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Severe hypoxemia during apnea in humans: influence of cardiovascular responses

by

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ABSTRACT

When a diving human holds his or her breath, the heart beat slows and the blood vessels constrict in large portions of the body. In diving mammals such as seals, similar responses effectively conserve oxygen for the brain, enabling them to dive very deep and to stay underwater for a long time.

The principal aim of this thesis was to study the biological significance of bradycardia (a slowing of the heart rate) and vasoconstriction during apnea in exercising humans. The question was whether these cardiovascular mechanisms also in humans would temporarily "conserve" oxygen (i.e. temporarily reduce O_2 uptake in muscles etc.) and thus protect the brain from a level of hypoxia that would otherwise cause unconsciousness in a breath-hold diver.

A second aim was to determine the inter-individual variation among the human subjects in terms of the degree of bradycardia during apnea, in order to explore whether the intensity of these cardiovascular responses would make some individuals more fit to survive underwater swimming and apnea than others.

Our results indeed showed inter-individual differences such that a high degree of bradycardia during apnea correlated significantly with higher levels (= better conservation) of arterial oxygen saturation. Thus, the subjects with the lowest heart rates during exercise and apnea had the best preserved saturation measured with earlobe pulse oximetry. Also, we found that the cardiovascular responses to apnea in exercising humans clearly delay the development of hypoxemia by reducing the rate of uptake from the main oxygen store, i.e. the lungs.

We found that stroke volume of the heart was not altered during apnea with air and consequently that the bradycardia was associated with a proportional reduction of the cardiac output. There was a significant correlation between the degree of vasoconstriction and the intensity of the bradycardia in the group of subjects, so that subjects with the largest degree of vasoconstriction also had the largest degree of bradycardia. We also found that when the breath was held with oxygen and there was no hypoxemia, stroke volume was increased and the increase in blood pressure was delayed but reached the same high level as during apnea when hypoxemia developed due to lack of oxygen.

We measured heart rates during static apnea (the ability to hold your breath as long as possible without passing out) in both training and competition. We found that heart rates were significantly higher both before and during competitive apnea than the corresponding control values during training. One of our subjects experienced a hypoxia-induced loss of motor control during the competition. We suggest that there is an increased risk of hypoxic syncope due to the reduced bradycardia during *competitive* apnea, compared to training.

We also report results from experiments on breath-hold diving to 40 m depth, and underwater swimming in a pool, supporting the notion that the heart rate responses to apnea observed under the present laboratory conditions fairly well represent those occurring during actual breath-hold diving.

Keywords: diving response, breath holding, bradycardia, vasoconstriction, hypoxia
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To my grandmother Lena Lindholm for awakening my fascination with science by helping me as a 3 year old child to raise tadpoles and catch frogs at her estate Tuna.

Warning:
Breath-holding activities are inherently dangerous and should not be done without proper training and supervision. The experiments described in this thesis were done under medical supervision on healthy subjects.

LIST OF PUBLICATIONS

This thesis is based in the following papers which will be referred to in the text by their roman numerals:

I Lindholm P, Sundblad P and Linnarsson D. Oxygen-conserving effects of apnea in exercising men. J Appl Physiol 87: 2122-2127, 1999

II Lindholm P and Linnarsson D. Pulmonary gas exchange during apnoea in exercising men. Eur J Appl Physiol 86: 487-491,2002

III Peter Lindholm, Jessica Nordh and Dag Linnarsson. Role of hypoxemia for the cardiovascular responses to apnea during exercise. Am J Physiol Regul Integr Comp Physiol published June 20, 2002

IV Peter Lindholm, Jessica Nordh and Mikael Gennser. Effects of competition on heart rate during apnea in breath-hold divers. Submitted 2002

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CONTENTS

LIST OF ABBREVIATIONS

$(a\text{-}v)DO_2$	Arterio-venous oxygen difference
BTPS	Body temperature and pressure saturated
CO	Cardiac output
ECG	Electrocardiogram
HR	Heart rate
MAP	Mean arterial pressure
$PACO_2$	Mean alveolar carbon dioxide pressure
PAO_2	Mean alveolar oxygen pressure
$P_{ET}CO_2$	End-tidal carbon dioxide pressure
$P_{ET}O_2$	End-tidal oxygen pressure
R	Gas-exchange ratio
RV	Residual volume
SaO_2	Arterial oxygen saturation
SD	Standard deviation
SEM	Standard error of the mean
STPD	Standard temperature and pressure dry
SV	Stroke volume
SvO_2	Venous oxygen saturation
TPR	Total peripheral resistance
TTI	Transthoracic impedance
VC	Vital capacity
W	Watt

1 INTRODUCTION

Two quotes from a review in the Handbook of Physiology 1996 accurately define the scientific background of this thesis (Lin and Hong 1996):

"…many diving animals seem to have mechanisms that conserve O_2 during breath-hold diving. Although these animals are most often engaged in short, shallow, aerobic dives, they occasionally perform very deep, long dives in which extreme bradycardia, peripheral vasoconstriction, marked reduction in cardiac output, and constant blood pressure are observed. As a result, O_2 consumption decreases markedly, prolonging dive time. Whether such O_2-conserving mechanisms exist in humans is not known..."

"…an O_2-conserving diving reflex in humans adapted to diving. However, the existence of such a reflex is still obscure and more solid data are needed."

A description of breath-hold diving and bradycardia can be found in Diving and Asphyxia on page 65-66 (Elsner and Gooden 1983):

"Perhaps one of the earliest allusions to a cardiovascular response to breath-hold diving in man is found in a book of travels in the Northern Sahara by Colemieu cited by Heller, Mager & von Schötter (1900). The author describes a group of desert dwellers who dive for the purpose of maintaining their supply of fresh water. In this account the author mentions a diver's pulse rate before and immediately after diving.

