t-test.

8.3. Results

40 dives with rectangular profiles (8 dives per profile) were achieved right on the computed limits (Table 8.1). Total bottom time was 1032 min. No case of DCS was encountered. Bubbles were detected in 16 of these dives, 14 were precordial bubbles. Only, 6 of divers had simultaneously VGE after the same dive. The duration of bubbles extents from one single observation to 345 min. while the maximum onset time is 105 min. Peak times ranges from the first measurement (0 min.) up to 105 min. (Table 8.2).

Table 8.1

M4 No-d limits calculated for 3500 m

Depth (m)	15	18	21	24	27	30
NLHE, $\delta = 4$ fsw	38	29	24	21	17	14

50 dives below no-d limits were carried out with a total bottom time of 837 min. Bubbles were observed in 6 of these dives. One diver was identified to have circulation problems due to a past injury. She had grade 1 in a 21 m/18 min. dive aborted because of cold problems (onset time 15 min, duration 15 min.). Diver BY had grade 1 bubbles after 10 m/40 min. dive (single detection, onset time 60 min.). The site of the detections was the left femoral vein in both cases. Those divers were not allowed to dive the following days. In a 24 m/18 min. dive, grade 1 and 2 bubbles were observed in two divers following an emergency ascent with a rate greater than 18m/min. Diver ME had grade 1 VGE at first two measurements, Diver HD had grade 2 bubbles at the first measurement and he complained about temporary pain on his left knee appearing right after surfacing. Detailed neurological examination and pressure cuff test did not show any evidence of DCS. Finally,

grade 2-3 bubbles were observed in two divers who were suspected to fail to correct the reading of their depth gauge, i.e. add 4 meter, to the 22 m reading of their depth gauge. Their bottom time was 20 min. One of them, diver EÇ had grade 2 on the first detection only. For the second diver (DV), the time parameters of VGE were as follows: onset time = 0, peak time = 0, maximum grade = 3, duration = 75 min. Diver DV complained about a temporary pain at the left arm. Detailed neurological examination and pressure cuff test did not show any evidence of DCS. Both diver HD and DV were treated with oxygen. In addition to this, 8 mg Dexamethazone was injected intramuscularly and 250 mg aspirin was given.

Table 8.2
Time parameters of the precordial VGE scores

Subject	Day	Depth (m)	Onset time[a] (min.)	Maximum Grade	Peak time[b] (min.)	Duration[c] (min.)
ME	10	24	0	III	0	90
ME	11	27	30	I	30	0
ME	12	18	0	I	0	0
RC	6	15	45	I	45	0
UÖ	11	27	15	II	15	135
AT	4	24	75	I	75	0
AT	6	21	0	III	15	45
BÖ	4	24	30	III	30	60
ZÖ	6	15	0	III	0	60
LO	5	24	0	I	0	0
LO	6	27	0	I	0	0
BY	6	15	150	I	150	0
BY	11	24	15	I	15	60
FH	5	21	30	III	30	130

[a] Onset time: the interval from the first measurement (0 min) to first detection of VGE.
[b] Peak time: the interval from the first measurement to the detection of maximum VGE score
[c] Duration: the interval between the onset time and the last detection of VGE. 0 min. duration corresponds to a single detection.

After a 21 m/24 min dive, bubbles were observed at precordium (grade I at rest, grade III after movement) and right femoral vein (grade I after movement) of subject FH

(Table 8.2). The diver did not show any symptoms of DCS during the post dive monitoring period (8 hours, 22 min). The subject went sleeping around 22:00. At 02:30 AM (13 hours following surfacing), he wake up and came with complaints about numbness in his left toe and right finger tips, with pain in his left leg and his back and also a sharp pain in the right part of his chest. Detailed medical examination did not show any evidence of DCS. The complaints were vague and temporary. 8 mg Dexamethazone was injected intramuscularly, for the sake of early intervention in case of development of symptoms.

Grade II bubbles were observed in the pulmonary artery and right subclavian vein of diver AT in the first measurement following decompression of the 21 m/24 min dive (Table 8.2). 30 minutes after the surfacing, the diver complained from a vague feeling of pain in the right elbow. Pure oxygen was administrated and the symptoms disappeared within 15 min. Detailed medical examination did not show any evidence of DCS. Above cases were not considered to be DCS.

The regulator of diver SS froze at 10 m at the 4^{th} min of the dive. Although he started to use the octopus of his buddy, he could not ascent and had a panic because of the low visibility caused by the sediment layer. His buddy ditched his weight belt and both surfaced. None of them had any symptoms related to the fast ascent.

Before departure, average hematocrit level was 45.16 ± 0.626 (mean ± S.E., N=25). No significant change has been observed in the hematocrit levels upon arrival (day 4) or during the stay at 3412 m. However, the hematocrit level of one of the long term residents, who did not participate in the experimental dives, increased from 47 (day 4) to 55 (day 17).

The average $TcPO_2$ expressed in torr of the second (N=7) and third group (N=9) increased from 35.9 ± 4.9 (day 4) and 39.8 ± 3.1 (day 3) to 41.6 ± 4.4 and 50.6 ± 3 (day 8) respectively (mean ± SE; $p<0.05$ and $p<0.005$). On day 8, in group 3, after breathing pure O_2 for 15 minutes, the average $TcPO_2$ increased to 329 ± 6.1 (mean ± SE) while the $TcPCO_2$ remained unchanged. The $TcPCO_2$ levels did not change significantly during the stay at altitude (28 ± 1.7, mean ± SE, day 4; group 2; 29.8 ± 0.85. mean ± SE, day 3, group

3). No significant change was observed between the sea level $TcPO_2$ or $TcPCO_2$ levels before and after the expedition (day 0-12, N=7).

The bio-impedance analysis of the 50 kHz data yielded a significant increase of %2.708 in percent fat fraction of group 3 (day 0-12, p = 0.059, N=10, using the equation in reference 119) together with an average weight loss of 0.675 kg (p=0.022). The results of the existing Bio-Impedance Analysis (BIA) equations exhibited a significant decrease in the FFM, ranging from 1.04 to 3.027 kg,

Table 8.3

The mean FFM change in the Expedition Kaçkar '94

Reference[a]	Mean decrease in FFM ± S.E.	p
113	1.440 ± 0.659	0.028
114	3.027 ± 0.856	0.0031
115	1.129 ± 0.157	2.51e-5
116	1.043 ± 0.150	3.4e-5
117	2.031 ± 0.514	0.0016
118	2.555 ± 0.723	0.0031

[a]The reference of the equation used for BIA

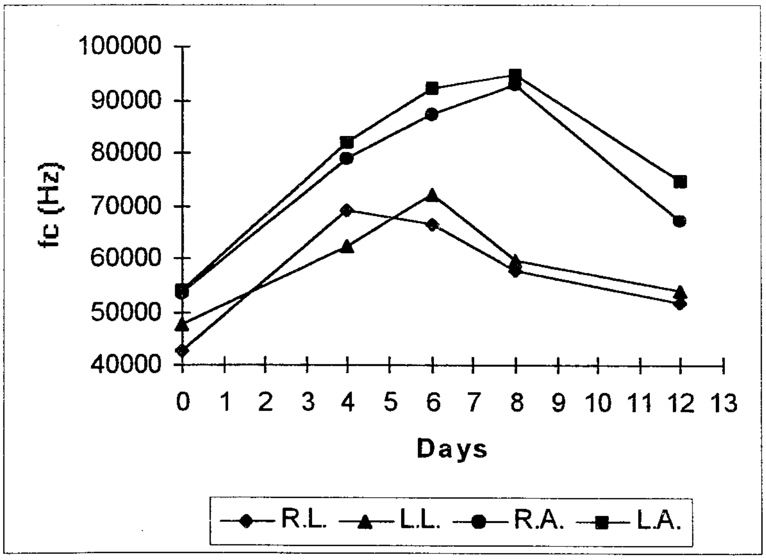


Figure 8.1. The characteristic frequency (fc, mean, N=10) of the limbs during the expedition.

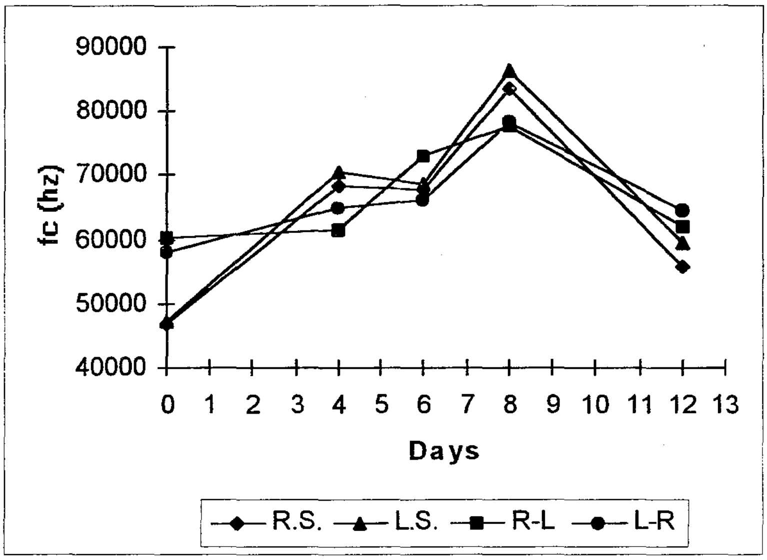


Figure 8.2. Whole body fc (mean, N=10).

Characteristic frequencies (fc) changed during the expedition for all measurement sites, partially restored upon coming back to sea level [120] (Figures 8.1 and 8.2). The extremities, the trunk and whole body impedances exhibited different trends during the expedition. The resistance of the legs at 5 kHz increased significantly upon ascent (day 0-4, $p<0.005$ right leg, $p<0.03$ left leg). On the other side, the resistance of the arms and the trunk decreased significantly after the ascent (day 0-4, $p<0.03$ trunk, $p< 0.005$ left arm, $p<0.0007$ right arm). The arms and the trunk resistance stabilized on day 6 and 8. They returned to pre ascent value after coming back to sea level (Figures 8.3, 8.4 and 8.5).

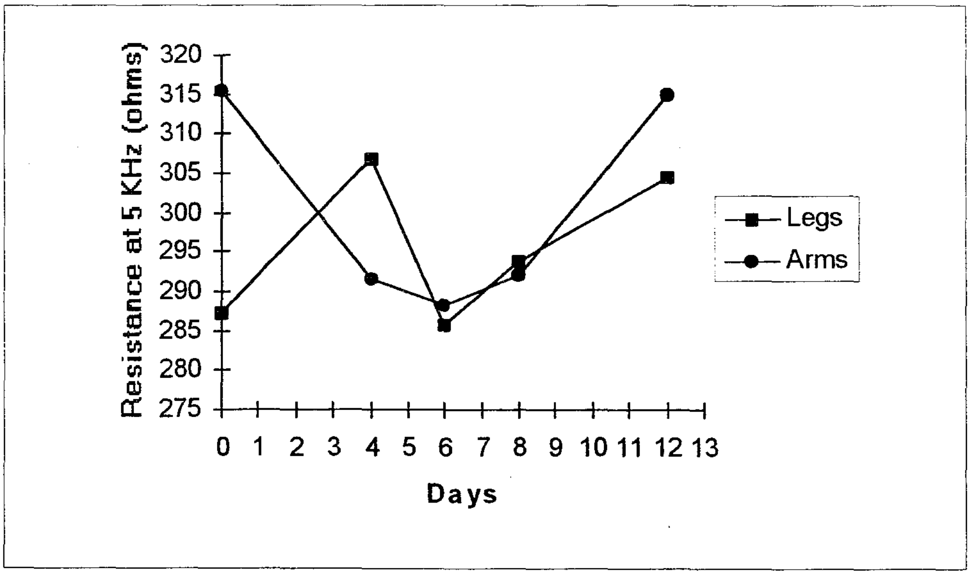


Figure 8.3. The change in the resistance of the arms (N=20) and legs (N=20) at 5 kHz occurs in different directions.

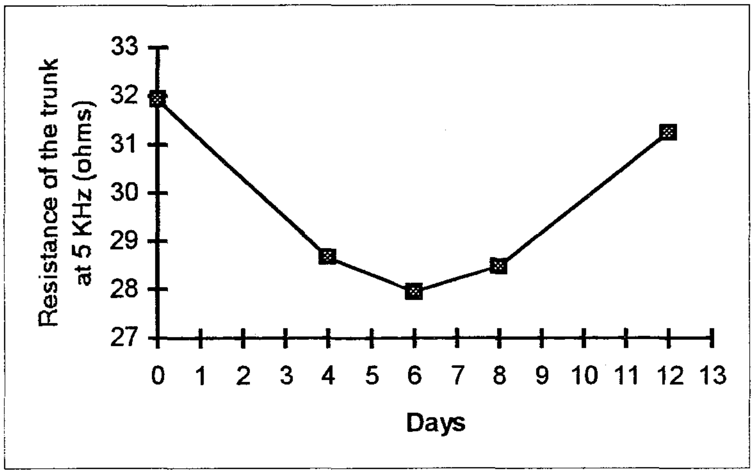


Figure 8.4. The change in the resistance of trunk (N=10) at 5 kHz is similar to the arms.

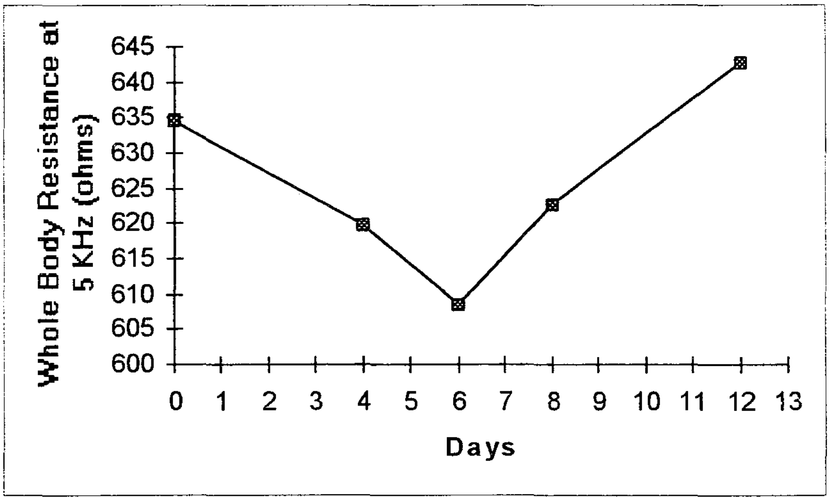


Figure 8.5 The change in the whole body resistance at 5 kHz (N=40, all possible electrode combinations).

8.4. Discussion

The results of the bubble counts are to be discussed in chapter 9.

In case of full acclimatization, the increase in the partial pressure of alveolar oxygen was estimated to be 7.18 torr [13,84]. The measured changes in $TcPO_2$ are close to this value, however, the predicted decrease in the alveolar CO_2 is not observed. The increase in $TcPO_2$ values indicates an increase in the oxygen carrying capacity of the blood.

This can be due to several factors such as the increase in ventilation, P_{50} value, 2,3 DGP, hemoglobin concentration or red blood cells. The percent increase of $TcPO_2$ in group 2 ranges from 70% to -23% (day 4-8) and from 100% to -2% (day 3-8). The large variation of the $TcPO_2$ values reflects also the individual cardiopulmonary adaptation capacity of each diver to attitude. The change in the near arterial levels of O_2 means a decrease in the magnitude of the oxygen window. This will in turn effect the rate of diffusion of nitrogen molecules to or from decompression bubbles [87], but no correlation has been found between the VGE counts and the $TcPO_2$ values.

Hematocrit measurements provided an important feedback for the divers in controlling their hydration level.

An attempt to quantify the body composition changes due to altitude yielded unacceptable result [76]. In this study, multisite measurement approach is held to expand earlier studies performed at the conventional frequency of 50 kHz. In addition to this, multifrequency technique is used to monitor the changes in ECF volume. No correlation has been found between the sea level fat fraction (0.226 ± 0.029, mean $\pm$ S.D, N=13) and the bubble counts. The average weight loss is found to be less than the FFM loss assessed by BIA at 50 kHz. Considering the activities of the divers, any increase in the fat mass is questionable, therefore, conventional BIA at 50 kHz is believed to overestimate the dehydration due to altitude. This is probably due to the fact that the conventional method is based on the analysis of whole body impedance that reflects mainly the impedance of the limbs rather than the trunk [111]. Another explanation is that the equations compiled from the literature are derived for a given electrolyte concentration. Hypoxia causes the failure energy of Na^+/K^+ pumps. Thus, the decrease in impedance may be not only due to fluid loss but also a shift in electrolyte balance. This hypothesis suggests that the electrolyte measurements should also be conducted in parallel with the impedance measurements.

The low frequency bio-electrical resistance is mostly determined by the amount of ECF. Because of the anthropometric factors, the resistance of the limbs is much larger than that of the trunk. Therefore, the whole body impedance measurements can be misleading in the assessment of ECF changes, especially in case the arms and the legs exhibit an opposite trend; because of this, each limb and the trunk should be measured. Our measurements indicated a post ascent decrease in the ECF of the legs and an increase in the ECF of the arms and the trunk. The post ascent loss from lower limbs is consistent with the water loss associated with the trekking effort whereas the increase in ECF in upper limbs and the trunk can be explained by the fluid shift due to hypoxia. These results are consistent with findings of Gunga et al [120], who observed measurable fluid shifts to the upper part of the body at moderate altitude.

No correlation has been observed between the bubble counts and the duration of the stay at altitude. Due to the seemingly random nature of bubble formation, no significant effect of the measured physiological changes on the bubble counts could be identified.

9. EXPEDITION KAÇKAR '97

9.1. Material and Methods

The same set of no-d limits and same training procedures as in '94 Expedition was used. Twenty-four divers (sixteen male, eight female, aged 21 to 32 years) gave informed consent to join the expedition. The team consisted of 14 instructors, 6 Two Star and 4 One Star CMAS equivalent divers with diving experiences ranging from 1 to 13 years. During the medical check-ups two divers were eliminated because of arrhythmia and hypertension. The team was divided into a main test subjects group and 3 support groups. The main group consisted of nine divers and their stay at the Lake was planned to last 16 days. Each support group consisted of 3 to 8 divers who were supposed to supply fresh food, diving, camping or measurement logistics if needed. Same procedures of camping, climbing and diving were followed as '94 Expedition. Pulse rates were measured twice daily; blood pressure and spirometric measurements (Autospiro-SDS, Medical Equipment Designs Inc, IL) were carried out with one day interval. The spirometer is not affected by changes in altitude (Operation Manual). Cochran Nemesis II dive computer was used for depth measurements and the depth versus time recordings. After each dive, the dive computer was connected to a Notebook (Compaq, Armada 1120) and the profile was transferred to the hard disk.

15, 18, 21, 24, 27 and 30 m. no-d limits were tested. Divers were monitored for VGE using a continuous Doppler ultrasound device (2, 3.5, 5 MHz Mini Dopplex, Huntleight, UK). Femoral, precordial and subclavian measurements were carried out, both at rest, after knee or arm bends. The first measurement was taken within 20 minutes following surfacing and went on until 120 minutes with 20 min. intervals.

9.2. Results

Systemic pressures did not show any significant change during the expedition (Fig. 9.1). On the other hand, pulse rates increased significantly upon ascent, but dropped gradually, until day 11 (Fig 9.2). That day, five of the group members climbed to the summit of Mt Kaçkar (3937 m). The functional vital capacity (FVC) dropped significantly following arrival to the Lake but recovered on the following measurements, finally increased upon coming back to sea level (Fig 9.3).

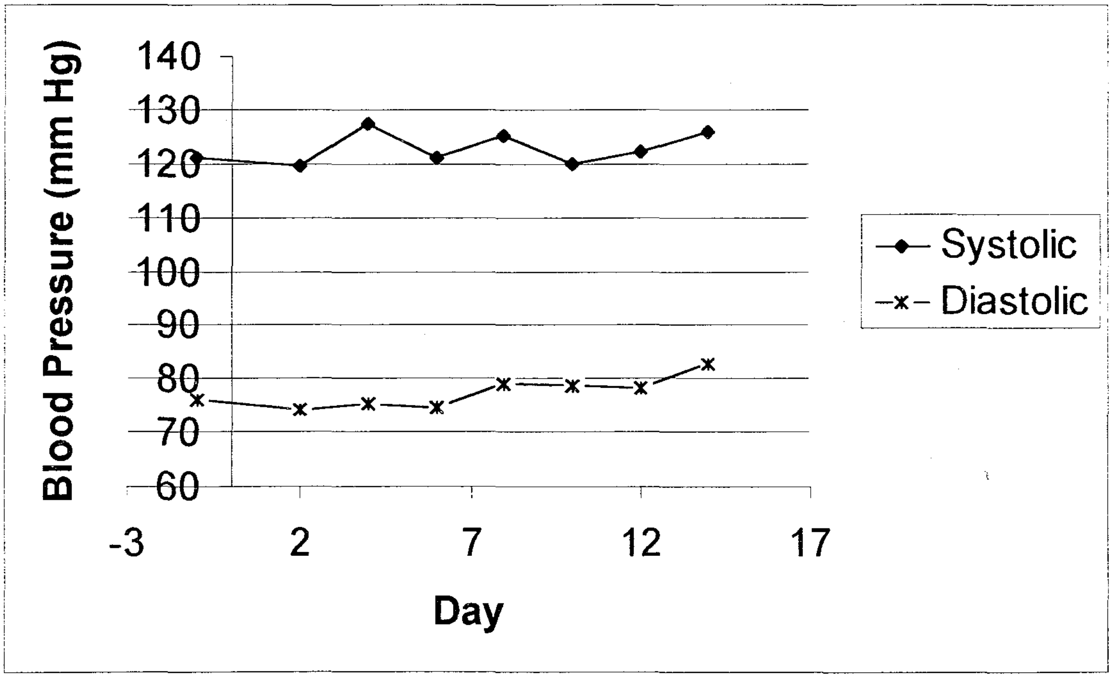


Figure 9.1. Systemic pressure of long term residents (n=7). No significant change was observed during the expedition.