The water-supply is obtained from artesian wells which are up to 130 feet in depth. The 'eye' of these wells often gets stopped up with sand, brought up from below by the spring or blown in from above. The difficult and dangerous work of clearing the 'eye' is carried out by a guild of divers. A single diver brings up as much sand as he can in three to four minutes. Not infrequently a diver loses his life over his work. The decent and ascent are made by means of ropes which are let down the well. The diver stops up his ears with wax, and, getting into the water, waits a while to get used to the temperature. He then gives the signal, fills his lungs as much as he can with a couple of breaths, and sinks under. His comrades can follow his movements by the two ropes which reach to the bottom. Three minutes and two seconds have already gone by, and one is beginning to get anxious, when he rises to the surface half asphyxiated and almost unconscious. His comrades grip him and hold him while he gets his breath, then he climbs out and goes and warms himself by the fire, while the next takes his turn. The young men of the guild seem strong and healthy, the old lean and straight-chested, but they stay under longer and suffer less. The young are too hasty, and that tells against them. The pulse is noted as being diminished in frequency- e.g., 86 before the decent, and 55 immediately after the ascent."

1.1 PHYSIOLOGICAL CONCEPTS IN APNEA RESEARCH.

1.1.1 Oxygen conservation

For the purpose of this thesis O_2 conservation is defined as a temporary postponement of the uptake of O_2 from the lungs and other O_2 stores, and an associated slowing of the rate of arterial desaturation, resulting in a prolongation of the period until vital functions are threatened by hypoxia. We do not attempt to study any metabolic adaptations that might reduce total O_2 need. The possibility of a reduced metabolism during apnea in humans has not been shown and cannot be studied with the methods used in this thesis.

1.1.2 Diving response

The diving response (in some literature referred to as the diving reflex) is a combination of vasoconstriction and bradycardia and has been studied in both humans and other animals. It is mainly elicited by the respiratory arrest *per se*, but is also influenced by multitude of other factors such as face immersion, hypoxemia, and hypercapnia (Hong 1987; Manley 1990). The basic response pattern is similar regardless of whether apnea is done in dry conditions or the subject immerses the upper part of the face in water during apnea (Stromme et al. 1970; Manley 1990). For the purpose of this thesis we use the term “diving response” for the cardiovascular responses that develop during apnea, also in the studies where no face immersion or diving is involved.

1.2 PREVIOUS STUDIES OF THE DIVING RESPONSE

When a diver is swimming under water (breath-holding), oxygen stores in the lungs and blood will be consumed. When oxygen partial pressure reaches a critically low level in the brain, the diver will become unconscious.

The diving response as demonstrated in diving mammals postpones the oxygen consumption during apnea, and acts by reducing the amount of blood that is pumped out into the body in such a situation. The residual blood flow is mainly targeted to the brain and heart while the rest of the body has to manage with little or no oxygen delivery for a short while. The energy for muscle work is then temporarily supplied by anaerobic mechanisms, such as depletion of phosphagen stores and production of lactate. The result of this is that the blood and pulmonary oxygen stores can provide oxygen to the brain for a much longer period of time. The diving response has been shown to extend diving time in diving mammals; Weddel seals dive 95% of their dives within the aerobic diving limit, but for long dives or if the access to the surface is hampered, there is profound bradycardia and lactate production. Anaerobic dive times can be 4 times longer than dives within the aerobic diving limit (Butler and Jones 1997; Kooyman et al. 1999).

Studies of diving humans show that there is bradycardia during apnea (Scholander et al. 1962; Lin and Hong 1996; Schagatay and Andersson 1998), and one consequence is a reduction in cardiac output (Bjertnaes et al. 1984; Ferrigno et al. 1986). The magnitude of this bradycardia varies greatly between studies and individuals (Manley 1990; Schagatay and Andersson 1998).

In 1965 Wolf et al. (Wolf et al. 1965) performed a study on breath-holding in resting human subjects. During apnea there was bradycardia and the experimenter managed to abolish the bradycardia during apnea by harassing the subjects. This study showed a slightly larger desaturation of arterial blood and no bradycardia when the subjects were exposed to the mental stress of harassment while performing apneas. They also found that plasma lactate levels increased less compared to the control apneas with bradycardia. Andersson and Schagatay (Andersson and Schagatay 1998) studied resting subjects during apnea with and without face immersion. Face immersion produced lower heart rates during apnea and arterial oxygen saturation decreased more during the dry apneas. However, in none of these studies did saturation decrease more than 4 per cent units from the eupneic control and was thus probably not in the range that would be expected in a physically active diver.

Signs of oxygen conservation in humans were also shown in a study by Feretti et al. (Ferretti et al. 1991), who examined three members of a family of elite divers (Enzo Maiorca and his daughters). Data showed increased anaerobic metabolism in those divers compared to control subjects during apnea, thus suggesting a shift in metabolism during extreme dives so that oxygen presumably would be saved for vital organs while other parts of the body sustained metabolism anaerobically.

1.3 EXERCISE AND THE DIVING RESPONSE

Would these cardiovascular responses during apnea (bradycardia and peripheral vasoconstriction) work in humans to increase the amount of time a person can go without breathing before brain hypoxia causes unconsciousness?
The previous studies on this subject have been performed during resting conditions (Wolf et al. 1965; Andersson and Schagatay 1998).

In designing the present studies, where we employ an experimental model with *exercising* humans, we reasoned as follows:

- During rest there is very limited blood flow and O_2 delivery to many peripheral tissues such as muscle and skin. From a teleological standpoint it could be argued that the physiological need for conserving oxygen during apnea would arise during physical activity rather than during rest, since in both animals and humans apnea is normally associated with underwater swimming.
- Previous studies of resting subjects might not have been able to reveal the full potential of cardiovascular responses during apnea, because the degree of hypoxia that has been attained has not been sufficiently severe. During exercise, however, the metabolic demands are elevated by an order of magnitude, with a resulting rapid and severe arterial desaturation during apnea.

Thus, by studying apnea during exercise it might be possible to elucidate whether the cardiovascular responses during apnea are essential for preventing unconsciousness in humans. Also the role of hypoxemia per se could be studied within a range relevant for the physiologically active swimmer.

1.4 ARE SOME INDIVIDUALS BETTER ADAPTED TO SURVIVE SWIMMING UNDER WATER?

Since the stores of oxygen are vital for long dives and the lung is the major O_2 store, a large lung volume is naturally beneficial for a breath-hold diver, as well as a good swimming technique that keeps oxygen consumption low. The diving response (in terms of bradycardia during resting apnea) has been shown to be highly variable among humans (Manley 1990; Schagatay and Andersson 1998). The variability in resting apneic bradycardia has been correlated to diving experience and breath-holding ability (Schagatay and Andersson 1998). If this bradycardia acted to conserve oxygen during exercise and apnea, the strength of the response would be a factor together with lung volume and swimming economy to render some humans more likely to survive long breath-hold dives.

1.5 COMPETITIVE APNEA AS AN EXPERIMENTAL MODEL

Breath-hold diving has been a means of gathering food for thousands of years. Breath-hold diving of the Ama of Japan was chronicled in the Gishi-Wajin-Den 268 B.C, (Nukada 1965), and spearfishing competitions have been held for decades. Among the breath-hold divers, some people focused mainly on setting deep diving records; (most famous are Enzo Maiorca (first to 50 m) Jaques Mayol (first to 100 m), and Umberto Pelizzari (first to 150 m). During recent years, and as the material of this thesis has been collected, apnea has developed into a sport with competitors from all over the world participating in world championships.

From the perspective of a scientist with interest in the physiologic responses of humans to combined apnea and physical activity there is much to be learnt from the experience accumulated within the community of competitive breath-hold divers. This is so especially for safety aspects and risk assessment but also for their personal observation of their own physiological responses and their assessment of procedures for optimal performance. Also, training and competition in various types of apnea and underwater swimming can be used as an experimental model, providing data can be collected with scientifically established methods without interfering with the athlete's performance.

The following models of competition are practiced internationally:

1. Rest and apnea *"Static Apnea"*:
This is practiced in a swimming pool where the athletes try to hold their breath as long as possible while floating motionlessly; the current world records are 8.06 minutes (men) and 6.16 minutes (women).
Similar laboratory analogues have been studied intensely, mainly dry or with face immersion (Hong et al. 1971; Manley 1990; Lin and Hong 1996; Schagatay and Andersson 1998; Ferretti 2001).

2. Exercise and apnea *"Dynamic Apnea"*:
The athlete tries to swim as far distance as possible in a pool without breathing, and with or without fins.

3. Rest, apnea and pressure *"No Limits"*:
The diver uses a weight to get down into the depths and an airfilled lifting bag to get back to the surface. This category has been extensively studied on Enzo Maiorca and his two daughters (Ferretti et al. 1991; Ferrigno et al. 1991; Ferrigno et al. 1997).

4. Exercise, apnea and pressure *"Constant weight"*:
This is when the athlete gets down to and up from the depths by swimming with fins; the current world records are 87 m (men) and 70 m (women). Swimming is the most practiced form of breath-hold diving, both in spearfishing and the sport of apnea.

In competitions, a diver that surfaces with any observable signs of hypoxia will be disqualified and not allowed to make any further attempts that day.

About half of the volunteers for the studies in this thesis practice apnea as a sport, and included among them are many Swedish record-holders and also the Swedish national team from 2001, who took the bronze medal in the world championships.

2 AIMS

"To make plans and project designs brings with it many good sensations; and whoever had the strength to be nothing but a forger of plans his whole life would be a very happy man: but he would occasionally have to take a rest from this activity by carrying out a plan- and then comes the vexation and sobering up." Friedrich Nietzsche

The principal aim of this thesis was to study the biological significance of bradycardia and vasoconstriction during apnea in exercising humans. The question was whether these cardiovascular mechanisms would temporarily "conserve" oxygen (i.e. temporarily reduce O_2 uptake in muscles etc.) and thus protect the brain from a level of hypoxia that would otherwise cause unconsciousness in a breath-hold diver.
A second aim was to determine the inter-individual variation among the human subjects in terms of the degree of bradycardia during apnea, in order to explore whether the intensity of these cardiovascular responses would make some individuals more fit to survive underwater swimming and apnea than others.

More specifically the aims were:

-to show whether bradycardia and vasoconstriction during apnea are of importance for slowing the rate of arterial desaturation, thereby preventing unconsciousness in humans.

-to confirm that a slowed rate of arterial desaturation is the result of a slowing of the O_2 uptake in the lungs in individuals with a strong bradycardic response to apnea.

-to quantify the degree of vasoconstriction and reduction of cardiac output during apnea in exercising humans.

-to analyze whether the individuals with the strongest bradycardic responses also had the strongest vasoconstrictive responses during apnea, with or without concomitant hypoxemia.

-to determine whether or not hypoxia is a main factor in determining the cardiovascular responses to apnea.