20 dives with rectangular profiles were achieved right on the computed NLHE, δ = 4 fsw limits. No case of DCS was encountered. Bubbles were detected in 14 of these dives; 4 of these were precordial bubbles (Table 9.1). The duration of bubbles extents from one single observation to 80 min. while the maximum onset time is 60 min. Peak times ranges from the first measurement (0 min.) up to 60 min. The Doppler scores of Kaçkar '94 and '97are illustrated in Figure 9.5.

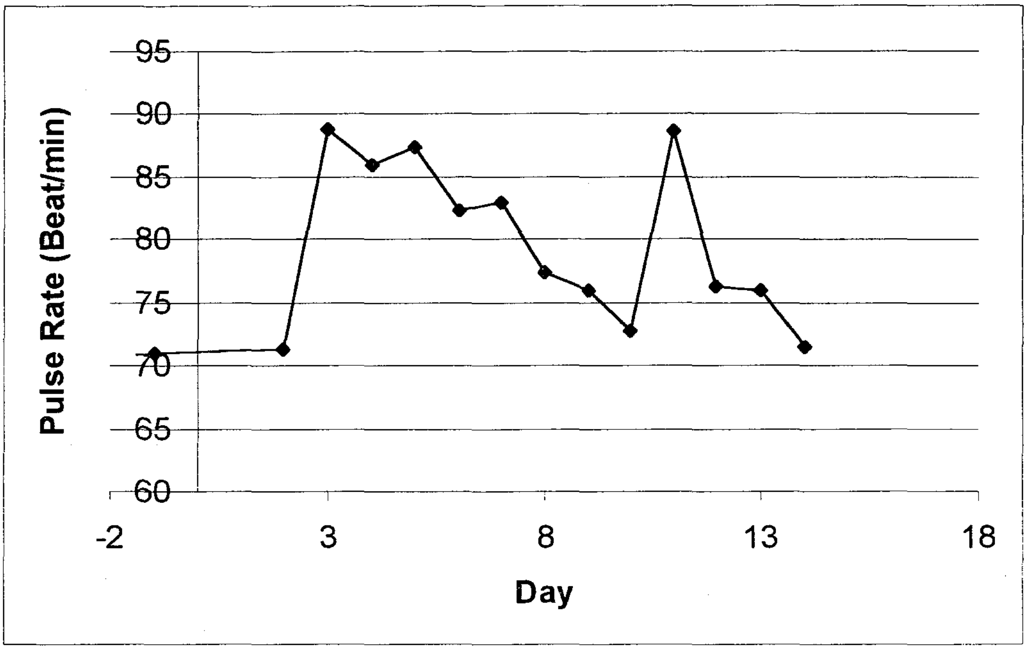


Figure 9.2. Pulse rate of long term residents (n=7). The increase in the 11th day corresponds to the ascent of 5 members to the summit of Mt Kaçkar (3980 m).

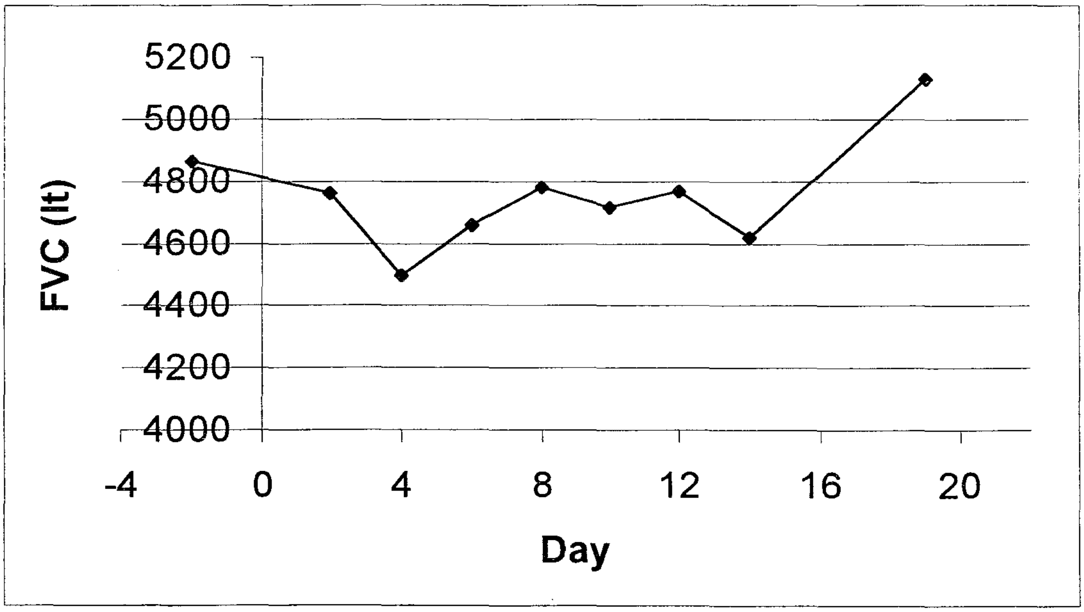


Figure 9.3. Functional vital capacity of the long-term residents (n=6). A marked decrease following the ascent (day 2) is followed by a stabilization period (day 4-14). Upon coming back to sea level, the FVC is higher than the pre expedition values.

Table 9.1

Time parameters of the VGE scores

Subject	Day	Depth (m)	Onset time[a] (min.)	Maximum Grade	Peak time[b] (min.)	Duration[c] (min.)
OE	7	27	0	II	0	20
AT	9	30	60	I	60	0
BÖ	9	30	0	I	0	80
OE	10	15	60	I	60	0

[a]Onset time: the interval from the first measurement (0 min) to first detection of VGE.
[b]Peak time: the interval from the first measurement to the detection of maximum VGE score
[c]Duration: the interval between the onset time and the last detection of VGE. 0 min. duration corresponds to a single detection.

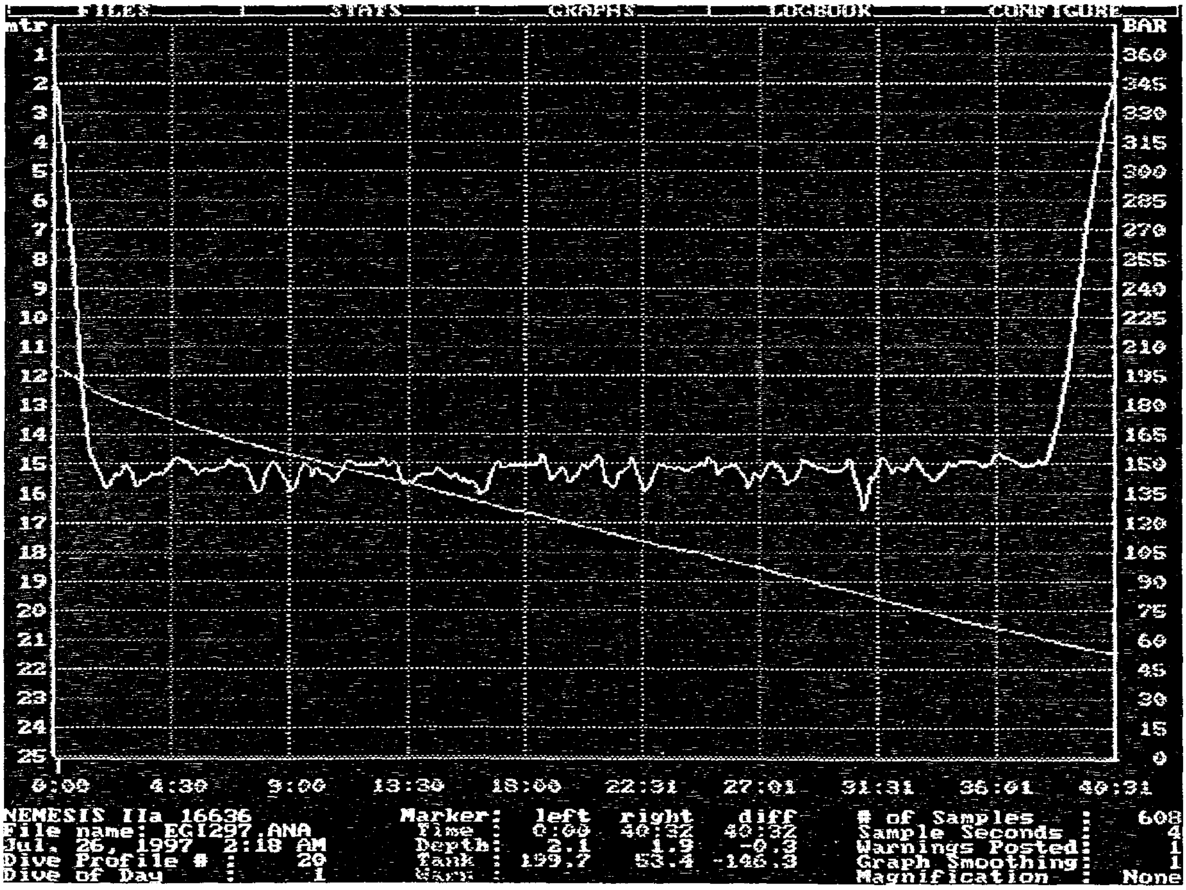


Figure 9.4 Dive computer output from a test dive. Horizontal axis represents the time (min), vertical axis is the depth (m).

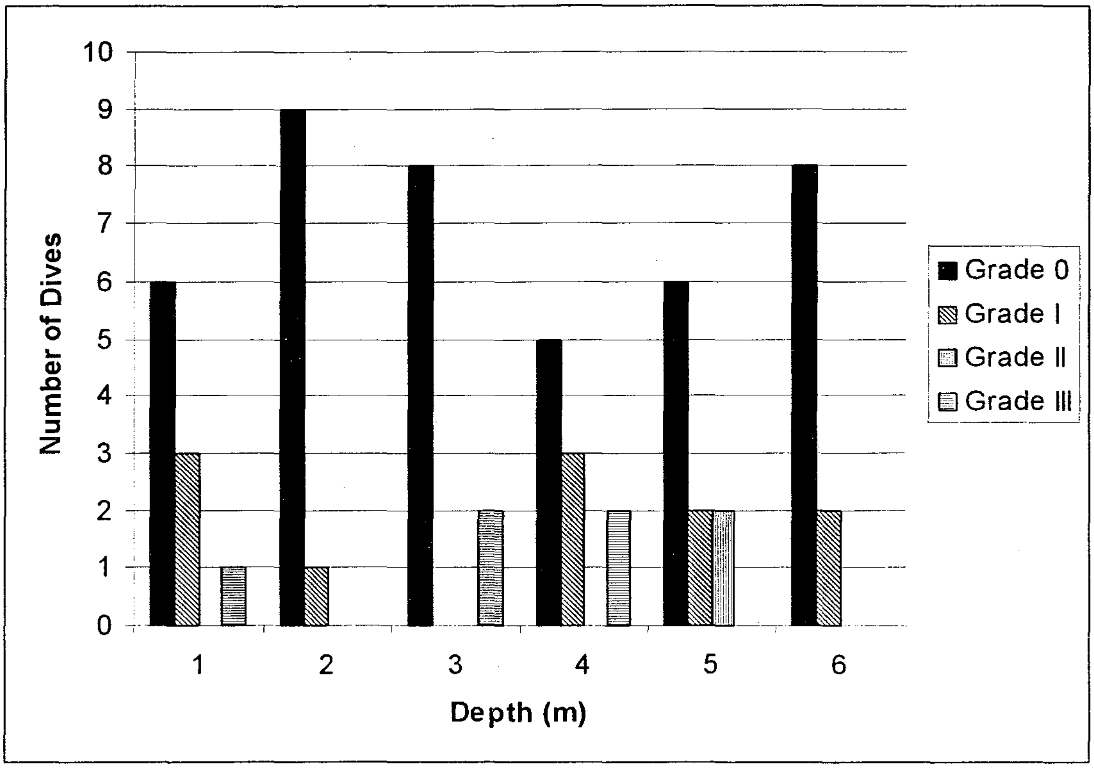


Figure 9.5. VGE scores of Kaçkar Expeditions (1994 and 1997). 10 man dives were accomplished per profile.

There was only one case of emergency in Kaçkar '97 expedition. Diver NI was an experienced diving instructor, but during her first dive to the Lake, where she had 200 bar/10 lt. tank, she hyperventilated and gave "out of air" signal at 26 m and 4^{th} min of the dive. Although she started to use the octopus of her buddy, she tried to ditch her weight belt. Her buddy prevented the weight belt release, took control of her buoyancy control device and both surfaced. None of them had any symptoms related to the fast ascent.

During the pulmonary functional tests (day –2), 24 years old subject OU had a lower functional vital capacity and a lower forced expiratory flow compared with the standard population while no pathological symptom was found in the patient history, auscultation and all other clinical inspections held. On day 2, in all the pulmonary functional test parameters a dramatic decrease occurred pointing a mild restriction. In the medical inspection no pathology was found. A day later, the symptoms of acute mountain sickness were observed in the subject (incapacitating, nausea and vomiting, fatigue, lightheadedness, difficulty in sleeping) and he was given a bed rest for one day. The clinical inspection of the subject again showed no pathological pulmonary sounds with auscultation. In the following day, all the symptoms the acute mountain sickness disappeared while the pulmonary tests parameters showed a progressive decrease (a decrease until day 8 and a recovery onwards). Subject told he was "normal" after day 3.

9.3. Discussion

The proposed NLHE, with δ =4 fsw, no-decompression stop limits for 3500 m. are more conservative than linear extrapolation of M values, but give longer no-stop times than tables calculated using Cross corrections of the US Navy tables except for 12 and 15 m.

Based on the previous expeditions, δ was estimated to be 4 fsw for all compartments at 3500 m. However, linear extrapolation of M values of 80, 120, 160 and 240T compartments gave tissue tolerances which are less than the M value of the 40T compartment for altitudes greater than 7424 m (see section 2.2.1). For all tested depths, the controlling tissue is 40 T according to NLHE, with δ = 4 fsw. Thus, for longer exposures, where the decompression is controlled by slower compartments, one may suggest $\delta > 4$ fsw for the 80, 120, 160, 200 and 240 T compartments. In fact, the EVA exposure data implies δ values as high as 11 fsw. for the 240 T tissue at 3353 m [12]. The M values suggested for flying after diving [14] also imply higher δ values (Table 9.2).

Table 9.2
δ values corresponding to flying after diving M values at 8500 ft

Compartment half time (min)	δ (fsw)
5	16.3
10	13
20	9
40	4.8
80	6.4
120	6
160	5.45
200	5.9
240	5.6

60 dives without any DCS case corresponds to a 0% risk of DCS with 95% confidence limits of 0.00-5.96 based on binomial distribution. The risk of each profile is calculated using the correspondence of the bubble scores and DCS occurrences in DCIEM air dives [89]. These results are based on 921 air dives, most of them from a study on no-decompression limits. Using a scientific table (e.g. Documenta Geigy) the 95% confidence intervals based on the binomial distribution are computed (Table 9.3).

Table 9.3.
Correspondence between Precordial bubbles and DCS risk [89]

	Bubble grade (Spencer scale)				
	0	I	II	III	IV
%DCS	0.2	1.2	4.7	11.6	20.0
95% CI	0.0-0.9	0.0-6.3	1.0-13.1	6.9-17.9	6.8-40.7

Assuming that the risk of having DCS in case of observing given bubble score after a sea level dive is the same as an altitude dive, the risk of having DCS for each depth/time combination can be computed using the following expression:

$$P(DCS) = \sum_{i=0}^{4} \frac{n_i}{N} \cdot p_i(DCS)$$

Where P(DCS) is the risk of having a hit, n_i is the number of divers with bubble grade i for the specific profile, N is the total number of dives performed on the profile (n=10) and p_i(DCS) is the DCS risk associated with grade i. The estimated risks per profile (Table 9.4) are within the acceptable 95% confidence limits of the US Navy [121], but may not be suitable for recreational or scientific diving operation where the acceptable DCS risk is zero [122].

Although the NLHE, with $\delta = 4$ fsw no-d limits were calculated for an ascent rate of 18 m/min., the field tests were performed using 6 m/min. If the same algorithm is used with 6 m/min. ascent rate, the only reduction in no-d limit (1 min.) occurs for 27 m and 30 m, because of the increased gas uptake of the 40T compartment. In fact 6 m/min ascent rate was chosen to ensure a slow transition to hypoxia. The SaO_2 level following high altitude diving measured by LePêchon et al. suggest that the elevated partial pressure of oxygen during the dive may protect the diver from hypoxia for about 20 min [19]. However the number of data is limited. Thus low ascent speed and restriction of the surface swimming distance at high altitude are advised.

Table 9.4
The % DCS risk of the tested profiles

Profile	% DCS risk
15m/38 min	1.6
18m/29 min	0.3
21m/24 min	2.5
24m/21 min	2.8
27m/17 min	1.3
30m/14 min	0.4

During the calculation of gas uptakes the density of the Lakes are assumed to be equal to that of seawater. Since the depths are measured with depth gauges calibrated for seawater, the pressure measurement corresponds to the salt-water depth. In addition to that, the dive computer used in the last expedition indicated salt water, because of the high mineral content of the Lake (explanation given by the manufacturer). Using the limits calculated for seawater depth entries in a fresh water lake will only introduce an extra factor of safety.

Decompression stop dives were not within the scope of the expeditions. Existing altitude dive tables suggest shallower stops than at sea level. This practice is based on the CRT algorithm that supposes corrections to preserve the same decompression stop depth to surface level ratio. Although, CRE and LEM algorithms perform recalculation of the tables instead of converting the sea level ones, they also suggest shallower stops [2,4]. However, as shown during the expeditions described in this work, the control of buoyancy near the surface is difficult at altitude. On the other hand, if an algorithm based on the singularity of M values is used to plan dives requiring decompression stops, the use of M values equal or greater than M_0 will solve the problem of altitude adaptation of the stop depth and duration. For instance, if the surface level ambient pressure is 70.695 kPa, then the decompression stop depth will be 10 feet where the absolute pressure is equal to sea level and the decompression duration will be controlled by the M_0 value.

10. OPERATIONAL PROBLEMS OF HIGH ALTITUDE DIVING

10.1. Definition of Altitude Diving

There is no consensus on the minimum altitude that implies modifications of decompression and diving procedures for inland diving. The minimum altitude ranges from 0 to 700 m (Table 10.1). On the other hand, BSAC tables suggest the use of different tables even at sea level, in case of a significant drop in the atmospheric pressure due to meteorological conditions [25]. The absence of data supporting this method and the practical problems involving the computation of denitrogenation during the atmospheric fluctuations make such a practice impossible. For a given altitude, it would be logical to accept the fluctuations in the atmospheric pressure as "allowable" for practical purposes. The minimum altitude corresponding to the "allowable" atmospheric fluctuation should be the threshold for modification of diving and decompression procedures.