-to determine whether the likely more stressful situation during a competition results in a smaller reduction in heart rate in response to apnea than during training.

-to determine whether the heart rate responses to apnea during actual diving in field conditions are accurately reflected during dry and wet laboratory simulations.

3 MATERIAL AND METHODS

3.1 SUBJECTS

The subjects in the first study were a random selection of medical student volunteers. Paper II and III included many amateur breath-hold divers among other volunteers. Study 4 was done with amateur breath-hold divers competing in the Swedish Apnea Championship 2001.

There was a systematic selection of volunteers who were able to hold their breath during the sometimes quite strenuous experiments. This was commented upon by one reviewer (paper II), who found it "utterly remarkable that the subjects held their breath as long as they did". In total, paper II-III, three volunteers had to be excluded from data interpretation due to their inability to perform apneas of sufficient duration to make evaluation useful.

3.2 MEASUREMENTS

3.2.1 Composition and flow of respired gases

The system used for gas supply and respiratory measurements has been described previously (Verbanck et al. 1996). Briefly, the system allowed continuous measurements of respired gas flow and concentrations, and rebreathing with preset bag volumes. Gas analysis was performed with a quadrupole mass spectrometer (QMG 420, Balzer, Lichtenstein) modified for respiratory measurements (Innovision AS, Odense, Denmark). The gas analyzer was calibrated against mixtures of known concentrations (AGA Gas AB, Lidingö, Sweden).

Respired flow was determined with a bi-directional ultrasonic flowmeter (Buess et al. 1986).

Steady-state $\dot{V}O_2$ and $\dot{V}CO_2$ before apnea was determined from the product of respired flow and O_2 and CO_2 fractions to obtain inspired and expired volumes of O_2 and CO_2. Net inspired O_2 volume and expired CO_2 volume were determined from a series of complete breaths for approximately 50 s ending 10 s before apneas (Linnarsson 1974). In addition, the pulmonary O_2 and CO_2 exchanges during apnea were computed as: $[RV*F_i + V_b*F_b] - [(RV+V_E)*F_f]$ (Liner et al. 1993), where F_i and F_f are the end-tidal gas concentrations during expirations to residual volume (RV) before (initial) and after (final) apnea, V_b and F_b are the volume and gas fraction of the gas inspired from the bag before apnea, and V_E is the volume expired to RV immediately after apnea. End-tidal readings obtained at RV were considered sufficiently representative for the over-all gas remaining in the lungs at RV. This assumption is supported by the generally accepted method to determine lung diffusing capacity from end-tidal samples during expiration to RV (American Thoracic Society 1987)(paper II).

Subjects also performed two 15 s rebreathing maneuvers for determination of cardiac output (CO) from R22 uptake (Bonde-Petersen et al. 1980), one after the

second apnea and the other after the fourth apnea using a normoxic gas with 1.6% $CHClF_2$ (Freon 22, R22) and 5% helium in nitrogen (paper III).

Vital capacity (VC) was determined for each subject when sitting on the cycle ergometer. The largest value out of 3 trials was adopted (paper III).

Residual volume (RV) was determined with a helium dilution method where subjects expired to RV and then rebreathed a standardized gas volume containing 5% He.

3.2.2 Heart rate

During the "dry" experiments an electrocardiogram (ECG) was acquired from chest electrodes and a combined amplifier and beat-by-beat tachometer (Biotach ECG, mod 20-4615-65, Gould Inc., Valley View, OH, USA). During arrythmias, intervals between systolic blood pressure peaks were measured to determine beat-by-beat HR (Paper I-III).

Heart rate during swimming and static apnea was measured with the Polar^{tm} NV system which consists of an electrode band across the chest and a watch with data storage capability worn on the wrist. Heart rate was stored as R-R intervals and data were analyzed with Polar Precision Performance 2.0 and Microsoft Excel (Paper IV).

3.2.3 Arterial oxygen saturation

Arterial oxygen saturation (SaO_2) was measured in the earlobe with a beat-by-beat pulse oximeter (Satlite trans, Datex Engstrom, Finland). The subject's earlobe was rubbed with an ointment containing capsaicin to enhance local blood flow (Benoit et al. 1997). In a comparison between the results of invasive measurements and those obtained with a technique which was identical to that used in the present study, Benoit et al. found an agreement within 2 % units (Benoit et al. 1997).

3.2.4 Blood pressure

Blood pressure was measured invasively in six subjects in paper I; the rest of the blood pressure measurements in paper I and in paper III were done non-invasively.

For invasive blood pressure measurement a 20-gauge catheter was inserted in the radial artery under local anesthesia with lidocaine hydrochloride, the radial artery catheter was connected to a disposable transducer (Smith Industries Medical Systems, Ref 1768, Kirchseeon, Germany) aligned to the horizontal level of the 4th intercostal space (heart level), and connected to an amplifier/monitor (type SMK 154-9 Hellige Servomed AG, Germany).

Non-invasive blood pressure measurements were done with a photoplethysmographic finger-cuff method (Finapres 2300, Ohmeda, Englewood, CO, USA). The Finapres device has previously been shown to provide continuous recordings of mean arterial pressure in close agreement with concomitant invasive recordings (Idema et al. 1989).

3.2.5 Other measurements and equipment

Transthoracic impedance (TTI) was recorded from two pairs of tape electrodes around the neck and lower thorax (Tedner 1978).
Subjects performed upright dynamic leg exercise on an electrically braked cycle ergometer (Type 380 B, Siemens-Elema AB, Stockholm, Sweden).