Table 10.1

Minimum altitude for modification of diving procedures

System	Altitude (m)
BSAC	0
CMAS	100
PADI	300
NAUI	300
IANTD	300
DCIEM	300
Bühlmann	700

To decide on the allowable fluctuation, atmospheric pressure data for the last 54 years compiled from Florya, Istanbul were used (elevation 36 m, latitude 40°59' N, longitude 28°48' E), is evaluated (Figure 10.1). Observations were recorded by Prime Ministry, General Directorate of State Meteorological Affairs between 1937 and 1990. The mean of the atmospheric pressure is 1011,4 hPa, while the minimum and maximum levels are 976.3 and 1011.4 hPa respectively. Maximum fluctuations occurred in January (63.1 hPA, mean of 55 years). Using Eq. 2.17 the altitude corresponding to 63.1 hPA was found to be 548.93 m. Thus the minimum altitude that implies modification of diving procedures should be larger than that value. In this thesis work, **inland diving above 600 m. is defined as "Altitude Diving".**

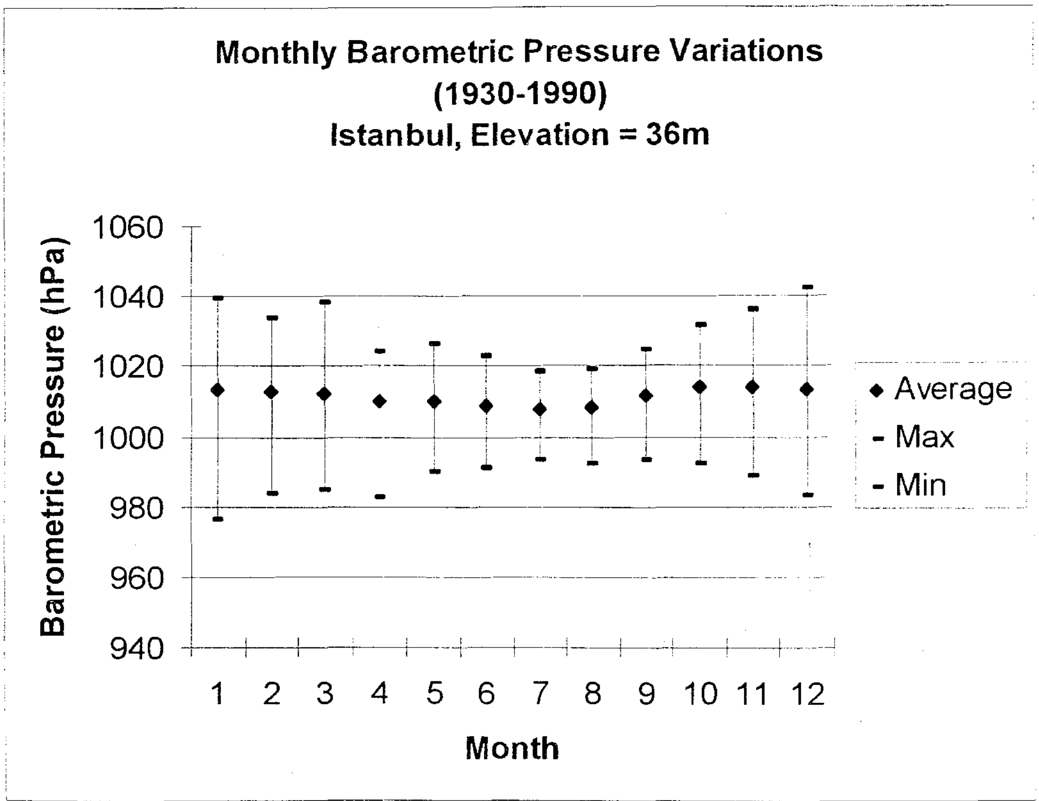


Figure 10.1 Atmospheric pressure data from Florya Station of Prime Ministry, General Directorate of State Meteorological Affairs (1937-1990).

There exist also a discrepancy between the conversion of altitude to atmospheric pressure. An alternative of the Eq 2.17 is given by Wienke [42]:

$$P_h = 33 \cdot \exp(-0.0000385 \cdot z) \tag{10.1}$$

where z is the elevation (feet). These values may differ slightly from measurements. The ambient pressure at altitude is in fact dependent on humidity, weather conditions, and latitude. The critical variable is the change in air temperature with altitude, and, therefore, model atmospheres have been constructed for different latitudes and seasons of the year. These different models give a large range of pressures (up to 20%) at a given altitude. However, if the model is aimed to be used for a latitude of 15° (in all seasons) and 30° (in summer) following equation predicts the P_h within %1 accuracy [123]:

$$P_h = \exp(6.63268 - 0.1112 \cdot h - 0.00149 \cdot h^2) \qquad (10.2)$$

where h is the altitude in km, and P_h is expressed in torr. The predictions are good because many high mountain sites are within 30° and many studies are made during the summer.

10.2. Definition of "High" Altitude Diving

Due to the sigmoidal shape of the oxygen dissociation curve, the effect of decreased partial pressure of oxygen exhibits a threshold altitude. This problem is also encountered in air transportation, where the passengers are aimed to be free from the hypoxia. Therefore the cabin is pressurized, otherwise oxygen breathing should be provided. The civil aviation rules impose that the cabin pressures should be above the equivalent pressure of 8000 feet. This rule is proven to be an adequate protection against hypoxia. In consequence, in this thesis, **altitude diving above 2400 m elevation is defined as "high altitude diving"**, where the effects of hypoxia should be taken into account. Diving above 2400 m is not considered as a common recreational activity. It would be more appropriate to include "High Altitude Diving" under the context of "Technical Diving" [23].

10.3. Ascent to High Altitude

There exist several altitude ascent strategies to protect from the harmful effects of hypoxia [13]. During the expeditions where the ascent from 560 m. to 3412 m. (1991) and from 1700 to 3700 m (1992) was accomplished in one day, one diver at 3412 m and two divers at 3700 m suffered from AMS. On the other hand, all members of the 1990, 1994, 1997 expeditions tolerated an initial ascent to 2200 m. After spending the night at 2200 m, all members except one in 1997 tolerated the ascent to 3412 m. Although sleeping at 1700 m did not protect the divers from AMS, spending the night at 2200 m, before ascending to 3412 m, provided a useful strategy for reducing AMS incidence. During the expeditions, significant changes in body parameters or AMS were observed during the first two days at altitude. Avoiding heavy exercise and diving, during the first two days at altitude is recommended. In case of the evidence of AMS symptoms at the end of the first two days, the diver should be transferred to a lower altitude.

10.4. Environmental Conditions

Several environmental conditions that imposed difficulties for the expeditions were identified: cold, ice, silt, humidity, thunder, sun radiation.

Some of the equipment was damaged during severe conditions of transportation: one of the mules fell down and discharged its load, which consisted of a semi-closed circuit underwater breathing apparatus (UBA) and 2 tanks. The tanks drifted some 50 meters before they hit the rocky river bed and the valves broke down as well as two depth gauges packed with them. No damage occurred to the semi-closed circuit UBA.

A centrifuge for Hct measurements, a radio transmitter, a spirometer, a video camera which were fully functional before departure did not work at the diving site possible due to the humidity or damage occurred during transportation.

In the 1992 expedition, two divers suffered from serious sunburns causing a serious problem during the dressing up of dry suit's rubber seals.

Most of above cited environmental conditions are characteristic to high altitude regions and should be considered before planning high altitude expeditions.

10.5. Equipment Problems

10.5.1. Depth Gauges

10.5.1.1. Electronic Depth Gauges. Some electronic depth gauges automatically compensate for altitude. Some of them are calibrated for seawater, therefore will read about 2.5% shallower then the ascent line, in case of fresh water diving. This may cause a hazard in decompression planning, if the tables devised for fresh water are used. If the tables indicate depths in terms of seawater and the fresh water gauge calibrated gauges are used, that will introduce a factor of safety in no-d dives. If decompression stops is involved, the use of fresh water calibrated gauges with sea water tables includes a risk, because the decompression will be performed at a lower pressure. The remarks about changes in salinity are also valid for other type of depth gauges.

10.5.1.2. Capillary Depth Gauges. These depth gauges measure the depth to surface ratio. Therefore they show deeper readings than the real depth. If one neglects the change in the salinity while switching to fresh water at altitude, the depth reading of these gauges can be used directly with a sea level table in order to accomplish cross corrections. However, the scale of these type of depth gauges are very narrow below 30 meters and the air inside the capillary can easily leak causing reading errors. Consequently, they should always be used with a back up gauge.

10.5.1.3. Bourdon or Diaphragm Type of Depth Gauges. When the ambient pressure decreases, the needle of these depth gauges will be pinned against 0 post; thus the readings will always be shallower than the real depth. The difference is equal to the P_0-P_h expressed in terms of fresh water. For instance, in Kaçkar Expeditions, Bourdon type of gauges were used by adding 4 m to the actual reading. Some of the gauges are equipped with a zero adjustment button allowing re-zeroing at altitude. Thus, no correction is necessary, except for the salinity changes.

It has been claimed that gauges can be damaged by having the needle pinned against the 0 post when above sea level and may become less accurate after being taken to altitude. To test this hypothesis, 9 depth gauges (3 Oceanic, 3 US Divers and 3 Uwatec) were tested in wet hyperbaric chamber, before and after the 1997 expedition. They were also immersed in the Lake down to 30 m, in a couple of dives. The chamber tests included read-out with 3 m. increments down to 30 m. The same reading intervals were used during depressurization to estimate the hystherisis. The chamber pressure was measured with a manometer (Pakkens Inc.) calibrated with a traceable instrument (Superb Instrumentation, traceability: UME-97.MBA.010, 13.02.1997, S&Q Mart certificate no:11 239, 27.06.1997). The results suggest that all gauges, except one, were as accurate as they were before the expedition (Figure 10.2 and 10.3). The damaged gauge was reported to give significantly lower readings (up to 7 m) during the altitude dives. This diaphragm type of depth gauge is suspected to be damaged during the severe transportation conditions.

10.5.2. Dive Computers

The decompression planning of dive computers is discussed in section Chapter 2. The dive computers were used in all Kaçkar expeditions to provide a back up for the depth gauges. Seldom they were used for decompression planning. In one of these cases, divers accidentally encountered a depth/bottom time combination that was not within the range of the tables. During a test dive originally planned as to 24-m/22 min, divers went down to 28 m at the beginning of the dive. They kept this level, and used the information provided by Aladin Pro dive computer to surface. At the 18th min. of the dive, before leaving the bottom the dive computer was still giving 2 min to no-d limit, and gave no decompression during any instant of the ascent. After this dive, grade II-III precordial bubbles were observed in one of the divers, both at 10th and 50th min recordings. This diver showed neurological symptoms of central nervous system DCS, including a pathological Babinski on the right side and no plantar response on the left. After that dive, the use of dive computers for decompression planning was completely abandoned. Another dive computer, Scubapro DC-11 was locked in Süphan expedition, prior to the dives. The Cochran dive computer that was used in Kaçkar 97 recorded the tank air, temperature breathing rate. The temperature read out of dive computer is found to be very slow but the depth measurement is accurate (Figures 10.4). Wienke suggested a decrease in the air consumption due to altitude [24]. In contrary, the breathing rate increases to compensate for hypoxia. Through observation of computer records, no significant change in the air consumption was found.

10.5.3. Buoyancy Problems

Most of the inland dives are performed in fresh water. The decrease in the density of water will decrease the buoyancy of the diver. Assuming a neutral buoyancy in salt (density assumed to be equal to1.025), the loss of buoyancy will account for about 2.5% of body weight. On the other hand, Wienke suggested an increase in buoyancy that amounts roughly 0.2% for each multiple of 1000 feet [24]. According to these assumptions, at 3500 m, above changes tends to neutralize each other. In fact, in Kaçkar expeditions, divers wearing neoprene foam diving suits preferred to use the same amount of weight as they wore in sea dives.

Buoyancy control problems were also common because of the increased depth to surface ratio. Especially, near the surface, buoyancy control of the neoprene dry suits requested high proficiency due to the increased volume of the closed cell structure during the ascent. Henderson neoprene type of dry suits, with deflation button mounted on the chest caused difficulties in the buoyancy control because of the unusual site of the button and also the difficulty in draining excess air remaining above the valve. The use of these suits was abandoned after a couple of dives. Descent and ascent lines were very useful in supporting the buoyancy control.

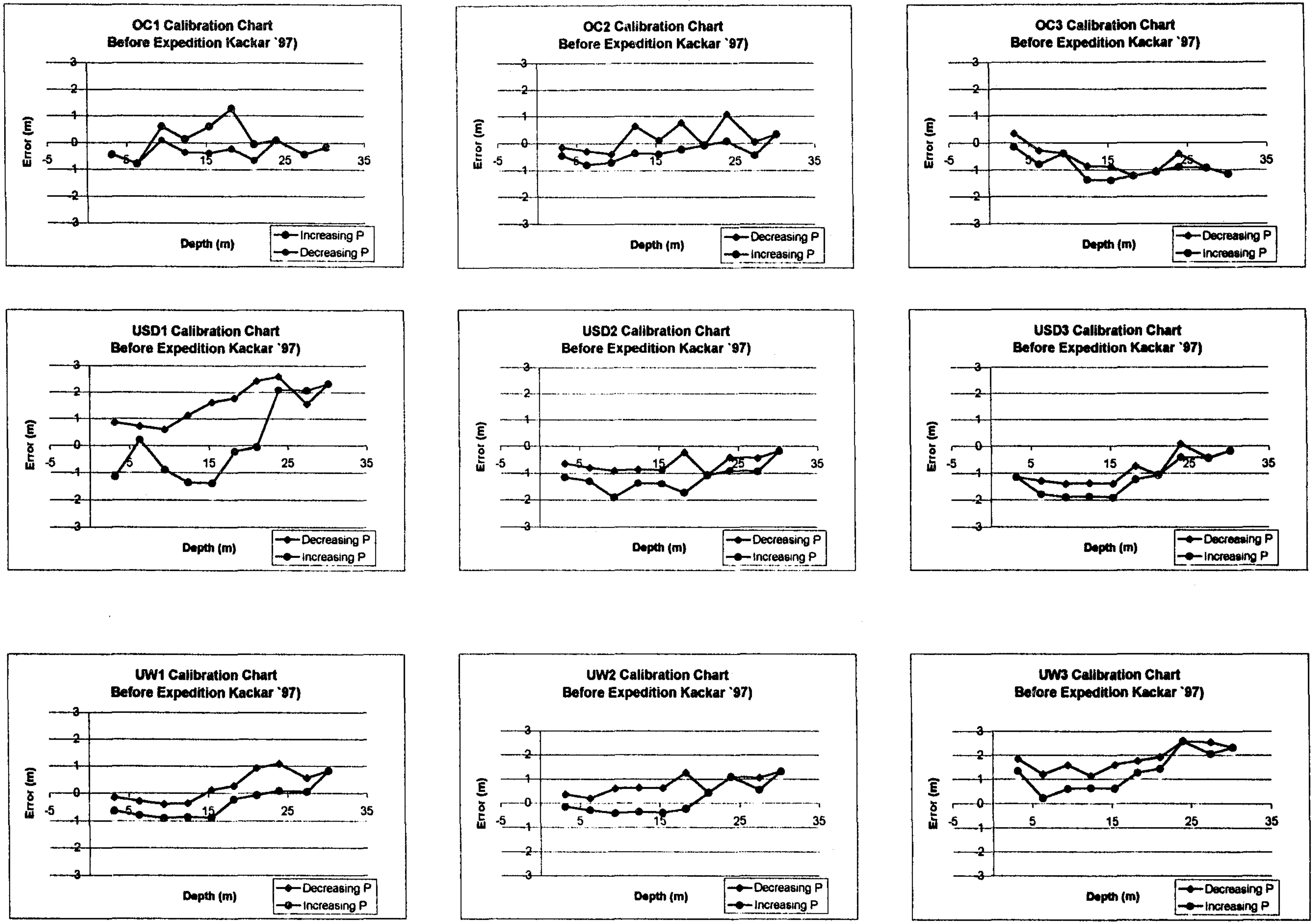


Figure 10.2. Validation of depth gauges before Kaçkar '97

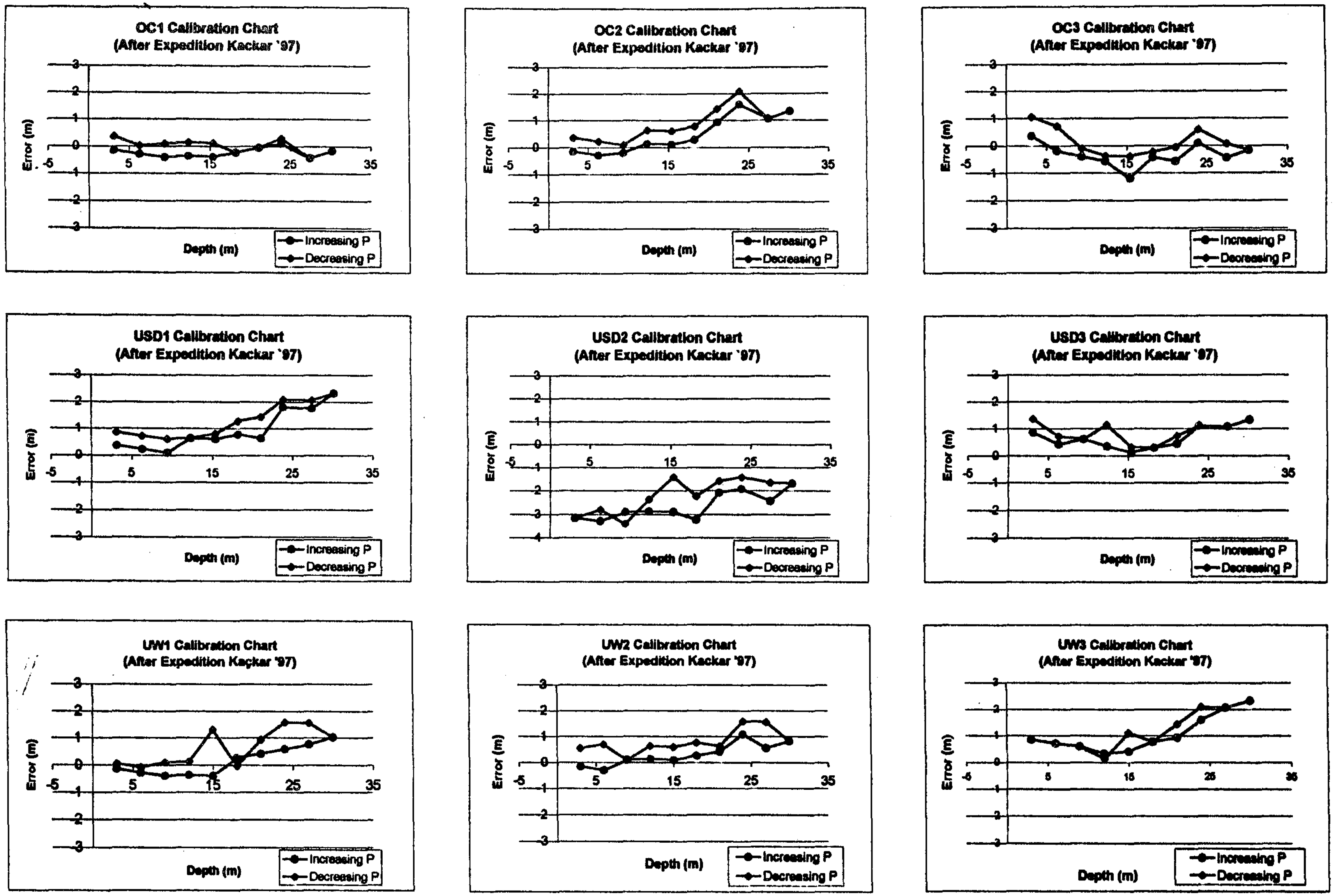


Figure 10.3. Validation of depth gauges after Kaçkar '97

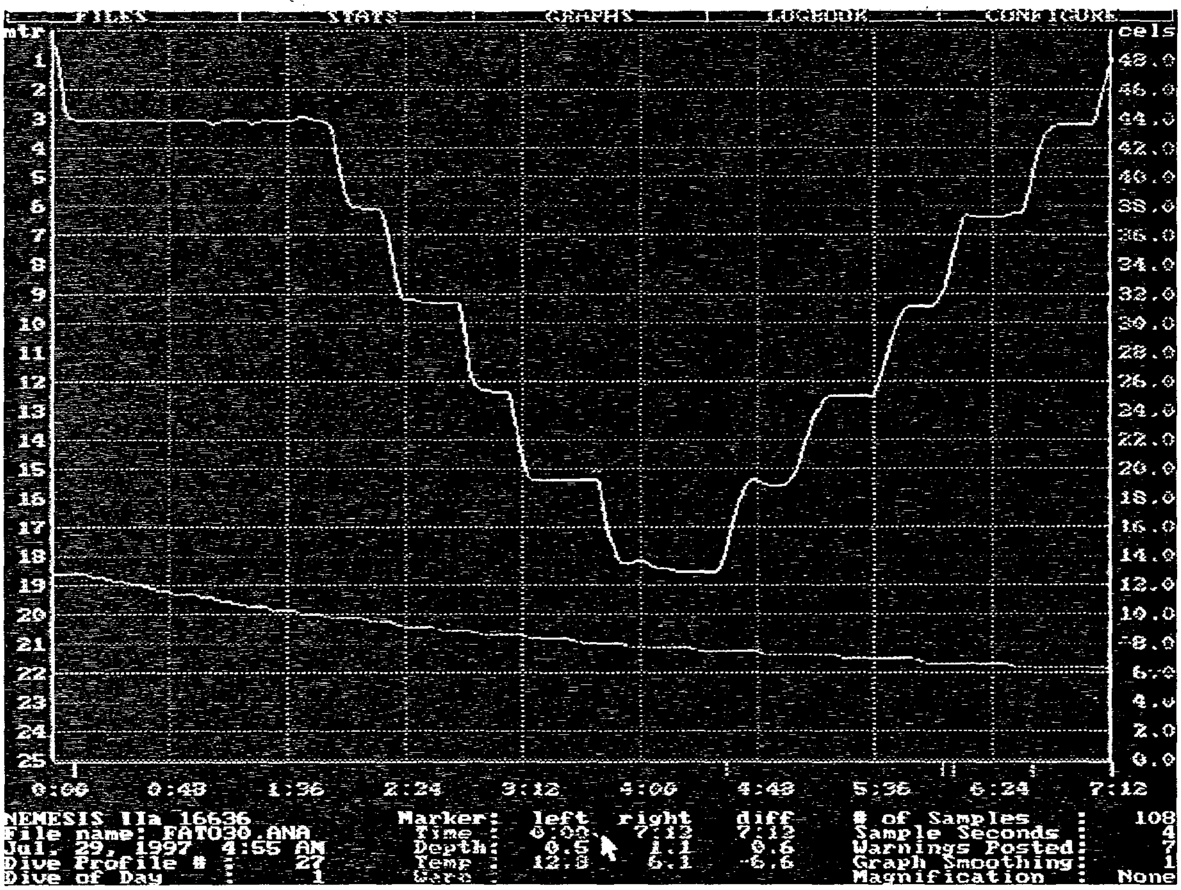


Figure 10.4. Temperature and depth records of a test dive where the computer is taken down to 18 m with 3 m. intervals. The reference is a depth marked rope. Temperature measurement of the dive computer is very slow. It takes more than 6 minutes to stabilize. Horizontal axis represents the time (min), vertical axis is the depth (m).