3.3 DATA ACQUISITION AND ANALYSIS

3.3.1 Hardware and software

All measurements were recorded with a computer-based data collection system (Biopac Systems Inc., Goleta, CA, USA). Calibrated analogue signals were A/D converted and recorded at 200 Hz per channel, and subsequently stored and analyzed with an AcqKnowledge 3.2.6 software package (Biopac Systems Inc., Goleta, CA, USA).

3.3.2 Stroke volume and cardiac output

Stroke volume (SV) was calculated in paper III from ten beats during baseline before apnea, and during the last ten beats of each apnea. SV was determined with a modification of the impedance method originally described by Kubicek et al. (Kubicek et al. 1970). Thus SV estimates were obtained from the maximal first derivative of the impedance signal together with ejection time, which was assessed from the contour of the second derivative of the blood pressure curve (Soderstrom et al. 1999). The impedance estimates of stroke volume were calibrated during steady-state exercise using simultaneous rebreathing measurements of cardiac output and impedance cardiography. The calibration factor obtained in this way for each individual was then used to calculate SV from transthoracic impedance and blood pressure tracings during apnea. Cardiac output (CO) was obtained as SV*HR, and total peripheral resistance (TPR) as MAP/CO.

3.3.3 Statistics

Differences between conditions were analyzed using a paired Student´s t-test for dependent variables. Also, multiple regression analysis and ANOVA were used (Statistica, Statsoft, Tulsa, OK, USA). Significance was accepted at the 5% level.

3.4 PROCEDURES

Generally, in papers I-III subjects performed steady-state leg exercise for about one hour and performed repeated apneas and rebreathing maneuvers. Apneas were of fixed durations (paper II) or as long as possible (papers I and III). In study IV subjects were studied as they performed static apnea in a swimming pool. For detailed protocols of the experiments, please refer to papers I-IV.

4 ETHICAL AND METHODOLOGICAL CONSIDERATIONS

4.1 ETHICAL APPROVAL

All the experimental protocols were conducted in conformity with the principles of the Declaration of Helsinki and had been approved by the Ethics Committee of Karolinska Institutet. All subjects gave their informed consent after receiving a description of the procedure and potential risks involved.

4.2 SCIENTIFIC JUSTIFICATION

We reasoned that if the diving response is of any importance in humans it has to serve to increase the ability to stay conscious as long as possible during apnea situations. In order to show this experimentally we wanted to bring the subjects to as severe hypoxemia as possible within safety margins based on previous experimental studies and practical experience.

4.3 SAFETY PRECAUTIONS

The equipment used to monitor hypoxemia was a pulse oximeter with an earlobe probe. We chose an ear probe instead of the more common finger probe to measure SaO_2 for several reasons: the circulation time from the lungs to the earlobe is about 3-6 seconds (Blumgart and Rowlands 1971), and thus more representative of the actual hypoxemia in the brain, whereas a finger probe would have a delay time of 10-30 seconds (Bjurstedt and Wigertz 1971) depending on work load and cardiac output. Also, since we include strong vasoconstriction in our hypothesis, it would seem improper to measure hypoxemia in a tissue with supposedly severely restricted circulation. Furthermore, in a methodological study of pulse oximeters where the authors used sleep apnea patients, data suggested that finger probes underestimate the degree of arterial desaturation (West et al. 1987). To circumvent such problems in the present study we ensured adequate blood flow in the earlobe by local application of a vasodilating ointment (Benoit et al. 1997).

The manufacturer's specification is that the pulse oximeter is valid down to 50% O_2 saturation. A study by Benoit et al. (Benoit et al. 1997) has confirmed this down to a saturation of 57% with simultaneous blood gas analyses.

4.4 PREVIOUS RELEVANT EXPERIMENTS WITH SEVERE HYPOXEMIA

4.4.1 Aviation and altitude

The most reliable data on the effects of acute hypoxia is available in the literature of aviation medicine. Macmillian reports a "time of useful consciousness" of 40 seconds with an explosive decompression to an altitude of 10668 m (35000 ft) while breathing air (Macmillian 1988). Ambient pressure is then 179 mmHg (23.9 kPa). Alveolar PO_2 would be approximately $(179-47_{H2O}-30_{CO2})*0.21= 21$ mmHg (2.8 kPa). Depending on PCO_2 ranging 20-40 mmHg (2.7-5.3 kPa), PO_2 will range 24-19 mmHg (3.2-2.5 kPa).

(Ernsting et al. 1988) "*Consciousness is lost when the jugular venous oxygen tension is reduced to 17-19 mmHg. The corresponding cerebral arterial oxygen tension varies with cerebral blood flow, which itself depends upon the arterial tensions of oxygen and carbon dioxide. Thus the arterial oxygen tension that produces a jugular venous tension sufficiently low to cause unconsciousness can lie between 20 and 35 mmHg depending on the degree of hypocapnia. Accordingly, although consciousness is usually lost when the alveolar oxygen tension is reduced to 30 mmHg or below for a significant period of time, it is possible to lose consciousness with an alveolar oxygen tension as high as 40 mmHg if there is marked hyperventilation, or to retain consciousness at an alveolar oxygen tension as low as 25 mmHg if there is no hypocapnia*."

However, during apnea the level of hypoxia will not be stable, and thus the exact duration of "useful consciousness" is difficult to predict. An important implication of Ernsting's reasoning is that hypocapnia impedes oxygen transport to the brain at two levels; partly by reducing brain perfusion (Sokoloff 1996) and partly by shifting the O_2 dissociation curve of hemoglobin to the left (*c.f.* paper II).