10.5.4. Regulators

Freezing of the first and second stages of the regulators (Scubapro Mk2 and Mk5) and the inflator valves of buoyancy compensators (Spirotechnique, 1989 model SBC) were due to extreme cold (1994). These problems were eliminated in the 1997 expedition. Regulators with high cold water performance were used (Sherwood SRB, dry bleed first stage and Blizzard second stages). To reduce the flow rate of a given first stage, double exit tank valves were used. Divers were ordered to breathe through the regulator only after the first stage was totally immersed. The right regulator was used as primary, while the secondary had also dry suit and BCD inflator hoses. Thus, only 2 dives were aborted due to freezing of the regulators.

10.5.5. Amphibious Cameras and Housings

The cameras and housings are designed to resist external, not internal pressure. The port of all parts (body, flash sockets, battery compartments etc.) where the air will be trapped should be left open during the ascent. In fact, during the 1990 expedition, the team experienced difficulties in opening the battery compartment of a Nikonos IVA camera.

10.5.6. Compressors

In the 1994 expedition the compressor engine had problems at start-up due to the decreased partial pressure of oxygen. It had to be disconnected from the compressor V belt, started up as free running and left over the V-belt. In the following expedition the carburetor of the engine was sometimes primed with starting fluid. In fact, the manual of the compressor states that the carburetor of the engine (Honda GX120) should be modified for high altitude operations; even if the necessary modifications is made the engine horsepower will decrease approximately 3.5% for each 305 m elevation.

11. COMPUTATION OF DIVE TABLES USING CONTINUOUS TISSUE TIME CONSTANTS

11.1. Introduction

There are many models to describe the physiological processes related to decompression sickness [3-6,35-37,41,50,83,]. However, most decompression tables or dive computer algorithms are still based on the Haldanian principles (Eq 2.18) where gas exchanges are modeled by independent parallel compartments with different time constants. The safe decompression profile is determined by empirical permissible inert gas tensions (M values). The only difference from the Haldane paradigm, is to characterize the permissible inert gas tension in any given compartment as a function of the ambient pressure, instead of a fixed allowable ratio of inert gas tension to ambient pressure. In the literature, there is neither a consensus on the number of compartments, nor their M value function. Because of this dual discrepancy, the "conservativeness" of dive tables or computers will be a function of depth, bottom time and altitude [13]. This work is devoted to reducing the empirical nature of the tables to a single M value function, by assuming that the time constant is a variable. Thus the body is modeled as a parallel combination of infinite number of compartments in parallel so that the question of determining the time constants representative of the body becomes obsolete.

The above model is used to compute multilevel decompression schedules and decompression stop dives at 3500 m altitude. Decompression stop diving is not advisable for recreational diving, but is sometimes necessary for commercial, scientific, and military dives. Multilevel diving increases the dive time considerably. It is an appreciated method in both recreational and commercial diving, especially during inspection dives. Normally when the diver works at two different depths, he/she must select the decompression table corresponding to his/her deepest depth and his/her dive time is therefore reduced significantly. If the decompression is computed for two levels separately the decompression time decreases.

11.2. Material and Methods

In conventional table computation, for a given depth, the equation $M_0 = \Pi(t)$ should be solved for each compartment and the minimum time, *t*, is defined as the "no decompression limit". The compartment that yielded minimum allowable bottom time is considered as the "controlling tissue." The procedure is the same, in case one tries to find the maximum bottom time for safe ascent to a given depth (D). In that case, the equation $M(D) = \Pi(t)$ is solved for each compartment.

11.2.1. Existing $M(D,T_{1/2})$ Functions

In this work, it is assumed that $T_{1/2}$ can take any value, therefore it is assumed to be a variable. The constants (M_0 and a) in M(D) functions are specific to each compartment. They can be calculated in terms of tissue half lives to obtain a continuous $M(D,T_{1/2})$ function. A similar computation was performed by Wienke and Bühlmann for expressing the constants of US Navy M values and ZH-L16 system respectively [9,42] (Eq 11.1-11.4), but no effort was devoted to use a $M(D,T_{1/2})$ function to calculate critical compartments.

$$a(T_{1/2}) = 3{,}25 \cdot T_{1/2}^{(-0.25)} \tag{11.1}$$

$$M_0(T_{1/2}) = 152{,}7 \cdot T_{1/2}^{(-0.25)} \quad \text{(in fsw)} \tag{11.2}$$

$$a_b\,(T_{1/2}) = \{1{,}005 - T_{1/2}^{(-0.5)}\}^{-1} \tag{11.3}$$

$$M_{0b}(T_{1/2}) = 10 \cdot a(T_{1/2}) + 20 \cdot T_{1/2}^{(-1/3)} \quad \text{(in msw)} \tag{11.4}$$

Using Eq (2.2) it is possible to express the critical depth (D) a compartment can ascend safely:

$$D = \{M(D,T_{1/2}) - M_0(T_{1/2})\} \,/\, a(T_{1/2}) \tag{11.5}$$

$\Pi(t,T_{1/2}) = M\,(D,T_{1/2})$ is the limiting condition for the safe ascent. Combining Eq. 2.18 and 11.5 we get:

$$D(T_{1/2},t) = \{ f \cdot P_0 + f \cdot (P_B - P_0) \cdot (1 - \exp(-0.693 \cdot t / T_{1/2})) - M_0(T_{1/2}) \} / a(T_{1/2}) \quad (11.6)$$

Eq (11.6) can be used in two different ways:

a) For a given bottom time, the equation $\delta D(T_{1/2},t) / \delta T_{1/2} = 0$ is solved to find the depth of the decompression stop and the critical tissue that controls this ascent. This algorithm can be incorporated to dive computers.

b) To compute the no decompression stop limits, $D(T_{1/2},t) = 0$ and $\delta D(T_{1/2},t) / \delta T_{1/2} = 0$ equations were solved simultaneously on a PC using Mathcad 2.01 (Mathsoft Inc, Massachusetts) for the Bühlmann and US Navy M value expression (Eq 11.1-2 and Eq. 11.3-4 respectively) [124]. For a decompression stop dive, $D(T_{1/2},t)$ = Depth of decompression stop and $\delta D(T_{1/2},t) / \delta T_{1/2} = 0$ equations have to be solved. This method can be applied to derive decompression tables.

When the gas exchange during a linear ascent is accounted for, Eq 11.6 should be modified as:

$$D(T_{1/2},t) = \{0.79 \cdot P_B + 0.79 \cdot c \cdot (t - k^{-1}) - 0.79 \cdot [P_B - P_0 - c \cdot k^{-1}] \cdot e^{-k \cdot t} - M_0(T_{1/2})\}/a(T_{1/2}) \quad (11.7)$$

11.2.2. Hybrid $M(D,T_{1/2})$ Function

In addition to the above computation, alternatives of the Eq. 11.1-4 were calculated using a combination of the US Navy, Bühlmann and Kaçkar Expeditions M values. The condition for the safe ascent to depth D is $\Pi(t,T_{1/2}) = M(D,T_{1/2})$. Using this equation it is possible to get $t(T_{1/2})$ function whose derivative with respect to $T_{1/2}$ will give the minimum bottom time to ascent safely to depth D. The hybrid $M(D,T_{1/2})$ function was used to compute a multilevel no-decompression stop diving for 3500 m and was tested in Kaçkar '97 Expedition with 6 man dives. In this case, the first step of the multilevel dive was selected arbitrarily as 7 min. and the second level was computed such that no decompression stop is required. The test protocol is the same as the testing of no-d limits (See section 9.1).

11.2.3. Conservative Hybrid $M(D,T_{1/2})$ Function and Decompression Schedules for 3500 m.

Hybrid $M(D,T_{1/2})$ is fitted using the constraint that the fitted surface is lower than the data; thus a highest degree of conservatism is aimed. Nelder-Mead simplex search algorithm is used for fitting the surface [125,126] using Matlab software. It is a direct search method that does not require gradients or other derivative information. If n is the length of x, a simplex in n-dimensional space is characterized by the n+1 distinct vectors which are its vertices. In 2D-space, a simplex is a triangle; in 3D-space, it is a pyramid.

At each step of the search, a new point in or near the current simplex is generated. The function value at the new point is compared with the function's values at the vertices of the simplex and, usually, one of the vertices is replaced by the new point, giving a new simplex. This step is repeated until the diameter of the simplex is less than the specified tolerance and the function values of the simplex vertices differ from the lowest function value by less than the specified tolerance, or the maximum number of function evaluations has been exceeded.

The data used for fitting the surface are the M values of: Kaçkar Expeditions (NHLE with δ=4fsw), USAF [14] (8500 feet), US Navy [127] (for D=0-70 fsw), Workman [7] (for D=0-70 fsw), Bühlmann [4] (for D=0-40 fsw and for altitudes 2500, 1500 and 700 m). This surface was used for the computation of altitude dives (h=3500 m) requiring decompression stops at 10 fsw. The method of computation of decompression stop dives was the same as the multilevel dives. The computation was divided into two parts. The bottom time of the dives involving a 20 fsw stop was found by solving $\Pi(t,T_{1/2}) = M(10,T_{1/2})$. An arbitrary bottom time and depth was chosen, such that it is greater than the no-d limit but smaller than the dives requiring decompression stops at 10fsw. The results are tabulated as a decompression table (Appendix B).

11.3. Results

11.3.1. Existing $M(D,T_{1/2})$ Functions

Continuous compartment method applied to Bühlmann M value functions yielded less conservative results for 12 to 21 m. as compared to the Bühlmann tables. When the safety factor of adding 2 m for the depth of the dive was used as in the original computation of Bühlmann tables (ZH-L16+2 column in Table 11.1), the continuous compartment method gave more conservative results, except for 12 m. Wienke M value functions yielded less conservative results than US Navy Standard Air Decompression Tables for 15, 18 and 21 m.

Table 11.1

No-d limits calculated from the DCS boundary of ZH-L16* and US Navy M values*

	ZH-L16		ZH-L16+2		US Navy	
Depth (m)	No-d limit (min)	$T_{1/2}$ (min)	No-d limit (min)	$T_{1/2}$ (min)	No-d limit (min)	$T_{1/2}$ (min)
12	206	67.4	123	42.4	175	116.6
15	99	34.8	67	24.8	113	58.1
18	57	21.3	42	16.5	75	34.3
21	37	14.8	33	13.3	52	21.9
24	26	11	24	10.2	37	14.7
27	20	8.7	18	8.2	27	10.3
30	15	7.3	14	6.9	20	7.4
33	12	6.3	12	6	15	5.5
36	10	5.5	10	5.3	12	4.2
39	9	5	8	4.8	9	3.2
42	8	4.6	7	4.4	7	2.5

*M values are not the same as those in the original table computations. $M(D,T_{1/2})$ functions are derived by Wienke and Bühlmann for US Navy M values and ZH-L16 system respectively [9,42].

11.3.2. Hybrid $M(D,T_{1/2})$ Function

There is a high correlation between the ln(M values) and $\ln(T_{1/2})$ for various models. The correlation is valid for a wide range of ambient pressure including the hypobaric range (Figure 11.1, Table 11.2).

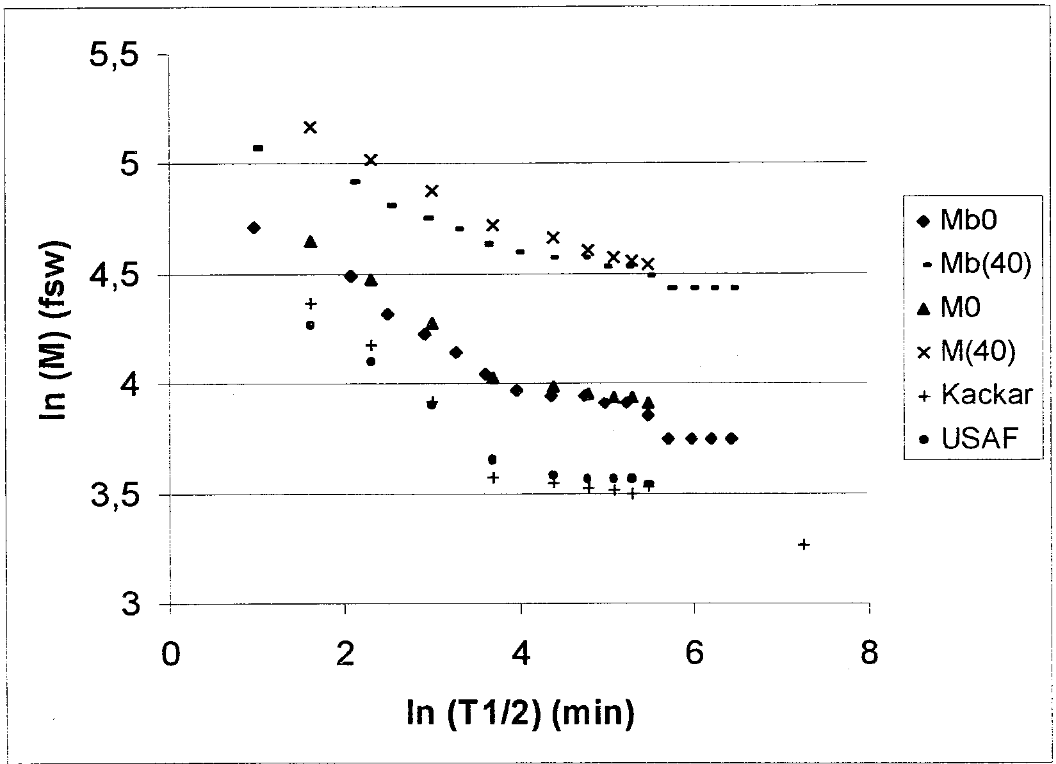


Figure 11. 1. There is a high correlation between $\ln(T_{1/2})$ and ln(M). USAF and Kaçkar M values are for altitudes of 8500 feet and 3500 m respectively.

The correlation still exists for the combination of M values of different models (Figure 11.2-11.8). There exist also a correlation between the gauge depth and coefficients of the linear curve fittings (Figure 11.9,11.10). The resulting relation between M values, depth and $T_{1/2}$ is:

$$M(T_{1/2},D) = \exp(p)\,(T_{1/2})^{q} \tag{11.8}$$

where $p = 4.775+0.017 \cdot D-1.503 \cdot 10^{-5} \cdot D^2$ and $q = -1.444 \cdot 10^{-5} \cdot D^2+0.002 \cdot D-0.177$ A sample multilevel schedule computed using Eq 11.8 is as follows: 7 min at 30 m followed by an ascent to 18 m in 2 minutes, 15 minutes is spent at 18 m, then the ascent to surface takes 3 min (Figure 11.11). No case of DCS was encountered with this profile with six divers; bubbles were observed in 3 dives, 2 of them were precordial bubbles (Table 11.3)

Table 11.2

Correlation between ln(M) and ln ($T_{1/2}$) for different gauge depths

Table	Depth	Correlation, r
Bühlmann	0	-0.97
	10	-0.97
	20	-0.97
	30	-0.98
	40	-0.98
Workmann	0	-0.96
	10	-0.97
	20	-0.98
	30	-0.98
	40	-0.99
US Navy [127]	0	-0.99
	10	-0.99
	20	-0.99
	30	-0.99
	40	-0.99
USAF	-9.21	-0.98
Kaçkar Expeditions	-11.715	-0.95

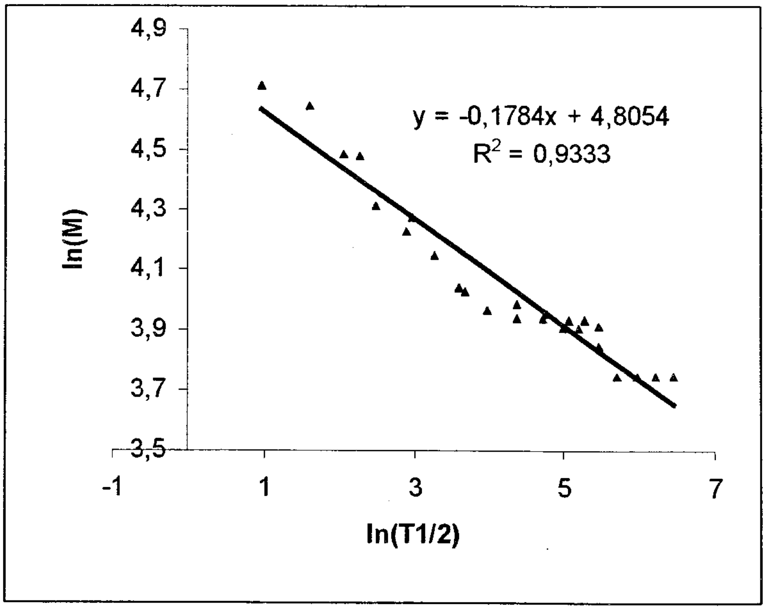


Figure 11.2. The correlation between ln(M) and ln($T_{1/2}$) for the hybrid data set (Workmann and Bühlmann) at sea level.

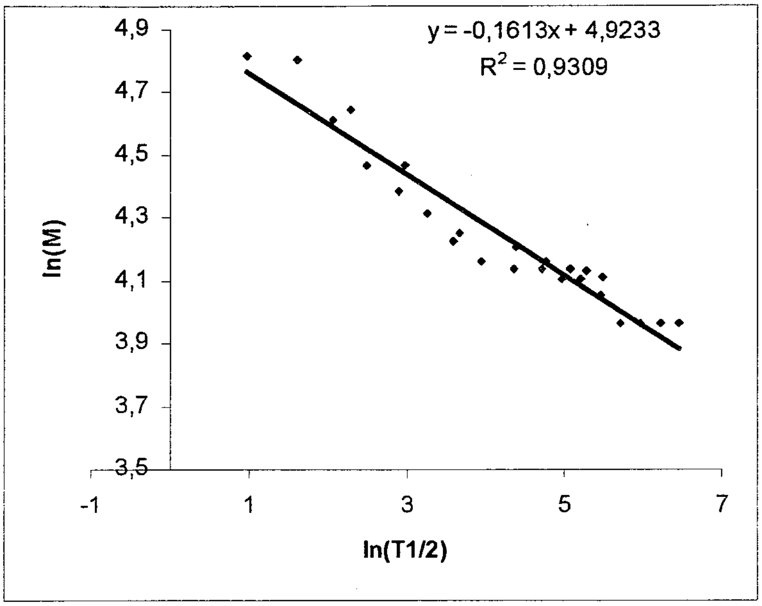


Figure 11.3. The correlation between ln(M) and ln($T_{1/2}$) for the hybrid data set (Workmann and Bühlmann) at 10 fsw gauge pressure.

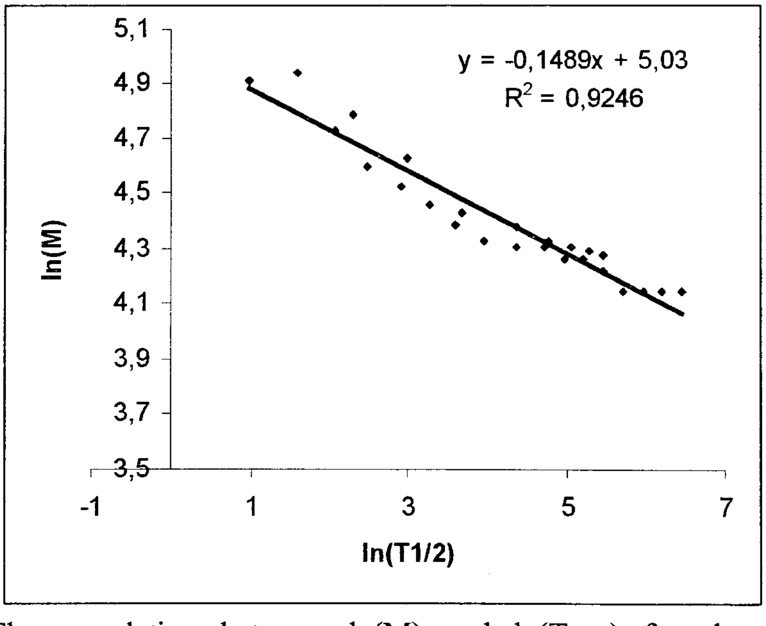


Figure 11.4. The correlation between ln(M) and ln($T_{1/2}$) for the hybrid data set (Workmann and Bühlmann) at 20 fsw gauge pressure.

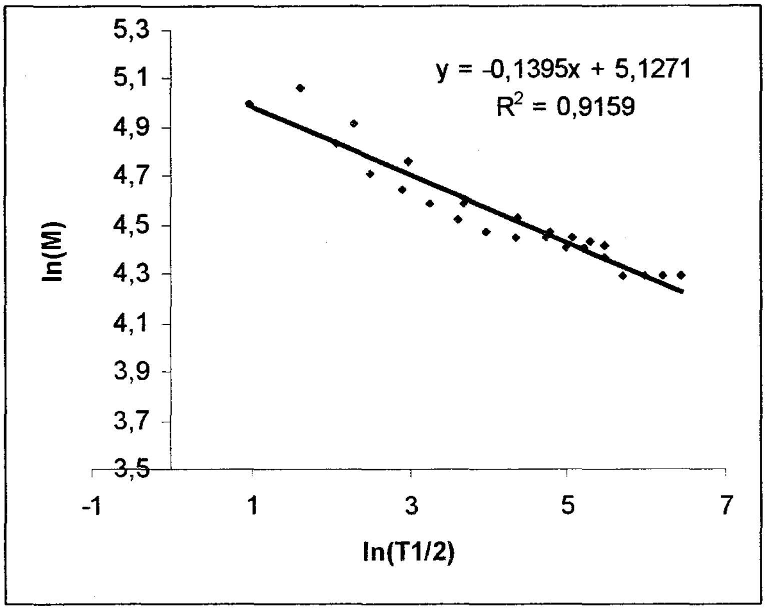


Figure 11.5. The correlation between ln(M) and ln($T_{1/2}$) for the hybrid data set (Workmann and Bühlmann) at 30 fsw gauge pressure.

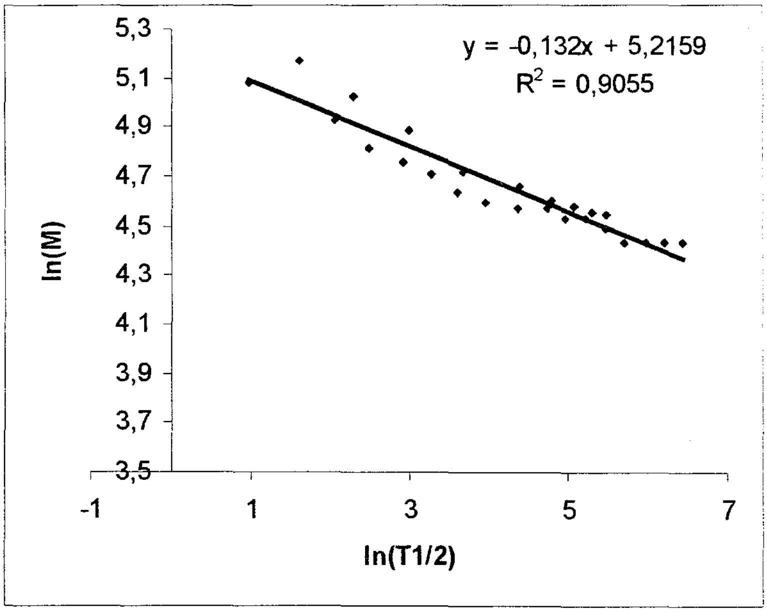


Figure 11.6. The correlation between ln(M) and ln($T_{1/2}$) for the hybrid data set (Workmann and Bühlmann) at 40 fsw gauge pressure.

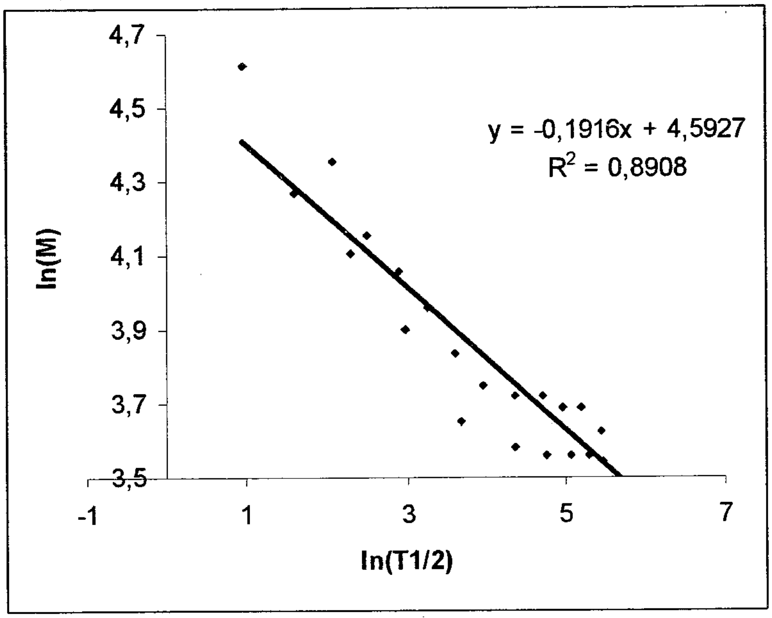


Figure 11.7. The correlation between ln(M) and ln($T_{1/2}$) for the hybrid data set (USAF and Bühlmann) at –9.21 fsw gauge pressure (equivalent of 8500 feet altitude).

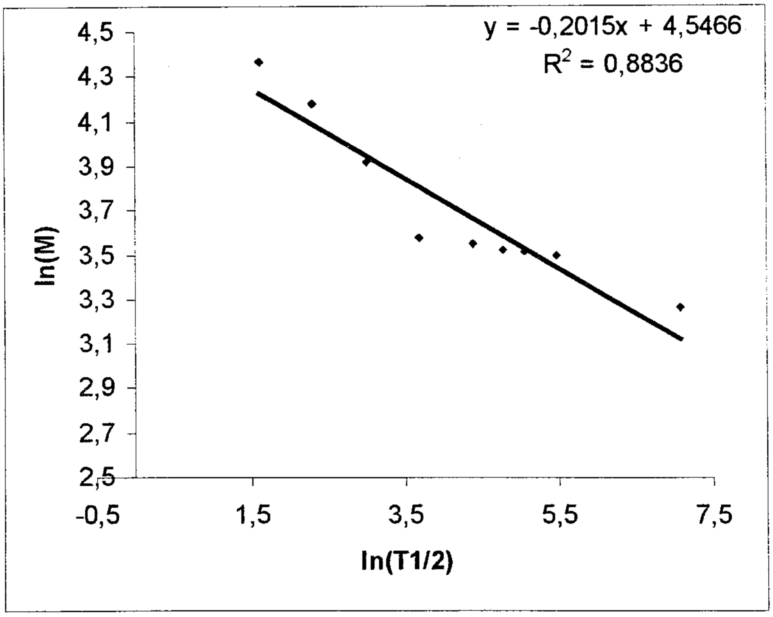


Figure 11.8. The correlation between ln(M) and ln($T_{1/2}$) for the hybrid data set (Kaçkar NLHE with δ = 4 fsw and altitude DCS limit at -11.715 fsw gauge pressure (equivalent of 3500 m). The altitude DCS limit is 3500 m (based on reference 10 and 12) and the controlling compartment $T_{1/2}$ is accepted as 1200 min.

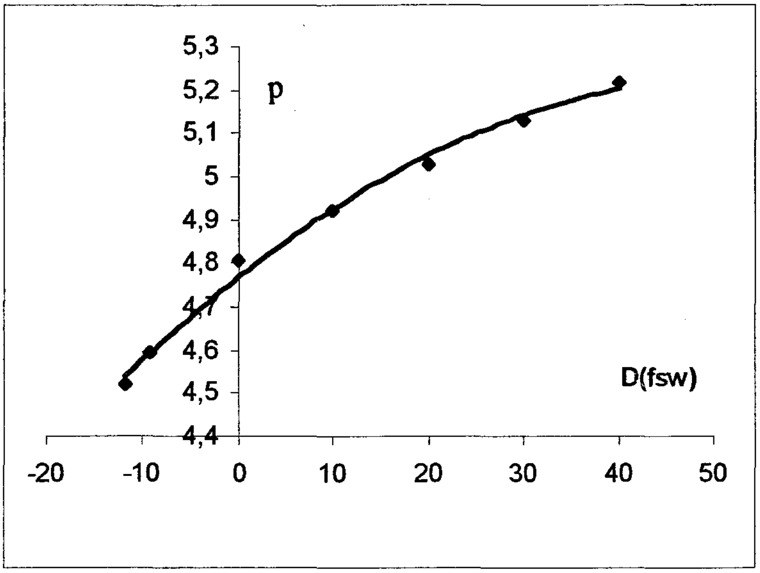


Figure 11.9. The correlation between the ln(M) axis intercept (p) and the gauge depth of Figures 11.2-11.7. $p = 4.775 + 0.017 \cdot D - 1.503 \cdot 10^{-5} \cdot D^2$

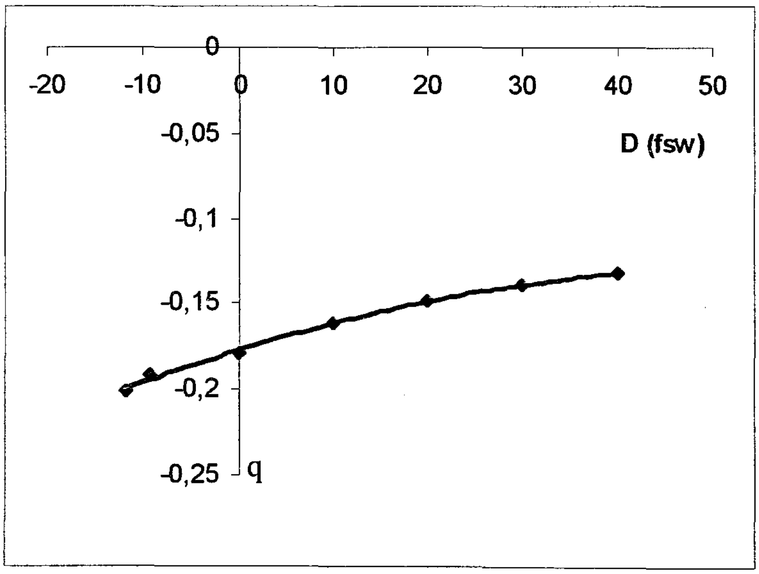


Figure 11.10. The correlation between the slope of the lines (q) depicted in Figures 11.2-11.7 and the gauge depth. $q = -1.444 \cdot 10^{-5} \cdot D^2 + 0.002 \cdot D - 0.177$

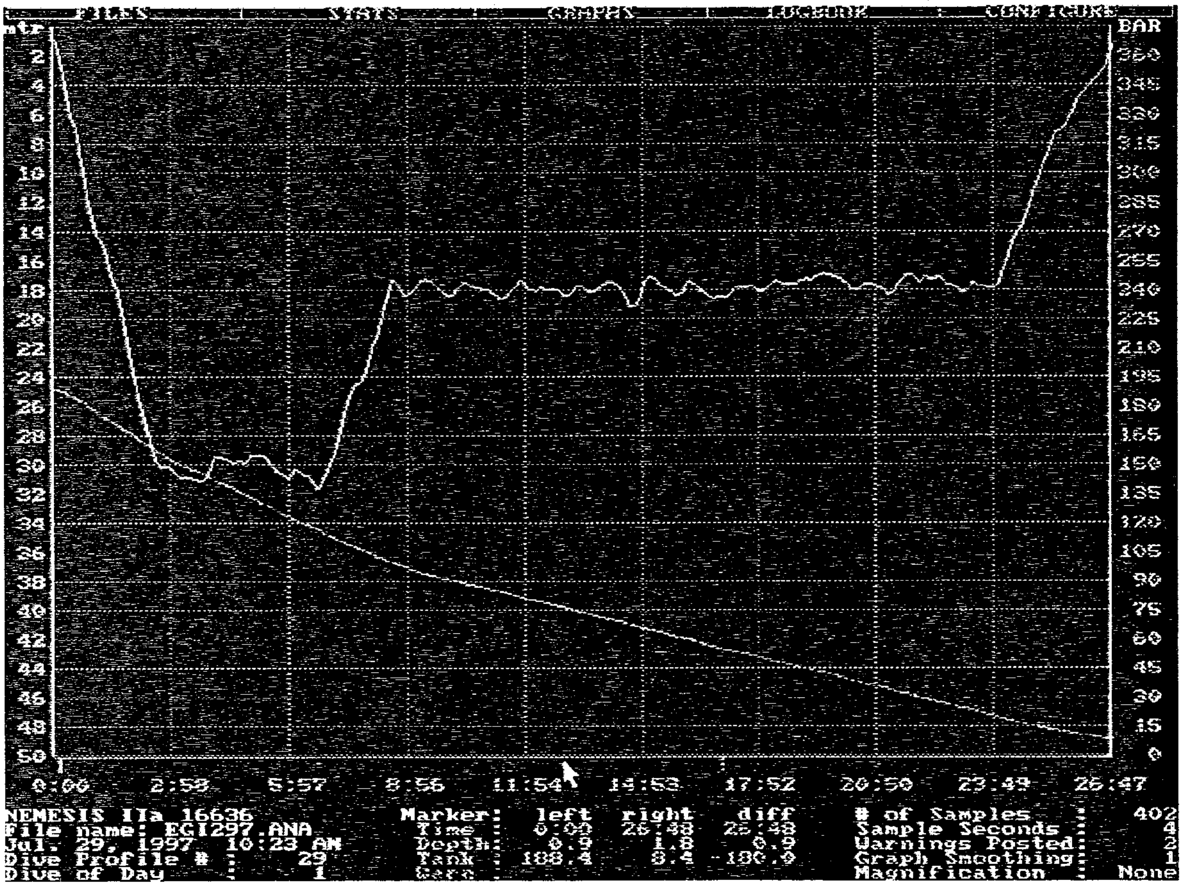


Figure 11.11. The tested multilevel profile (N=6 men dive). Horizontal axis represents the time (min), vertical axis is the depth (m).

Table 11.3

Time parameters of the VGE scores

Subject	Day	Onset time (min.)	Maximum Grade	Peak time (min.)	Duration (min.)
CD	11	20	II	20	80
DS	10	20	III	20	80

11.3.3. Conservative Hybrid $M(D,T_{1/2})$ Function

When the M values are computed for sea level and for 10 fsw, it has been observed for some compartments that Eq 11.8 yielded higher M values, which are not acceptable (Table 11.4). That was the reason for using. Nelder-Mead simplex search algorithm for fitting with the constraint that the curve is lower than every data point. The resulting surface (Figure 11.12) is described by the Eq 11.8 with:

$p = 4.7593+0.011058 \cdot D - 5.5274 \cdot 10^{-6} \cdot$

$q = -0.25708+0.0035169 \cdot D - 2.3412 \cdot 10^{-5} \cdot D^2$

Table 11.4

The M values computed from Eq 11.8

T	M_{calc}	M_0-M_{c0}	M_{10}	M_0-M_{c10}
2,65	99,73363	11,89976	119	5,252189
7,94	82,12737	6,653824	99,7	1,323953
12,2	76,11504	-1,28645	93,1	-6,14632
18,5	70,70771	-2,2293	87,2	-6,69868
26,5	66,35011	-3,23129	82,3	-7,37608
37	62,54383	-5,64868	78,1	-9,56536
53	58,68935	-5,8216	73,8	-9,40422
79	54,686	-3,15117	69,2	-6,47465
114	51,24883	0,285994	65,3	-2,56552
146	49,05301	0,753807	62,8	-2,31119
185	47,03994	2,766881	60,5	0,001807
238	44,98855	1,999554	58,1	-0,56261
304	43,08117	-0,82089	55,9	-3,27697
395	41,12998	1,130304	53,7	-1,00383
503	39,40748	2,852805	51,6	1,012283
635	37,8151	4,445185	49,8	2,884323

M_{calc}: Bühlmann M values calculated from Eq. 11.8. M_0 and M_{10} are the original M values corresponding to Bühlmann tables.

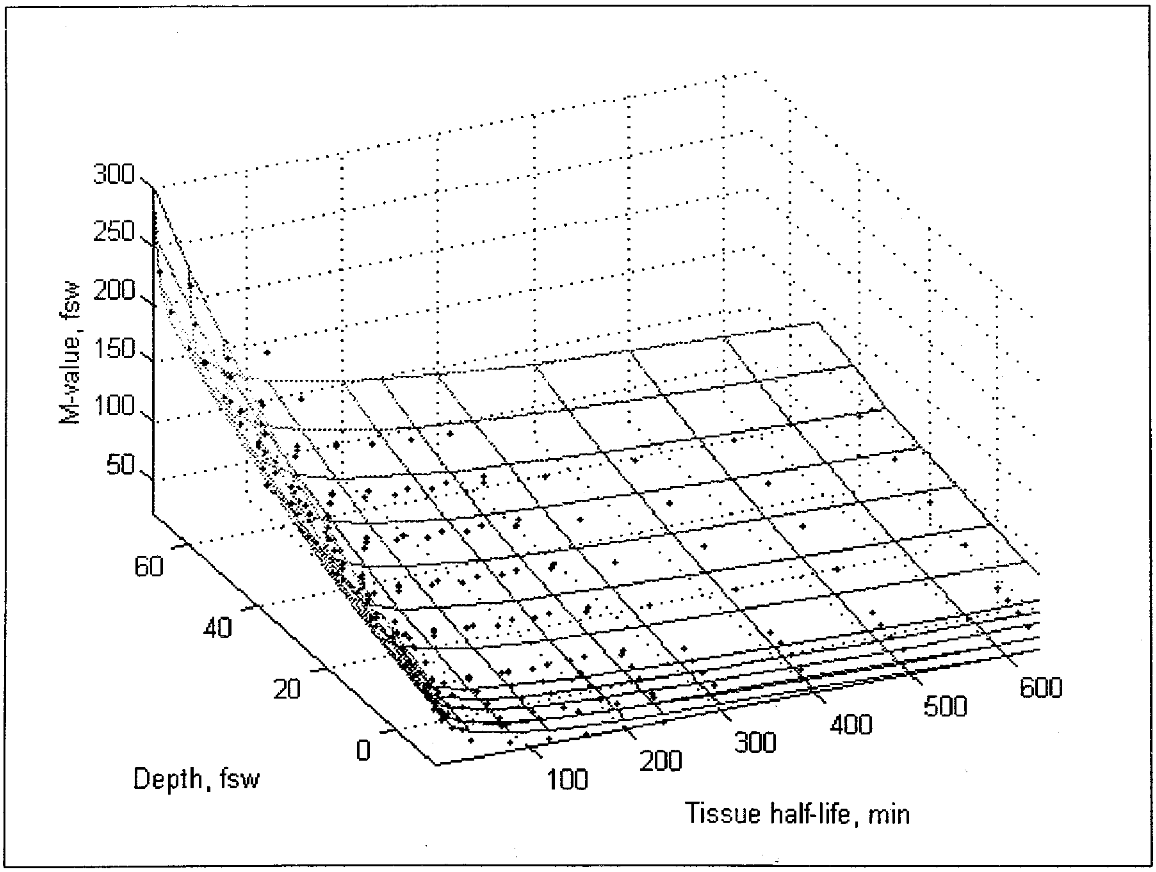


Figure 11.12. Conservative hybrid $M(D,T_{1/2})$ function.

11.4. DISCUSSION

The selection of tissue compartments representative of the body is often a problem [83]. Lewis and Shreeves used the computational power of computers to perform the calculations for 1530 tissues [128]. However, such an effort is time consuming and not feasible for the adaptation to diver carried decompression computers.

Within the scope of this work, instead of calculating the gas exchange for each of compartments, and finding out the critical one, for a given decompression stop, ascent to a given depth D is permitted when the derivative of $t(T_{1/2},D)$ with respect to $T_{1/2}$ is equal to zero to ascent to a given depth D and then this equation is solved to calculated the critical tissue for a given depth. Therefore, the question "Which tissue time constants are representative of the body?" is bypassed and an improvement of the existing neo Haldanian computation algorithm is achieved. For a given bottom time, the $\delta t(T_{1/2},D) / \delta T_{1/2} = 0$ equation can be used to find the shorter bottom time as well as the half life of the tissue which controls this ascent. The method can be easily incorporated in a dive computer.