4.4.2 Diving and breath-holding

Hong et al. report PAO_2 of 24-36 mmHg (3.2-4.8 kPa) with corresponding $PACO_2$ of 51-66 mmHg (6.8-8.8 kPa) without any subject losing consciousness (resting, apnea with intermittent rebreathing) (Hong et al. 1971). Ferretti et al. (Ferretti et al. 1991) report exhaled PO_2 of 29 and 28 mmHg (3.9 and 3.7 kPa) after resting apneas of 270 and 300 seconds, respectively.

Hyperventilation followed by apnea during exercise has been reported to produce convulsions, PAO_2 was measured to values between 22 and 26 mmHg (2.9 and 3.5 kPa) (Åstrand 1960). The same author also did tests without preapnea hyperventilation (and thus higher end apnea CO_2). These tests did not cause convulsions at a PAO_2 of 26 mmHg (3.5 kPa).

In their classic work showing the physiological basis of shallow water blackout (ascent blackout), Lanphier and Rahn describe one subject hyperventilating and then exercising lightly on an ergometer cycle during a chamber simulated dive to 2 ATM (10m): "*upon ascent, his PO_2 dropped to 24mmHg, O_2 uptake ceased, and there is evidence that O_2 was being extracted from the blood. Impairment of consciousness occurred.*" (Lanphier and Rahn 1963)

A PO_2 of 25 mmHg (3.3 kPa) will correspond to a SaO_2 of 40-50% in resting subjects (depending on PCO_2 70-39 mmHg (9.3-5.2 kPa)) and a PO_2 of 30 mmHg (4.0 kPa) will correspond to SaO_2 values of 50-60% (PCO_2 70-39 mmHg (9.3-5.2 kPa)) (a higher CO_2 will correspond to a lower SaO_2 for a given value of PO_2) (Rahn and Fenn 1955).

4.4.3 Other studies on hypoxemia

It is common clinical knowledge that cardiac arrest lasting longer than 4-5 minutes leads to irreversible brain damage (Siesjö 1987). This is sometimes misinterpreted to

mean that conscious breath-holding of 4 minutes (or more) also leads to brain damage (personal observation).

Weeks of high altitude climbing is known to cause at least temporary signs of impaired psychomotor and mental abilities in humans (Raichle and Hornbein 2001). There is of course a long exposure to severe hypoxia at those altitudes. The current opinion is that hypoxia alone cannot explain the residual cognitive deficits in high altitude climbers. As long as there is blood flow through the brain, severe hypoxemia will not cause cellular injury even though relatively modest hypoxia in combination with ischemia causes injury. (Simon 1995; Raichle and Hornbein 2001). However, during high altitude climbing, hematocrit increases due to increased production of erythrocytes, and dehydration also often results from the strenuous work of climbing high mountains. Thus reports of cerebral thrombi in high altitude climbers could give a plausible explanation to the brain damage independent of direct effects of hypoxia (Severinghaus 2001).

Rossen et al. performed a study on transient ischemia (Rossen et al. 1943) where blood flow to the brain of human subjects was stopped until they passed out. No residual effects of brief unconsciousness from brain ischemia were observed but only short-term effects were studied.

The best studied transient brain ischemia and hypoxemia in human subjects is the acceleration-induced loss of consciousness (G-LOC) that occurs in military aviation, both in flight and during centrifuge training of pilots to endure high +Gz. G-LOC is a short loss of consciousness lasting 10-15 seconds, and could provide some insights into the hypoxic syncope or loss of motor control that is associated with apnea as a sport. The current conclusion from G-LOC research in humans is that there are no adverse neurological effects (Whinnery 1991). This might suggest that occasional syncope when performing apnea should not lead to brain damage (unless near-drowning is involved).

Also, Jones (Jones 1991) reports:

"...we do have one modern followup report on four individuals who underwent extensive G-LOC experiences in the 1940's (Wood et al. 1947). Three of these volunteers had complete followup physical, neurological, imaging (CT, MRI) and neuropsychological testing 40 years later, in 1988 (Wood et al. 1988). No adverse CNS effects attributable to their centrifuge experiences were noted by the examining flight surgeon (Younge, personal communication, 1989)."

4.5 IMPLICATIONS FOR THE PRESENT EXPERIMENTAL DESIGN

Our subjects were not allowed to hyperventilate before apnea in exercise experiments (paper I-III). Considering the above mentioned data we set the limit to abort a breath-hold at 50% O_2 saturation in our ethics application. Some subjects with a combination of high apnea tolerance and rapid arterial desaturation had to be told to start breathing when SaO_2 fell rapidly into the 55-50% range. As seen in Fig 2 (subject A) and Fig 9 (subject shown in top panels), SaO_2 levels continued to fall somewhat below 50 % before rapidly increasing as a result of resumed breathing. There were no objective signs of hypoxia in the subjects except discoloration of the skin and lips, but

some subjects reported some dizziness or clouding of the mind towards the end of apneas with severe hypoxemia.