The function $M(D,T_{1/2})$ which represents the surface of the DCS boundary is depicted in Figure 11.12. On the other hand, $D(T_{1/2},t)$ function the shallowest depth that one can ascend safely. Any decompression stop D_i, is represented by the intersection of $D(T_{1/2},t) = D_i$ surface and $D(T_{1/2},t)$ function curves. The intersection is a plot of $t(T_{1/2})$ function. The coordinates of the vertex of $t(T_{1/2})$ function versus $T_{1/2}$ determine the half life of the critical compartment and the bottom time allowed to ascend safely to depth D. (Figure 11.13). When applied to Eq 11.8 $t(T_{1/2})$ function is:

$$t(T_{1/2}) = -(T_{1/2} / \ln(2)) \,.\, \ln(1 - (\exp(p)\, T_{1/2}{}^{q}\, P_0)/(P_B - P_0)) \qquad (11.9)$$

The decompression times calculated using Conservative Hybrid Model are very long (See Appendix B). Therefore, the use of enriched air nitrox, even pure oxygen, seems to be the ultimate solution for shallow and long duration diving at altitude. At this point the decreased ambient pressure would increase the maximum allowable depth for a given nitrox mixture. For example, a 1.6 atm partial pressure of O_2, which corresponds to the usage of pure oxygen at 6 msw. at sea level, will be reached at 9.5 m. with the same gas.

This method is only an extension of the limits of the empirical tables. It can be very useful as an initial trial in a non documented mode of decompression such as multilevel diving at altitude trials in Kaçkar '97 Expedition. However, no additional improvement is gained regarding the modeling of gas exchange or the pathophysiology of the DCS. For instance, the limitations of Eq. 11.8 are obvious, since the perfusion to tissue compartments may not be constant [129]. Also, the effect of ascent rate has to be incorporated to the computation. However, these are not the limitations of the concept of continuous tissue time constants, but they reflect the shortcomings of the existing deterministic gas exchange or DCS boundary equations.

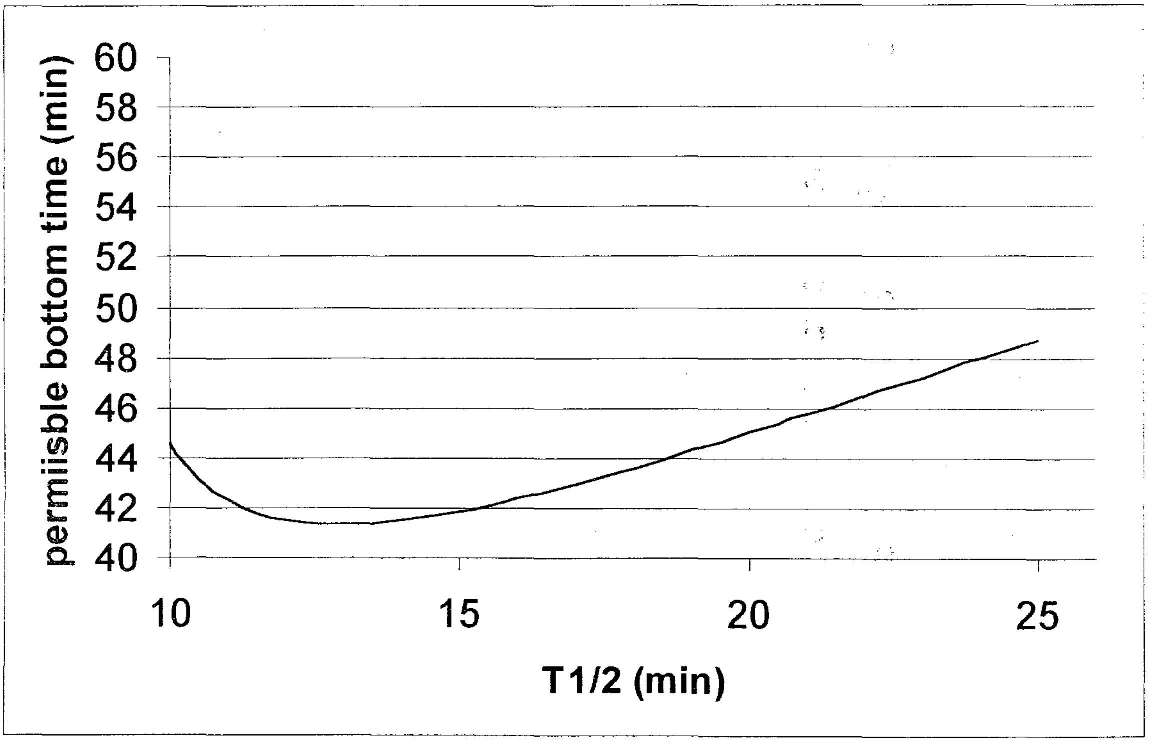


Figure 11.13. No-d limits of the compartments for a 70 fsw. dive at sea level calculated using the Hybrid Model. The minimum of $t(T_{1/2})$ function versus $T_{1/2}$ determine the half life of the critical compartment and the bottom time allowed to ascend safely to surface ($T_{1/2}$=10.375 min and t=32.93 min). The no-d limit corresponding to this dive is 50 min in USN Standard Air Decompression Tables and 35 min in Bühlmann Tables. If one uses Conservative Hybrid Model then the no-d limit drops to 27.695 min and the controlling compartment half-life becomes 91.731 min.

12. CONCLUSIONS

Diving at altitude is motivated by sportive activities, lymnological researches, underwater surveys, military and commercial operations. Altitude dives require different procedures than sea level because the surface level ambient pressure diminishes with increasing elevation, but there is no consensus on these procedures; including the definition of the altitude diving itself, which is observed to be arbitrarily set in different diving organization.

This thesis defines the altitude diving on the basis of meteorological data. Inland diving above 600 m. is called altitude diving. Beside this, "high altitude diving" is separately defined with respect to the elevation causing high altitude maladies. Based on the allowable cabin pressure civil air transportation, this threshold is set as 8000 ft.

The decompression methods exhibit a large discrepancy in the hypobaric domain. The general trend is to adapt the sea level tables to altitude. The lack of field-tested decompression methods is obvious. This thesis is a first attempt to classify and analyze existing methods of altitude adaptation of dive tables. As a result, the conservativeness of the adaptation algorithms is found to be a function of altitude, depth and bottom time.

Software to compute decompression schedules and to simulate gas exchange and bubble growth is developed within the scope of this thesis. The oxygen window is found to decrease with increasing altitude. That is the main reason of the modification of decompression tables. The simulations showed that repetitive deep diving may give rise to stabilized bubbles and therefore are extremely dangerous at altitude.

An important contribution of the thesis is the simulation that showed existence of supersaturated gas during a slow ascent to a moderate altitude. The supersaturated gas is proved to be enough to cause VGE in pigs even at 2000 m. altitude. This finding explains the rare cases of DCS in aviation and suggests a much lower threshold of altitude DCS than the commonly accepted 6000 m limit. This result also indicates the increased risk of DCS in case of immediate diving following air travel; because, beside the residual nitrogen from the sea level, bubble formation during the air transportation should be taken into account.

A new method of altitude adaptation (NLHE) is developed within the scope of this thesis. The no-d limits computed using that novel method are the first field-tested limits for high altitude. The results of these tests showed that these limits involve an acceptable risk of DCS.

A new concept in gas exchange and DCS boundary based on the simulation of continuous compartments is developed and applied to multilevel diving at altitude. Thus, the empirical nature of the tables is reduced to a single M value function, by assuming that the time constant is a variable. The body is modeled as a parallel combination of infinite number of compartments and the question of determining the time constants representative of the body becomes obsolete The test dives proved that the method is promising. In addition to these, decompression tables for 3500 m are computed using the hybrid conservative version of this model to ensure that the boundary is lower than existing models, aiming highest level of conservativeness in this **untested** series.

The diving techniques and experiences gained at the end of 5 altitude expeditions are also important contributions to the dive training literature. These are compiled in a booklet (Appendix A) to form a training standard compatible with CMAS system.

This thesis is a first attempt to define the effects of hypobaric hypoxia on diving. Although most of the investigated body parameters showed a significant change upon altitude exposure and during the stay, no clear evidence has been found to restrict the diving activities at a specific phase of adaptation, as far as the diver is free from altitude maladies. Meanwhile, adequate desaturation time should be spent at altitude since there are no well-documented experiments in diving literature to take into account the residual inert gas from the sea level.

APPENDIX A:

ALTITUDE DIVING SPECIALITY COURSE

PART I
(Standards & Requirements)

PART II
(Training program)

PART I (Standards & Requirements)

Table of Contents

I. Course classification (Type & Level)

The ALTITUDE DIVING SPECIALITY course is considered as an ADVANCED level speciality course.
That means that the required minimum entry level certificate is CMAS TWO-star DIVER OR EQUIVALENT.

II. Aim(s) & Objectives of the course

* To interest and introduce divers in a safe and competent way to the planning, preparation and performing of altitude dives under close supervision.
* To familiarize students with the diversity of fresh waters as well as skills, techniques and possible problems of altitude diving.
* To serve as a prerequisite for higher-level specialty courses.
* To form another important link in the chain of continuing training and education within the CMAS system.

III Entry requirements

1. student's min. age	: 16 years
2. certification equivalent	: TWO star CMAS OR EQUIVALENT
3. min. number of dives	: 40 (at least 2 of these performed within 2 weeks prior to the course)
4. other	: medical approval for diving: not older than 1 year medical approval for fitness to perform heavy exercise at 2400 m altitude.

NOTE: prior to attendance, a DRY SUIT DIVING SPECIALITY and ICE DIVING SPECIALITY COURSE is strongly recommended, but not mandatory.

IV Maximum student/instructor ratios

1. excellent visibility (average lake temperature above 18 °C)	: 6 : 1
2. excellent visibility (average lake temperature above 12 °C)	: 4 : 1
3. normal visibility (average lake temperature above 18 °C)	: 4 : 1
4. normal visibility (average lake temperature above 12 °C)	: 2 : 1
5. silt bottom (any level of visibility at surface)	: 1 : 1 (also for assistants)
6. cold water (below 10 °C) :	: 1 : 1 (also for assistants)
7. ice diving	: 1 : 1 (also for assistants)
8. poor conditions	: 1 : 1 (also for assistants)

NOTE: Assistants may be used on a 2:1 base (2 additional students per assistant) under conditions as mentioned under § 1 + 2 + 3 + 4.

V. Instructor / assistants requirements

1. instructor/course director:

a) certificate level : nat.fed./CMAS ONE-star instructor

b) proof of experience :
* instructor must be in active teaching status as required by his national federation
* must be of proven ability and practical experience (at least 20 logged altitude dives, 10 ice dives, 20 dry suit dives)
* must have assisted another instructor on at least 1 course
* must have submitted his own course outline which has been approved by the federation's Technical Committee, or must use a standard outline proposed by the federation itself.
* must have approved and valid training in diving rescue techniques, medical 1st aid and accident management by a recognized training organization.

2. assistants:

a) generally :
* as required to the satisfaction of the course director
- medical approval for diving not older than 1 year
- not having been identified as susceptible to Acute Mountain Sickness (AMS) in his or her previous altitude experiences.

b) certificate level :
* must hold at least nat. fed. CMAS THREE-star diver certificate OR EQUIVALENT

c) proof of experience :
* must have participated successfully in an ALTITUDE DIVING SPECIALITY Course, a DRY SUIT DIVING Course and an ICE DIVING Course (or equivalent training)
* have at least 10 logged altitude dives
* must have attended this course at least once as an inactive "observer" (without any task and responsibilities) to become familiar with relevant procedures
* have at least 100 logged dives overall

d) other :
* must have approved and valid training in diving rescue techniques and medical 1st aid by a recognized training organization

VI. Special course requirements

1. Course approval : approval by national (or regional) technical committee (or by the national/regional training manager) required for the FIRST course of this type by this instructor.

2. facilities : a) classroom : * adequate classroom, according to the needs of the course and the students

b) water : * no current, easy access for the entries.
* necessary precautions in case of ice diving
* time and site chosen as to insure adequate natural light and visibility.

c) diving site : * a shelter should be provided in case of diving in cold remote locations

3. diving equipment : - diving flag
- ropes, lines, reels
- adequate thermal protection
- otherwise standard scuba diving equipment
* instructor(s) AND assistant(s) MUST be equipped with alternate air source (2 regulators; at least octopus system)
* for diving in waters with temperatures less then 5 ^{O}C all regulators should comply with the EN250 Norms. First stage of the regulators should have adequate anti-freezing performance and second stage (alternate air source included) should be equipped with a heat exchanger to prevent freezing
* It is strongly recommended that in waters with temperatures less than 10 ^{O}C and depths deeper than 20 m. all involved instructors, assistants and participants should carry TWO SEPARATE first stages systems.
* during any kind of scuba diving activities, ALL involved instructors, assistants and participants MUST carry some form of buoyancy device (BC/ABLJ) with power inflation (direct feed). Power inflators should be serviced BEFORE arriving at the altitude to prevent any stacking
* ALL involved instructors, assistants and participants MUST be equipped with pressure gauges
* bourdon type or electronic depth gauges, both WITH altitude compensation are STRONGLY

RECOMMENDED. In case of the absence of zeroing options, calibration factors SHOULD BE CALCULATED BEFORE arrival to the diving site and gauges SHOULD BE ON SITE CALIBRATED using a marked rope BEFORE ANY DIVE TRAINING.

4. Other equipment / material :
- ev. buoy(s), markers for entry / exit
- ice drill
- emergency medical kit with oxygen
- communications (phone, radio, walky-talky) nearby
- signal light
- corresponding recognition material (C-card, badge, wall certificate)

5. other restrictions :
- entry / exit must be made from land, from the same place, clearly marked and well visible from the water
* drift dives are prohibited during training
* long distance surface swimming SHOULD BE AVOIDED, because of hypobaric hypoxia
* maximum altitude should be 2400 m.
* minimum duration of one dive is 15 minutes
- duration must be restricted to 0.5 hr
* when diving above 2400 m. the stay at altitude should be limited to two weeks.
* depth limits according to certificate level of each participant (as a maximum under best conditions) and according to local circumstances; however 20 m. should never be exceeded during this course

NOTE: dive duration must be planned so as not to reach the reserve (normally 40-50 bar)

* all diving should be made within no-decompression stop limits of officially used tables or dive computers, adequate for that altitude. FIELD TESTED DIVE TABLES or DIVE COMPUTERS SHOULD BE USED. TABLES OR DIVE COMPUTERS BASED ONLY ON THE THEORETICAL EXTRAPOLATION OF SEA LEVEL EXPERIMENTS SHOULD NEVER BE USED.
* the first dives should start after waiting for the adequate desaturation time as suggested by the table or dive computer
* an adequate waiting period should precede the first dives so as to ensure proper acclimatization to the lack of oxygen
* staying above 2000 m. for more than two weeks may change the physiological parameters. These, in turn, may effect the decompression parameters. These changes can be much more severe in case of high

altitude excursions (i.e. above 2400 m). Therefore, it is not advised to dive in periods following such activities until the body parameters stabilize

* divers should be free from the symptoms of AMS

6. supervision : - During the complete course, at least one authorized course director (instructor as outlined above) must always be present.
- Classroom lectures may be delegated to a qualified assistant who performs the lesson under the supervision of the course director.
- During practical training at the surface, a course director must be either in the water with the students, or in a cover boat, or on land as close as possible.
- During practical training underwater, the course director must always be present in the water and as close to the site of activity.
- Under no circumstances are the students allowed to be unattended in the water without supervision. A qualified assistant may perform such supervisory tasks.

7. emergencies : - detailed emergency plan for the chosen site must be made and explained to all staff and participants.
- at least one trained staff member, familiar with the dive site, first aid and relevant equipment must remain on land for coordination, supervision and emergencies.

VII. Student performance objectives

By the end of the course, students should be able to:

1. explain and demonstrate proper planning, preparation and techniques for altitude dives
2. explain the barometric effect of altitude
3. identify and explain possible problems and hazards associated with the decreased ambient pressure and their prevention
4. identify and explain possible problems and hazards associated with the decreased ambient temperature and their prevention
5. explain the effects of hypoxia, symptoms of altitude related illnesses, mainly AMS as well as the prevention of these problems.
6. explain the effects of fresh water on diving techniques and equipment
7. explain the calibration of various type of depth gauges for altitude.
8. explain two different method of table adaptation for altitude
9. demonstrate the correct use of dive tables
10. pass successfully all oral and/or written forms of evaluation
11. perform proper buoyancy control while diving

12. demonstrate underwater navigation techniques while diving.
13. demonstrate the correct use of the buddy system before, during and after diving activities
14. perform all required exercises and assessments as requested without stress and pass successfully all forms of evaluation

VIII. Minimum course duration

1. recommended number of sessions: 4 (check-dive NOT included)

2. minimum duration:
   a) classroom : 3.5-4 hrs (1 session)
   b) confined water : 3-4 hrs (1 session, check-dive NOT included)
   b) open water : 5-6 hrs (2 sessions)

3. minimum number of dives : 3 (checkout dive NOT included)
   Note: * No more than 1 dive per day for altitudes above 2400 m.
   * Repetitive dives should be avoided
   * a 4th dive might be recommended

IX. Quality control / assurance

CMAS strongly recommends and encourages all federations to use an adequate system for quality control and assurance. A system in widespread use and of proven effectiveness is to send questionnaires to the students, followed by an analysis of the feedback.

Questionable cases should be further investigated and measures taken to avoid similar situations in the future.

X. Overview of complete Training System

For a complete overview of the CMAS Training -and Certificate System, please refer to the document "The new CMAS Training- and Certificate System (a general introduction)"

PART II (Training Program)

Table of Contents

I. Course schedule

1. recommended number of sessions: 1 (overall)

2. minimum duration:
   a) classroom : 3.5 hrs (1 session)
   b) confined water : 3 hrs (1 session)
   c) open-water : 5 hrs (1 session)

3. minimum number of dives: 3

4. lessons & topics (brief overview):
   a) theory
   TH1: Course administration
   altitude/pressure conversions
   high altitude physiology
   maladies
   equipment considerations
   cold water diving
   decompression tables
   fresh water fauna & flora
   hazards, problems and prevention
   orientation for PR1
   assignments

   b) practical
   PR1: first familiarization with dive site and equipment
   buoyancy control
   freezing problems
   coping with the silt bottom
   PR2a: building up confidence
   repetition of skills from dive #1
   observation of flora and fauna
   PR2b: re-enforcing confidence
   repetition of skills from dive #2
   (ev. Spec. assignments)
   (certification)

5. recommended schedule:
   a) theory
   - 1 session of approx. 4 hrs during week (e.g. on an evening)
   b) practical
   - 2 session of approx. 3hrs for each dive, on two successive days /e.g. weekend) which gives the best result or
     scattered during week according to the students' desire
     day 1: dive #1 (plus ev. an additional dive for a weak student; session PR1)
     day 2: dive #2 (session PR2a/2b)
     certification

   NOTE : Necessary period for altitude acclimatization and desaturation from excess nitrogen remaining from sea level should be taken into consideration

6. support material for students:
   a) used during classroom sessions: handout
   b) used for home study: s. above *(a list with further recommended literature may be given to the students)*

7. support material for instructor:
   - text as developed by his federation
   - other recommended literature
   - own / federation supplied video / slides

II. Minimum course content (syllabus)

1. THEORY LESSONS (Classroom)

1.1 TH1 (classroom; approx. 3.5 hrs.)

a) Introduction, course administration

b) topics: - main topic 1 general introduction to altitude diving
(catching students attention)
   * subtopic 1.1 students' expectations
   * subtopic 1.2 what is special with this type of activity

- main topic 2 high altitude physics
   * subtopic 2.1 altitude/pressure conversions:
     barometers, reading graphs, using equations
   * subtopic 2.2 high altitude climate
     temperature variation, forecasting the temperature, coping with the ice
     sun radiation

- main topic 3 high altitude physiology
   * subtopic 3.1 review of hypoxia
     definition, prevention, first aid
   * subtopic 3.2 hypoxia induced maladies
     Symptoms, prevention and first aid of:
     Acute Mountain Sickness (AMS), High Altitude Pulmonary Edema (HAPE), High Altitude Retinopathy (HAR), High Altitude Cerebral Edema (HACE)
   * subtopic 3.3 sunburns and hypothermia
     radiation hazards, prevention and first aid to sunburns
     review of hypothermia

**** *BREAK* ****

- main topic 4 equipment considerations, part 1
   * subtopic 4.1 calibration of depth gauges
     type of depth gauges, predive correction of the readings, calibration
   * subtopic 4.2 changes in buoyancy

effect of altitude on the wetsuit buoyancy, effect of fresh water, buoyancy variation near the surface

* subtopic 4.3 BC/ABLJ
  preferences, freezing problems, swimming techniques through the silt layer
* subtopic 4.4 dry suits
  types, inflation/deflation systems, underwear, swimming techniques, emergency situations, freezing problems.

- main topic 5 equipment considerations, part 2
  * subtopic 5.1 regulators
    changes in air consumption, type of first stage, preferences, second stage heat exchanges, freezing problems, preventive maintenance, breathing techniques against freezing
  * subtopic 5.2 compressor performance
    logistic problems,
  * subtopic 5.3 dive computers
    altitude limits, algorithm, reliability
  * subtopic 5.4 cameras
    humidity problems, blocking problems

**** *BREAK* ****

- main topic 6 dive tables
  * subtopic 6.1 correction method
    Cross corrections, equivalent ocean depth, depth of decompression stops, sample problems
  * subtopic 6.2 extrapolated tables
    Overview of DCIEM, BSAC and Bühlmann tables, study of the one dictated by the nat. federation, sample problems
- main topic 7 life in fresh waters
  * subtopic 7.1 fresh water fauna
    endemic species, food chain, pollution
  * subtopic 7.2 fresh water flora
    endemic species, food chain, pollution

**** *BREAK* ****

- main topic 8 problems and hazards / prevention
  * subtopic 8.1 fear and panic
  * subtopic 8.2 lost of orientation

* subtopic 8.3 low-air situation
* subtopic 8.4 buoyancy control
* subtopic 8.5 reduced visibility, no light

- main topic 9 emergency planning
  (what should be included in the plan etc.)
- main topic 10 accident management
  * subtopic 10.1 types of accidents
  * subtopic 10.2 prevention, countermeasures
  * subtopic 10.3 1st aid on site
  * subtopic 10.4 calling for help
  * subtopic 10.5 other actions
- main topic 11 site orientation for open water dives #1 (and ev. #2) specific assignments: students carefully review, check and adjust their for practical session

c) training aids used:
- text as developed by federation / diving school / OCC
- other recommended literature
- own / federation supplied video / slides

2. PRACTICAL LESSONS (Confined - and Open Water)

2.1 P1 (Confined water, dive #1; approx. 3-3.5 hrs.)

a) site orientation, review of important points from theory session

b) pre-dive briefing equipment & buddy checks, student dive objectives and dive plan presentation

c) confined water dive #1: objectives:
* analysis of different environmental conditions
* equipment familiarization
* communication, signals
* buoyancy control near the surface
* free flow on surface
* free flow during the dive
* swimming techniques over the silt
* basic navigation
* buddy techniques

d) spec. materials:
* diving flag, lamps, spare equipment
* chemical lights in case of ice diving
* 1st aid equipment
* food, refreshments

NOTE: Dehydration is common at high altitude. However, dehydration is known to increase the susceptibility of decompression illness. Altitude divers should be encouraged to drink water. For long term high altitude expeditions, it is also advised to prepare salt solutions to maintain the ion equilibrium of the body.

e) post-dive review (debriefing): * review of conditions and observations
* discussion of any problems
* tips and hints for solving these problems
* logbook entries
* entry training records
* stow equipment
* refreshments
* *(other)*

f) pre-information on next dive location (if not the same) and special equipment needs for further dive #2 and special assignments (if any)

This formal part of the event can be followed by social gathering (e.g. barbecue)

g) training aids used: (none specifically)

h) safety measures:
- 1st aid equipment easily accessible, position known to everyone
- lamps, if low visibility
- position of nearby communications (e.g. pay phone) known to everyone
- detailed emergency plan explained, laid down on paper and positioned near emergency equipment
- thorough briefing of staff
- "divemaster" on land for complete duration; controls entries and exits of all diving teams (book-keeping)
- thorough buddy check before entry (supervised)

2.2 PR2a (open-water, dive #2; approx. 3-3.5 hrs)

a) site orientation, review of experiences from dive #1

b) pre-dive briefing equipment & buddy checks, student dive objectives and dive plan presentation

c) open water dive #2: objectives:
* generally: gain confidence, observation of flora and fauna
* analysis of different environmental conditions
* communication, signals
* buoyancy control near the surface (repetition)
* free flow on surface (repetition)
* free flow during the dive (repetition)
* swimming techniques over the silt (repetition)
* application navigational & buddy techniques

d) spec. materials: same as with dive #1

e) post-dive review (debriefing): * review of conditions and observations
* discussion of any problems

* tips and hints for solving these problems
* logbook entries
* entry training records
* stow equipment
* refreshments

f) pre-information on next dive location (if not the same) and special equipment needs for further dive #3 and special assignments (if any)

g) training aids used: (none specifically)

h) safety measures: same as with dive #1

2.2 PR2b (open-water, dive #3; approx. 3-3.5 hrs)

a) site orientation, review of experiences from dive #1 and #2

b) pre-dive briefing equipment & buddy checks, student dive objectives and dive plan presentation

c) open water dive #2: objectives:
* generally: re-enforce confidence, observation of flora and fauna
* analysis of different environmental conditions
* communication, signals
* application navigational & buddy techniques

d) spec. materials:
* same as with dive #1 and #2
* recognition material (cards, diplomas, etc.)

e) post-dive review (debriefing):same as for dive #1 and #2

f) pre-information on next dive location: none

g) training aids used: (none specifically)

h) safety measures: same as with dive #1 and #2

2.4 at END of course
* administrative work
* distribution of recognition material in an appropriate manner
* social gathering, promotion of other specialty courses

III. Knowledge review & skills assessment

1. theoretical knowledge:

An assessment may be made in written or in oral form at the end of TH1, but it is not mandatory. If done in written form, a multiple choice QUIZ should be used. The wording "examination" should be avoided.

2. practical skills:

a) at start of course:

If there is any reasonable doubt about the student's entry-skills, a check-out dive may be performed PRIOR to the course.

b) during course : no formal test required; see below

c) at end of course: no formal test required; see below

Comments for b) and c)

The 2nd and 3rd dives may be used to observe and eventually assess the behaviors and the competence of the student without telling this to him. In case of unsatisfactory performance, the student should be invited to follow the next ALTITUDE DIVING course and to improve his skills in the mentioned area (or an extra 4th altitude dive may be offered).

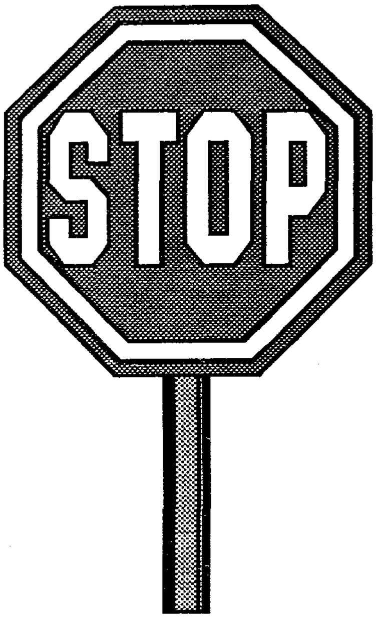
IV. Issuing of recognition material

May be given to the students at the end of lesson #2 (PR2) or on a separate meeting. Only students who have attended the whole course (and/or successfully passed any required assessment / evaluation) may receive the corresponding recognition material:

*** C-CARD**
*** BADGE (CHEVRON)**
*** WALL CERTIFICATE**

APPENDIX B

DECOMPRESSION TABLE FOR 3500 m



HIGH ALTITUDE DIVING IS A SPECIAL TYPE OF DIVING ACTIVITY THAT REQUIRES BOTH A HIGH DEGREE OF KNOWLEDGE AND SKILL IN THE AREAS OF DIVING AND MOUNTAINEERING.

DO NOT USE THIS TABLE UNLESS YOU HAVE AN ADEQUATE EXPERIENCE IN HIGH ALTITUDE DIVING.

WARNING!

ANY TYPE OF DIVING ACTIVITY INVOLVES EXPOSURE TO THE RISK OF DECOMPRESSION SICKNESS.

SINCE THIS RISK IS AFFECTED BY A NUMBER OF FACTORS OVER WHICH THE DIVER HAS NO CONTROL THIS TABLE CANNOT GUARANTEE RISK FREE DIVING FOR ANY USER,

MOREOVER THIS TABLE IS NOT TESTED!

DECOMPRESSION TABLE FOR 3500 m ALTITUDE

Depth (fsw)	Bottom Time (min)	Decompression Time at 10 fsw (min)
50	30	1
	40	5
	45	10
	50	20
	60	46
60	20	1
	30	5
	35	11
	40	22
	50	54
70	20	3
	30	14
	35	30
	40	50
	50	79
80	10	1
	15	2
	20	7
	25	14
	30	31

After arrival to 3500 m wait 16 hours to allow desaturation,

Ascent rate: 6 m/min,

Above table cannot be used for repetitive dive planning.

REFERENCES

1. Lipmann, J. and S Bugg, *The DAN Emergency Handbook*. J.L Publ, Carnegie, Victoria, Australia, pp. 20-21, 1991.

2. Böni, M., R. Schibli, P. Nussberger, and A.A. Bühlmann, "Diving at Diminished Atmospheric Pressure: Air Decompression Tables for Different Altitudes," *Undersea Biomed Res,* Vol. 3(3), pp. 189-204, 1976.

3. Boycott, A.E., G.C. Damant and J.S. Haldane, "The Prevention of Compressed Air Illness," *J Hyg Camb,* Vol. 8, pp. 342-443, 1908.

4. Bühlmann, A.A., *Decompression/Decompression Sickness*: Springer-Verlag, Berlin, 1984.

5. Hawkins, J.A., C.S. Schilling and R.A. Hansen, "A Suggested Change in Calculating Decompression Tables for Diving," *Nav Med Bull,* Vol. 33, pp. 327-338, 1935.

6. Van Der Aue, O.E., E.S. Brinton and R.J. Kellar, Surface Decompression, Derivation and Testing of Decompression Tables with Safety Limits for Certain Depths and Exposures. Research project X-47, NEDU Research Report I, US NEDU, 1945.

7. Workman, R.D., Calculation of Decompression Schedules for Nitrogen-Oxygen and Helium-Oxygen Dives. NEDU Research Report 6-65; US NEDU, 1965.

8. Behnke, A.R., B.G. Feen and T.L. Willmon. Harmful Effects of too Rapid Ascent in Aircraft. US NRC Comm Aviat Med Report 3, Washington DC, 1940.

9. Bühlmann, A.A., "Diving at Altitude and Flying after Diving," In Vann RD, eds. The Physiological Basis of Decompression, *Proceedings of the Thirty-Eighth UHMS,* UHMS No75 (phys) pp. 411-423, 1989.

10. Conkin, J. and H.D. Van Liew, "Failure of Straight-Line DCS Boundary when Extrapolated to Hypobaric Realm," *Aviat Space Environ Med,* Vol. 63(11), pp. 965-970, 1992.

11. Heimbach, R.D., P.J. and P.J. Sheffield, "*Decompression Sickness and Pulmonary Overpressure Accidents,*" in: R.L. DeHart (Eds.), *Fundamentals of Aerospace Medicine*, pp. 132-161, Philadelphia, PA: Lea and Febiger, 1985.

12. Kumar, K.V., D.S. Calkins, J.M. Waligora, J.H. Gilbert and M.R. Powell, "Threshold Altitude Resulting in Decompression Sickness," *Aviat Space Environ Med,* Vol. 61(8), pp. 685-689, 1990.

13. Egi, S.M. and A.O. Brubakk, "Diving at Altitude: A Review of Decompression Strategies," *Undersea Hyperbaric Med*, Vol. 22(3), pp. 289-300, 1995.

14. Bassett, B.R., Decompression Procedures for Flying after Diving, and Diving at Altitudes above Sea Level. USAF Report SAM-TR-82-47, 1982

15. Cross, E.R., "Technifacts from a Master Diver," *Skin Diver*, Vol. 16(12), pp. 60 et seq., 1967.

16. Cross, E.R., "Technifacts-High Altitude Decompression," *Skin Diver*, Vol. 19(11), pp.17 et seq., 1970.

17. Hennessy, T.R., "Converting Standard Air Decompression Tables for No Stop Diving or Diving from Altitude or Habitat," *Undersea Biomed Res*, Vol. 4(1), pp. 39-53, 1977

18. Sahni, T.K., M.J. John, A. Dhall and A.K. Chatterjee, "High Altitude Dives from 7000 to 14300 feet in the Himalayas," *Undersea Biomed Res*, Vol. 18(4), pp. 303-316, 1991.

19. Le Pêchon, J.C., A. Duvallet A and Y. Le Masson Y, "High Altitude (4517 m) Nitrox Diving with Semi-Closed Circuit UBA (SCANUBA)," *Proceedings of Twentieth Annual Meeting of European Underwater and Biomedical Society*, pp. 258-264, Istanbul, 1994.

20. Maas, F.J. et al. "High Altitude Dives from Mexico," *Proceedings of Tenth International Conference on Underwater Education*, Colton, CA. National Association of Underwater Instructors, pp. 251-258, 1978.

21. Flemming, N.C. and M.D Max, *Scientific Diving: a General Code of Practice*. On behalf of the Scientific Committee of the World Underwater Federation (CMAS), UNESCO, CMAS and Unv of FL, pp. 79-81, 1990.

22. *PADI Advanced Diver Manual*. Published by PADI, 1243 East Warner Ave., Santa Ana, CA 92705.

23. Taylor, G.L., "*Student Manual and Workbook for Safer Altitude Diving, Volume 1: Air & Nitrox*," IANTD pub, FL, 1996.

24. Wienke, B.R., "High Altitude Diving," NAUI Tech Library Pub, Montclair, CA, 1991.

25. *BSAC '88 Decompression Tables*. British Sub Aqua Club, 1988

26. Gleises, A., P.Ane and P. Izard, "Plongée en Altitude: 4200 m dans l'Himalaya," Commission Medicale FFESSM, INFOMED No. 4: pp. 23-28, 1992.

27. Leach, J., "Andean High Altitude Diving Expedition," *J Underwater Technol*, Vol. 12, pp. 27-31, 1986.

28. Leach, J., A. McLean and F.B. Mee, "High Altitude Dives in Nepali Himalaya," *Undersea Hyperbaric Med*, Vol. 21(4), pp. 459-466, 1994.

29. Leffner, C.T., "High Altitude Hyperbaric Operations at 3810 m in Bolivia," *Undersea Hyperbaric Med*, Vol. 24(Suppl), p. 14, 1997.

30. Cousteau, J.Y., "*Trois aventures de la Calypso: Galopagos, Titicaca, the Blue Holes,*" Doubleday, 1973.

31. Bühlmann, A.A., "*Decompression Theory, Swiss Practice,*" in P.B. Bennett and D.H. Elliot, (Eds.) *The Physiology and Medicine of Diving and Compressed Air Work*, London, Bailliere and Tindall, pp. 348-365, 1975.

32. "*DCIEM Diving Manual. Part 1. Air Diving Tables and Procedures,*" Publ. Universal Dive Techtronics, INS. (UDT), Canada, 1A-57, 1992.

33. Miller, J.M. and I.G. Koblick, "*Living and Working in the Sea,*" New York, NY, Van Nostrand Reinhold Company Publ., pp. 71-76, 1984.

34. Bell, R.L. and R.E. Borgward. "The Theory of High Altitude Correction to the US Navy Standard Decompression Tables: The Cross Corrections," *Undersea Biomed Res*, Vol. 3(1):1-23, 1976.

35. Behnke, A.R., "*Early quantitative studies of gas dynamics in decompression,*" in P.B. Bennett and D.H. Elliot (Eds.), *The Physiology and Medicine of Diving and Compressed Air Work*, pp. 392-416, London, Bailliere and Tindall, 1975.

36. Hills, B.A., "*Biophysical Aspects of Decompression,*" in P.B. Bennett and D.H. Elliot (Eds.), *The Physiology and Medicine of Diving and Compressed Air Work*, pp. 366-391, London, Bailliere and Tindall, 1975.

37. Yount, D.E., "*Growth of Gas Bubbles from Nuclei,*" in A.O. Brubakk, B.A. Hemmingsen and G. Sundnes (Eds.), *Supersaturation and Bubble Formation in Fluids and Organisms*, pp. 131-164, Trondheim, Norway, Tapir Pub., 1989.

38. *Proposition d'un Manuel de Procedures de Decompression à l'air*, pp. 278-283, Aubagne, France, L'imprimeries Louis Lartigot, 1987.

39. Smith, C.L., *Altitude Procedures for the Ocean Diver. Colton,* CA: NAUI Technical Publ, No.5, 1976.

40. *Aladin Pro Manual*, Uwatec AG, Switzerland.

41. Wienke, B.R., "Bubble Number Saturation Curve and Asymptotics of Hypobaric and Hyperbaric Exposures," *Int J Biomed Comp*, Vol. 29, pp. 215-225, 1991.

42. Wienke, B.R., *Diving Above Sea Level,* AZ, Best Publishing Company, 1993.

43. Basset, B.E., "And yet Another Approach to the Problem of Altitude Diving and Flying after Diving," *Proceedings of the Meeting Decompression in Depth,* Santa Ana, PADI, 38-48, 1979.

44. Ryder, H.W, C.D. Stevens, J.P. Webb and M.A. Blankenhorn, The measurement of Decompression Sickness, US NRC Comm Aviat Med Report 412, Washington DC, 1945.

45. Gray, J.S., Aeroembolism Induced by Exercise in Cadets at 23000 feet. US NRC Comm Aviat Med Report 260, Washington DC, 1944.

46. Allan, J.H., "Traumatic calcifications: a precipitating factor in "bends" pain," *J Aviat Med,* Vol. 16, pp. 235-241, 1945.

47. Rayman, R.B. and G.B. McNaughton, "Decompression Sickness: US Air Force Experience 1970-1980," *Aviat Space Environ Med,* Vol. 54(3), pp. 258-260, 1983.

48. Voge, V.M., "Probable Bends at 14000 feet: a Case Report, " *Aviat Space Environ Med,* Vol. 60(11), pp. 1102-1103, 1989.

49. Houston, C.S., "Occurrence of Bends, Scotomata, and Hemianopsia at Altitudes below 20000 feet," *J Aviat Med,* Vol. 18, pp. 165-168, 1947.

50. Van Liew, H.D., "Simulation of the Dynamics of Decompression Sickness and the Generation of New Bubbles," *Undersea Biomed Res,* Vol. 18(4), pp. 333-345, 1991.

51. Guyton, C. "*Aviation High Altitude and Space Physiology,*" in: *Textbook of Medical Physiology,* pp. 528-543, Philadelphia, Saunders, 1986.

52. Houston, C.S., "Mountain Sickness," *Scientific American,* Vol. 267(4), pp. 34-39, 1992.

53. *"The Lake Louise Consensus on the Definition and Quantification of Altitude Illness,"* in J.R. Sutton, G. Coates and C.S. Houston (Eds.), *Hypoxia and Mountain Medicine,* Oxford: Pergamon Press, pp. 327-330, 1991.

54. Mountain, R.D., "High Altitude Medical Problems," *Clin Orthop and Related Res* Vol. 216(3), pp.50-54, 1987.

55. Oelz, O., *"Acute Mountain Sickness,"* in: J. Vallaton and F. Dubas (Eds.), *A Color Atlas of Mountain Medicine,* pp. 51-52, London: Wolfe, 1991.

56. Johnson, T.S. and P.B. Rock, "Acute Mountain Sickness," *New Engl J Med,* Vol. 319(13), pp. 841-845, 1988.

57. Pollard, A.J., "Altitude Induced Illness," *British Med J,* Vol. 304(6838), pp. 1324-1325, 1992.

58. Richelet, J.P., "L'Adaptation à L'Altitude," *Recheche*, Vol. 18(194), pp. 1482-1492, 1987.

59. Bartsch, P., N. Pfluger, M. Audetat, et al., "Effects of Slow Ascent to 4559 m on Fluid Homeostasis," *Aviat Space and Env Med*, Vol. 62(2), pp. 105-110, 1991.

60. Huang, S.Y., L.G. Moore, R.E. McCullough, et al., "Internal Carotid and Vertebral Flow Velocity in Men at High Altitude," *J Appl Physiol*, Vol. 63(1), pp. 395-400, 1987.

61. Moore, L.G., S.Y. Huang, R.E. Mc Cullough, et al., "Variable Inhibition by Falling CO_2 of Hypoxic Ventilatory Response in Humans," *J Appl Physiol*, Vol. 56, pp. 207-210, 1984.

62. Severinghaus, J.W., H. Chiodi, E.I. Eger, B. Brandstater and T.F. Hornbein, "Cerebral Blood Flow in Man at High Altitude," *Circ Res*, Vol. 19, pp. 274-282, 1966.

63. Singh, I., P.K. Khanna, M.C. Srivastava, M. Lal, S.B. Roy and C.S.V. Subramanyam, "Acute Mountain Sickness," *N Engl J Med*, Vol. 280, pp. 175-184, 1969.

64. Kuwahira, I., N.C. Gonzalez, N. Heisler and J. Piiper, "Changes in Regional Blood-Flow Distribution and Oxygen Supply During Hypoxia in Conscious Rats," *J Appl Physiol,* Vol. 74(1), pp. 211-214, 1993.