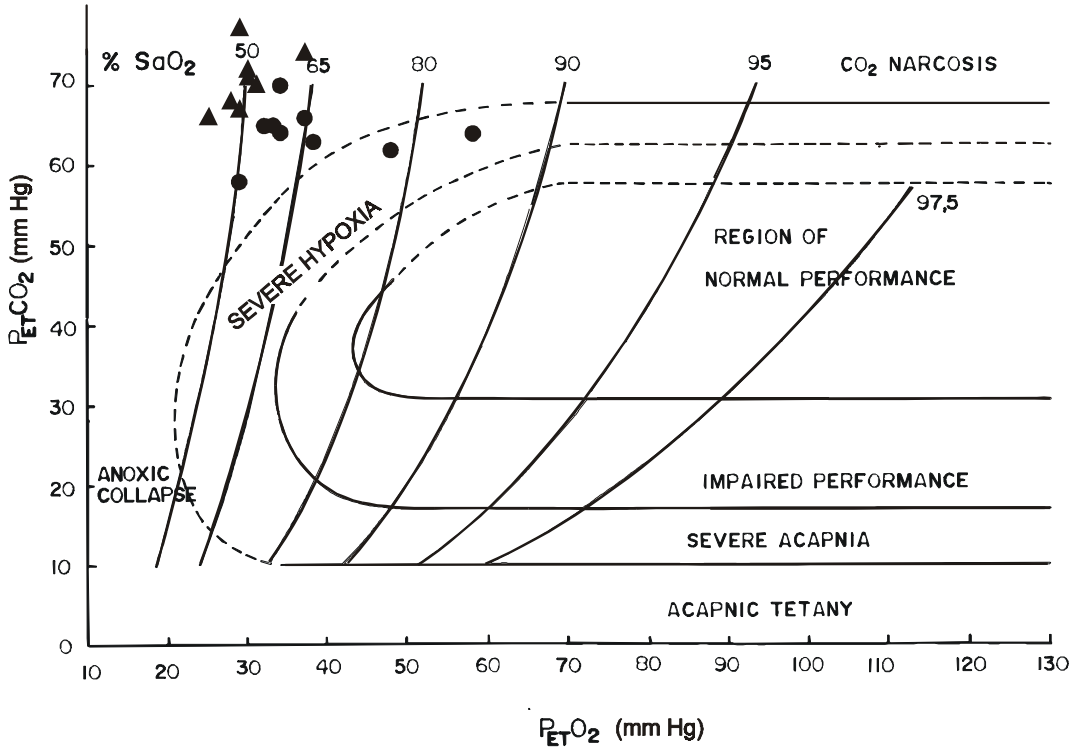

Fig 1 The O_2-CO_2 diagram (Rahn and Fenn 1955) with included SaO_2 isopleths calculated for humans at sea level taken from Feretti et al (Ferretti et al. 1991). Plotted data on $P_{ET}O_2$ and $P_{ET}CO_2$ from the most extreme apnea (●) or rebreathing (▲) from paper I, show that some of our subjects were well beyond severe hypoxia. N=9.

5 HYPERVENTILATION AND APNEA. A THEORETICAL ANALYSIS

"An increase in ventilation out of proportion to any increase in metabolic $\dot{V}O_2$*, therefore resulting in a low arterial* PCO_2*. Reduced arterial* PCO_2 *is therefore a criterion by which to determine whether a subject is hyperventilating or not."* (Whipp 1996).

When the carbon dioxide content in the blood has been reduced by hyperventilation, the drive to breathe is abolished, thus making it possible to hold the breath for a period that may be longer than the time it takes to reach critical hypoxemia (Craig 1961). This is very dangerous for the amateur breath-hold diver and every year accidents occur (sometimes fatal)(Craig 1976).

The apnea athletes, however, always hyperventilate before diving. They use a mode of ventilation that consists of slow and large breaths; approx 4-6 breaths/minute (Maiorca 1987) (personal observation).

Hyperventilation will reduce CO_2 in the body but also increase oxygen stores in both lungs and blood. This is due to more space in the lungs for oxygen when CO_2 is reduced. Also the increased cardiac output associated with a higher respiratory rate will increase venous O_2. Hyperventilation during head-out immersion in water will be more effective due to the higher cardiac output associated with immersion (Chang and Lundgren 1996).

5.1 CALCULATING THE POSSIBLE BENEFITS OF HYPERVENTILATION FOR APNEA DURATION

We use physiological data for a normal male individual.
Consider a man weighing 70 kg with a blood volume corresponding to 7 % of his body weight and a hemoglobin (Hb) value of 160 g/l (Greger and Bleich 1996). Consider a total lung capacity of 8 liters BTPS, and assume the blood distribution to be 25% arterial, 75% venous (Holtz 1996). For volume conversion, BTPS*0.8259 = STPD. The oxygen carrying capacity of Hb is 1.38 ml/g.

Without hyperventilation:
SaO_2 97%, SvO_2 75%, PAO_2 100 mmHg (13.3 kPa).
Blood: ((0.25*97)+(0.75*75))/100*70*0.07*160*1.38=871 ml O_2
Lungs: 8*0.8259*100/760 = 869 ml O_2
Total: 1740 ml O_2 STPD

With hyperventilation
SaO_2 99%, SvO_2 85%, PAO_2 135 mmHg (18.0 kPa).
Blood: ((0.25*99)+(0.75*85))/100*70*0.07*160*1.38=957 ml O_2
Lungs: 8*0.8259*135/760 = 1174 ml O_2
Total: 2131 ml O_2 STPD

For a normal person resting O_2 consumption is approximately 250 ml/min STPD (Shepard 1971).

Theoretically, the amount of apnea time "won" through hyperventilation is: (2131-1740)/250 = 1 minute and 34 seconds. (Note, however, that in this analysis the reduced tolerance to hypoxemia by hypocapnia has not been considered).

5.2 CALCULATING THE THEORETICAL LIMIT FOR BREATH-HOLD DURATION

If we consider a theoretical case of resting apnea, how long could it be possible to hold one's breath? Is it possible to explain the current world record of 8.06 minutes in terms of normal physiology? In the present calculation we use data for a male individual with a physiology well suited for apnea.