65. Ernst, E., C. Altmann and T. Saradeth, "Hemorheological Changes Following Exposure to Moderately High Altitude," *Clin. Hemorheology*, Vol. 11(5), pp. 303-307, 1991.

66. Palareti, G., M. Poggi, M.G. Tricarico, P. Torricelli, F. Cavazzuti and S. Coccheri, "High Altitude Expeditions: Haemorheologic Effects," *Clin Hemorheology*; Vol. 6(2), pp. 195-199, 1986.

67. Shah, G.A., C. Brand-Maher, J. Vangelder, C.H. Nair and D.P. Dhall, "High Altitude Expedition-Whole Blood Viscosity and Trental," *Int J Microcirc Clin Exp*, Vol. 7, pp. 154, 1988.

68. Le Roux, G., P. Larmignat, M. Marchal and J.P. Richelet, "Haemostasis at High Altitude," *Int J Sports Med,* Vol. 13(Suppl 1), pp. S49-S51, 1992.

69. Bebout, D.E., D. Story, J. Roca J, et al. "Effects of Altitude Acclimatization on Pulmonary Gas Exchange During Exercise," *J Appl Physiol*, Vol. 67(6), pp. 2286-2295, 1989.

70. Allen, C.B., S.D. Babyak and A. Tucker, "Changes in Platelet Count and Clotting Times in Men During Sequential Altitude or Hypoxic Exposures," *FASEB J*, Vol. 2(6), pp. 1721, 1988.

71. Lahiri, S., "*Physiological Responses and Adaptation to High Altitude*," in D. Robertshaw (Eds.), *MPT International Review of Science: Environmental Physiology, Physiology series 1, Vol. 7*, pp. 271-311, London: Butterworths, 1974.

72. Elliot, D.H. and J.M. Hallenbeck, "*The Pathophysiology of Decompression Sickness*," in: P.B. Bennett and D.H. Elliot, (Eds.), *The Physiology and Medicine of Diving and Compressed Air Work*, pp. 435-455, London: Bailliere and Tindall, 1975.

73. Wienke, B.R., *Basic Decompression Theory and Application*, Best Publishing Company, AZ, 1991.

74. Anand, I.S., Y. Chanrashekhar and S.K. Rao, et al. "Body Fluid Compartments, Renal Blood Flow and Hormones at 6000 m in Normal Subjects," *J Appl Physiol*, Vol. 74(3), pp. 1234-1239, 1993.

75. Deurenberg, P., R.D. Reynolds, M.P. Howard, A. Pietersma and J. Destoppelaar, "Changes in Body Composition During Exposure to Extreme Altitude," *FASEB J*, Vol. 5(5), pp. 1128, 1991.

76. Fulco, C.S., R.W. Hoyt, J.B. Carol, J. Gonzalez and A. Cymerman, "Use of Bioelectrical Impedance to Assess Body Composition Changes at High Altitude," *J Appl Physiol*, Vol. 72(6), pp. 2181-2187, 1992.

77. Krzywicki, H.J., C.F. Consolazio, L.O. Matoushi, H.L. Johnson and R.A. Barnhart, Body Composition Changes During Exposure to High Altitude," *Federation Proc*, Vol. 28(3), pp. 1190-1194, 1969.

78. Rubinstein, E.H., "Physiological Adaptations to High Altitude," *Seminars in Anesthesia*, Vol. 9, pp. 211-221, 1990.

79. Lahiri, S., "Dynamic Aspects of Regulation of Ventilation in Man During Acclimatization to High Altitude," *Respir Physiol*, Vol. 16, pp. 245-258, 1972.

80. Rahn, H. and A.B. Otis, "Man's Respiratory Response During and After Acclimatization to High Altitude," *Am J Physiol*, Vol. 157, pp. 445-449, 1949.

81. West, J.B., "Rate of Ventilatory Acclimatization to Extreme Altitude," *Respir Physiol*, Vol. 74, pp. 323-333, 1988.

82. Rahn, H. and W.O. Fenn, "*A Graphical Analysis of the Respiratory Gas Exchange*," American Physiological Society, Washington, 1955.

83. Schreiner, H.R. and P.L. Kelly, "*A Pragmatic View of Decompression,*" in C.J. Lambertsen (Eds.), *Underwater Physiology*, pp. 205-219, New York: Academic Press, 1971.

84. Egi, S.M., "Estimation of Oxygen Window During and After Altitude Exposures," *Proceedings of Twentieth Annual Meeting of European Underwater and Biomedical Society*, pp. 135-139, Istanbul, 1994.

85. Ward, M. (Eds.), "*Respiration, the Gas Phase,*" in *Mountain Medicine: A Clinical Study of Cold and High Altitude*, pp. 77-101, Crosby Lockwood Staples, London, 1975.

86. Hill, A.V., "The Possible Effects of Aggregation of the Molecules of Hemoglobin on its Dissociation Curves," *J Physiol*, 40:iv, 1910.

87. Van, Liew H.D., J. Conkin and M.E. Burkard, "The Oxygen Window and Decompression Bubbles: Estimates and Significance," *Aviat Space Environ Med*, Vol. 64(9), pp. 859-865, 1993.

88. Hamilton R.W., R.E. Rogers, M.R. Powell, R.D. Vann, R. Dunford, M. Spencer and D. Richardson, *The DSAT Recreational Dive Planner, Development and Validation of No-Stop Decompression Procedures for Recreational Diving*, Diving Science and Technology Inc. and Hamilton Research, Ltd., 1994.

89. Nishi, R.Y., "*Doppler Evaluation of Decompression Tables,*" in: Y.C. Lin and K.K. Shida (Eds.), *Man in the Sea Vol I*, pp. 297-316, San Pedro, CA: Best Pub, 1990.

90. Flook, V., O. Eftedal and A.O. Brubakk, "Comparison between Predictions of Gas Bubbles by a Mathematical Model of Decompression and Bubble Counts Detected in Pigs," *Proceedings of Nineteenth Annual Meeting of European Underwater and Biomedical Society*, pp. 278-282, Trondheim, Norway, 1993.

91. Holmen, I., V. Flook, A.L. Ustad and A.O. Brubakk, "Uptake and Washout Curves for Nitrogen in Pigs," *Proceedings of Nineteenth Annual Meeting of European Underwater and Biomedical Society*, pp. 79-83, Trondheim, Norway, 1993.

92. Mapleson, W.W., "An Electrical Analogue for Uptake and Exchange of Inert Gases and Other Agents," *J Appl Physiol*, Vol. 18, pp. 197-204, 1963.

93. Van Liew, H.D., J. Conkin and M.E. Burkard, "Bubble Equations and Prevention of DCS: is There Any Connection?," *Proceedings of Nineteenth Annual Meeting of European Underwater and Biomedical Society*, pp. 241-248, Trondheim, Norway, 1993.

94. Van Liew, H.D. "*Bubble Dynamics,*" in A.A. Pilmanis (Eds.), *Hypobaric Decompression Sickness*, pp. 17-34, Texas: UHMS Pub, 1992.

95. Van Liew, H.D., J. Conkin and M.E. Burkard, "How Big are Decompression Bubbles?" *Proceedings of Nineteenth Annual Meeting of European Underwater and Biomedical Society*, pp. 258-262, Trondheim, Norway, 1993.

96. Gürmen, M.N., R.A. Gilbert, A.J. Llewellyn and S.M. Egi, "A Population Balance Model for Decompression Sickness," *Proceedings of AICHE Annual Meeting*, Poster 278bb, Session 278, LA, 1997.

97 Aydın, S., Ş. Aktaş, S.M. Egi and M. Çimsit, "Altitude Dive Performed at 3412 m," *Proceedings of Eighteenth Annual Meeting of European Underwater and Biomedical Society*, pp. 135-137, Basel, 1992.

98. Spencer M.P., "Decompression Limits for Compressed Air Determined by Ultrasonically Detected Blood Bubbles," *J Appl Physiol*, Vol. 40(2), pp. 229-235, 1976.

99. Brubakk, A.O., A. Vik, B.M. Jenssen, A. Kleven and O. Eftedal, HADES: Animal Model and Testing Procedures, SINTEF report, STF23 F91010, Trondheim, 1991.

100. Holmen, I.M., V. Flook, A.L. Ustad and A.O. Brubakk, A Method for the Extraction of Nitrogen from Blood," *Proceedings of Eighteenth Annual Meeting of European Underwater and Biomedical Society*, pp. 145-146, Basel, 1992.

101. Vik A., "Vascular Gas Embolism During Air Infusion and After Decompression in Pigs," Ph.D. Dissertation, University of Trondheim, Norway, 1993.

102. Eftedal, O., R. Mohammadi, M. Rouhani, H. Torp and A.O. Brubakk, "Computer Real Time Detection of Intravascular Bubbles," *Proceedings of Twentieth Annual Meeting of European Underwater and Biomedical Society*, pp. 490-494, Istanbul, 1994.

103. Malconian, M.K., P. Rock, J. Devine, A. Cymerman, J.R. Sutton and C.S. Houston, "Operation Everest II: Altitude Decompression Sickness Incidence During Repeated Altitude Exposure," *Aviat Space Environ Med*, Vol. 58, pp. 679-682, 1987.

104. Waligora, J.M., D.J. Horrigan, J. Conkin and A.T. Hadley, Verification of an Altitude Decompression Sickness Prevention Protocol for Shuttle Operations Utilising a 10.58 psi Pressure Stage, Rep no. NAS 1.15:58259, S-534, NASA-TM-58259, Houston, TX: NASA, 1984:48.

105. Black, W.R. and R.L. Dehart, "Decompression Sickness: an Increasing Risk for the Private Pilot," *Aviat Space Environ Med*, Vol. 63, pp. 200-202, 1992.

106. Eckenhoff, R.G., C.S. Olstad and G. Carrod, "Human Dose-Response Relationship for Decompression and Endogenous Bubble Formation," *J Appl Physol*, Vol. 69, pp. 914-918, 1990.

107. Harvey, E.N., A.H. Whiteley, W.D. McElboy, D.C. Pease and D.K. Barnes, "Bubble Formation in Animals, II: Gas Nuclei and Their Distribution in Blood and Tissue," *J Cell Comp Physiol*, Vol. 24, pp. 23-34, 1944.

108. Egi, S.M., Ş. Aktaş, Y. Bahadırlar, F. Yeşilleten and O. Eftedal, "Kaçkar'94: Field Tests of Altitude Dive Tables Based on an Alternative Method of Hypobaric Extrapolation of Decompression Sickness Boundary," *Undersea Hyperbaric Med*, Vol. 22 (suppl), pp. 67-68, 1995.

109. Egi, S.M., Ş. Aktaş, F. Yeşilleten and O. Eftedal, "The Effects of Short Term Altitude Acclimatization on the Bubble Formation," *Proceedings of Twenty-first Annual Meeting of European Underwater and Biomedical Society*, pp. 68-73, Helsinki, 1995.

110. Yeşilleten, F., S.M. Egi and Y. Ülgen, "Multisite Multifrequency Measurement and Analysis of Bioimpedance Changes at High Altitude," *Proceedings of Ninth ICEBI*, pp. 259-263, Heidelberg, Germany, 1995.

111. Yeşillten F., "Multiple Frequency Bioelectrical Impedance Analysis to Assess Body Fluid Composition Changes with Altitude," MS. Thesis, Boğaziçi University, 1995.

112. Egi, S.M., Development of a software library for comparative studies of DCS. *Proceedings of Twentieth Annual Meeting of European Underwater and Biomedical Society*, pp. 484-489, Istanbul, 1994.

113. Lukaski, H.C. and W.W. Bolonchuk, "Theory and Validation of the Tetrapolar Bioelectrical Impedance Method to Assess Human Body Composition," *In Vivo Body Composition Studies*, pp. 410-414, 1987.

114. Lukaski, H.C., W.W. Bolonchuk, C.B. Hall and W.A. Siders, "Validation of Tetrapolar Bio-Electrical Impedance Method to Assess Human Body Composition," *J Appl Physiol*, Vol. 60, pp. 1327-1332, 1986.

115. Segal, K.R., M. Van Loan, P.I. Fitzgerald, J.A. Hodgdon and T.B. Van Itallie, "Lean Body Mass Estimation by Bioelectrical Impedance Analysis: a Four Site Cross-Validation Study," *Am J Clin Nutr*, Vol. 47, pp. 7-14, 1988.

116. Van Loan, M. and P. Mayclin, "Bioelectrical Impedance Analysis: Is it a Reliable Estimator of Lean Body Mass and Total Body Water?" Hum Biol, Vol. 59, pp. 299-309, 1987.

117. RJL Systems, Manufacturer of Commercially Available Four-Terminal Impedance Analyzer Model BIA-101, Detroit, MI.

118. Deurenberg, P., J.A. Weststrate and A.J. Hautvast, "Changes in Fat Free Mass During Weight Loss Measured by Bioelectrical Impedance and by Densitometry," *Am J Clin Nutr*, Vol. 43, pp. 33-36, 1989.

119. Khaled, M.A., M.J. McCutcheon, S. Reddy, P.L. Pearman, G.R. Hunter and R.L. Weinsier, "Electrical Impedance in Assessing Human Body Composition: the BIA Method," *Am J Clin Nutr*, Vol. 47, pp. 789-792, 1988.

120. Gunga, H.C., K. Kirsch, F. Baartz, H.J. Steiner, P. Wittels and L. Rocker, "Fluid Distribution and Tissue Thickness Changes in 29 Men During 1 week at Moderate Altitude (2315 m)," *European J Appl Physiol Occup Physiol*, Vol. 70(1), pp. 1-5, 1995.

121. Thalmann, E.D., "USN Experience in Decompression Table Validation," in H.R. Schreiner and R.W. Hamilton (Eds.) *Validation of Decompression Tables: Proceedings of the 37th UHMS Workshop*, pp. 33-42, Bethesda, MD, UHMS Pub, 1989.

122. Vann, R.D., *"The use of risk analysis to develop decompression procedures,"* in W. Sterk and R.W. Hamilton (Eds.), *Operational Dive and Decompression Data: Collection and Analysis*, pp. 100-106, EUBS Pub, 1991.

123. West, J.B., "Prediction of Barometric Pressures at High Altitudes with the Use of Model Atmospheres," *J Appl Physiol*, Vol. 81(4), pp. 1850-1854, 1996.

124. Egi, S.M., "Computation of Dive Tables Using Continuous Tissue Time Constants," *Proceedings of Twenty-second Annual Meeting of European Underwater and Biomedical Society*, pp. 299-302, Milan, 1996.

125. Lagarias, J.C., J.A. Reeds, M.H. Wright and P.E. Wright, "Convergence Properties of the Nelder-Mead Simplex Algorithm in Low Dimensions," To appear in *SIAM Journal of Optimization.*

126. Nelder, J. A. and R. Mead, "A Simplex Method for Function Minimization," *Computer Journal*, Vol. 7, p. 308-313, 1991.

127. *US NAVY Diving Manual*, NAVSEA 0994-LP-001-9010. Navy Department, Washington DC 20362,1973.

128. Lewis, J.E. and K.W. Shreeves, *The Recreational Diver's Guide to Decompression Theory, Dive Tables and Dive Computers*, pp. 68-69, PADI, Santa Ana, CA, 1993.

129. Hills, B.A., "Intermittent Flow in Tendon Capillary Bundles," *J Appl Physiol: Respirat Environ Exercise Physiol*, Vol. 46(4), pp. 696-702, 1979.

VITA

S. Murat Egi was born in Istanbul, on March 12^{th}, 1965. His first encounter with the underwater word dates his high school years. In 1984, he graduated from Saint Joseph high school in Istanbul. He began his undergraduate studies in 1984 at Boğaziçi University Electrical Engineering Department. The same year, he enrolled to Boğaziçi University Skin and Scuba Diving Club (BÜSAS), and got the SCUBA diving certificate. He became an active member of the Club and started Turkish Navy Frogman Course. He completed the course with outstanding degree and was assigned as Diving Instructor of the BÜSAS. In 1989, he received his BS degree in Electrical Engineering from Boğaziçi University. The same year, he got the University President Award due to his success on both academic and extracurricular activities. In 1990, he took part in the first high altitude diving expedition to 2200 m. He enrolled in MS studies in Boğaziçi University Biomedical Engineering Institute the same year. In participated both diving and planning phases of the following High altitude diving expeditions on Mt Kaçkar and Mt Süphan 1992. He completed his MS degree in 1992, in Biomedical Engineering Institute at Boğaziçi University. The same year he started his doctoral studies in the same Institute. In 1993, he got a research grant from European Council for Higher Education for the animal experiment phase of his thesis to be carried out in SINTEF UNIMED, Section for Extreme Work Environment, Trondheim, Norway. In 1994, he started manned testing stage of the thesis, in Boğaziçi University.

The work presented in this dissertation was started in September 1992 and completed in March 1999. It was supported by Boğaziçi University Foundation, Turkish Navy, Quicksilver, Denizbank, STFA Marine Construction, DHL Worldwide Express, Istanbul Medical Faculty Department of Marine and Underwater Medicine, Unilever, Nivea, Karanlık Oda, Banvit, AN-PA, Gerçal Marine, Raks, Yılmaz Balıkadam, Endiksan, Outdoor, Quantum, SINTEF UNIMED Section for Extreme Work Environment and Boğaziçi University Research Fund. The resulting publications are listed in the following page.

LIST OF PUBLICATIONS

Aydın, S., Ş. Aktaş, S.M. Egi and M. Çimsit, "Altitude Dive Performed at 3412 m," *Proceedings of Eighteenth Annual Meeting of European Underwater and Biomedical Society*, pp. 135-137, Basel, 1992.

Egi, S.M., Development of a software library for comparative studies of DCS. *Proceedings of Twentieth Annual Meeting of European Underwater and Biomedical Society*, pp. 484-489, Istanbul, 1994.

Egi, S.M., "Estimation of Oxygen Window During and After Altitude Exposures," *Proceedings of Twentieth Annual Meeting of European Underwater and Biomedical Society*, pp. 135-139, Istanbul, 1994.

Egi, S.M., O. Eftedal, S. Koteng, I. Holmen and A.O. Brubakk AO, "Yüksek irtifa dekompresyon hastalığı sınırının yavru domuzların pulmoner atardamarındaki kabarcıkların sayımı ile belirlenmesi (Investigation of altitude decompression sickness threshold by pulmonary artery bubbles counts of pigs, in Turkish)," *Proceedings of 1st BIYOMUT*, pp. 212-215, Istanbul, 1994.

Egi, S.M., Ş. Aktaş, Y. Bahadırlar, F. Yeşilleten and O. Eftedal, "Kaçkar'94: Field Tests of Altitude Dive Tables Based on an Alternative Method of Hypobaric Extrapolation of Decompression Sickness Boundary," *Undersea Hyperbaric Med*, Vol. 22 (suppl), pp. 67-68, 1995.

Egi, S.M., Ş. Aktaş, F. Yeşilleten and O. Eftedal, "The Effects of Short Term Altitude Acclimatization on the Bubble Formation," *Proceedings of Twenty-first Annual Meeting of European Underwater and Biomedical Society*, pp. 68-73, Helsinki, 1995.

Yeşilleten, F., S.M Egi. and Y. Ülgen, "Multisite Multifrequency Measurement and Analysis of Bioimpedance Changes at High Altitude," *Proceedings of Ninth ICEBI*, pp. 259-263, Heidelberg, Germany, 1995.

Egi, S.M. and A.O. Brubakk, "Diving at Altitude: A Review of Decompression Strategies," *Undersea Hyperbaric Med*, Vol. 22(3), pp. 289-300, 1995.

Egi S.M. and Ş. Aktaş. "Diving at Altitude: Results of Four Expeditions," *Proceedings of the 1st International Tunisian Meeting on Diving and Hyperbaric Medicine*, p. 15, Tunusia, 1996.

Egi, S.M., "Computation of Dive Tables Using Continuous Tissue Time Constants," *Proceedings of Twenty-second Annual Meeting of European Underwater and Biomedical Society*, pp. 299-302, Milan, 1996.

Gürmen, M.N., R.A. Gilbert, A.J. Llewellyn and S.M. Egi, "A Population Balance Model for Decompression Sickness," *Proceedings of AICHE Annual Meeting*, Poster 278bb, Session 278, LA, 1997.

Egi S.M. "Yüksek İrtifa Dalışlarında Malzeme Sorunları (Equipment Problems in High Altitude Diving Expeditions, in Turkish)," *Proceedings of 2nd Underwater Science and Technology Meeting, SBT '98*, pp. 10-14, Istanbul, 1998.

Egi S.M. and E. İnelmen, "The Role of Extra-Curriculum Activities in the Life Long Education of Engineers," Accepted for publication in UICEE, 1999.

Egi S.M., Ş. Aktaş, O. Eftedal, N. Gürmen, S. Aydın and A.O. Brubakk, "Computation and testing of no-decompression stop limits for diving at 3500 m altitude," Submitted to Undersea Hyperbaric Med., 1999.

Egi SM and N. Gürmen, "Computation of Decompression Tables Using Continuous Tissue Time Constants," Submitted to Undersea Hyperbaric Med., 1999.