We assume that the subject is not stressed by this task and can keep his heart rate at around 40-50 and his metabolism at resting values. We assume that he is completely at rest and that he consumes 250 ml O_2/minute (Shepard 1971). During apnea, O_2 consumption may possibly be lower during the first part (the easy-going phase)(Lin et al. 1974) since the subject is not breathing, and may be higher later on, when there are diaphragmal contractions. For this calculation we assume that overall energy cost is 250 ml/minute.

We assume that the subject's weight is 75 kg; with a blood volume corresponding to 8% of body weight (normal value is 6-8%) (Greger and Bleich 1996) this gives 6.0 liters of blood.

Normal hemoglobin levels in blood range 133-182 g/l (Greger and Bleich 1996). One gram of Hb can carry 1.38 ml O_2. We assume a Hb value of 182 throughout the apnea (including any splenic stores of Hb) (Hurford et al. 1990; Schagatay et al. 2001). Blood with a hemoglobin value of 182g/l can carry 251,16 ml O_2/l blood. Approximately 25% of the blood volume is arterial blood and 75% venous (Holtz 1996).

Our subject's lungs have a residual volume of 1.5 l, a vital capacity of 8,5 l and the ability to pack 2 liters. Thus he has a total gas volume of 12 liters BTPS in the lungs. We also assume that he has a high tolerance for CO_2 and good ability to survive asphyxia down to PAO_2 of 25 mmHg, with a 40% saturation in arterial blood at breaking point.

We consider him to have slow blood flow in muscle, skin etc, and assume a venous saturation of 10% in 25% of the total blood volume. For the rest of the venous blood (50% of total blood) we assume a saturation of 30% at breaking point.
We assume hyperventilation before apnea, giving an O_2 saturation of 100% and 88% in arterial and venous blood, respectively (personal observation). This will also cause PAO_2 to be around 135 mmHg (18.0 kPa) (Ferretti et al. 1991).

Desaturation of arterial blood 100-40=60
Desaturation of venous blood 88-(10*1/3+30*2/3)=88-70/3=88-23=65

Usable Blood stores: ((0.25*60)+(0.75*65))/100*75*0.08*182*1.38=961 ml O2

Usable Lung stores: 12*0.8259*(135-25)/760 = 1434 ml O_2
Total usable oxygen stores: 2395 ml O_2

2395 ml / 250 ml/min = 9.58 = 9 minutes and 34 seconds.

5.2.1 Limitations:

This calculation does not consider tissue oxygen stores, neither does it consider whether it is possible to hyperventilate to such values of hypocapnia before apnea and still produce enough CO_2 to get enough hypercapnia towards the end of apnea to increase the tolerance to severe hypoxemia. The calculation includes assumptions on energy consumption without the cost of breathing and with diaphragmal contractions. We have speculated in a moderate effect of the diving response, limiting blood flow and reducing venous SO_2 to 10% in 25% of the total blood volume. We have not considered whether it is possible to hold ones breath after packing the lungs (Hamilton et al. 1993) without increasing oxygen consumption.

5.3 TRADEOFF BETWEEN BENEFITS AND RISKS WITH HYPERVENTILATION

As pointed out above (under previous relevant experiments with severe hypoxemia) a high CO_2 increases tolerance to low PO_2. Theoretically, the best way to achieve a long apnea would be to hyperventilate to increase O_2 stores but within limits to keep CO_2 as high as possible. Then if the athlete can endure high CO_2 (Schaefer 1965; Davis et al. 1987; Grassi et al. 1994) he can hold his breath to a very low PO_2. Martin Stepanek has the current world record in Static Apnea of 8 minutes 6 seconds. His method of holding his breath includes a high CO_2; he had his first diaphragmal contractions (Lin et al. 1974) after 4 minutes. The following 4 minutes he endured 72 contractions, suggesting a high CO_2 (personal communication July 2002).

CO_2 could therefore have the effect that a subject who can hold his breath for 5 minutes with a high CO_2 becomes unconscious during a shorter apnea after hyperventilating too much.

Dr P.G. Landsberg wrote his thesis on the subject of breath-hold diving and hyperventilation: Hyperventilation: An unpredictable danger to the sports diver (Landsberg 1987) (sports diver=spear fisher), and one of his main conclusions was: "*To prohibit hyperventilation during breath-hold diving, is not a successful safety measure as Lanphier & Rahn have shown that this practice gives a diver an extra 10 to 20 seconds diving time. A strict buddy system and ensuring that the divers are not negatively buoyant will be more effective safety measures. However, the unpredictable nature of the effects of hyperventilation should be explained to the divers who should be encouraged to work out their own individual safe dive profiles using a depth gauge and watch*."

6 PRINCIPAL RESULTS

6.1 OXYGEN-CONSERVING EFFECTS OF THE CARDIOVASCULAR RESPONSES DURING APNEA WITH EXERCISE (PAPER I AND II)

In paper I and II we report results from studies of the impact of the cardiovascular responses on arterial oxygen desaturation and in paper II we determined how the rate of O_2 uptake in the lungs changed with time during apnea. The principal findings are summarized in Fig 2 and 3. There was a significant negative correlation between the rate of arterial desaturation during apnea and the concomitant bradycardic response. Also, in paper II (Fig 2, p 490), we showed that the gradual arterial desaturation during apnea was accompanied by a gradual decline of the O_2 uptake from the lungs to the blood that was larger than could be solely the result of the fall in SaO_2. Thus the O_2 uptake data provided further indirect evidence of a reduction of lung blood flow during apnea. Subsequently, Andersson et al (Andersson et al. 2002) have shown when face immersion is added to apnea during exercise, cardiovascular responses were similar to those reported in paper I and II.

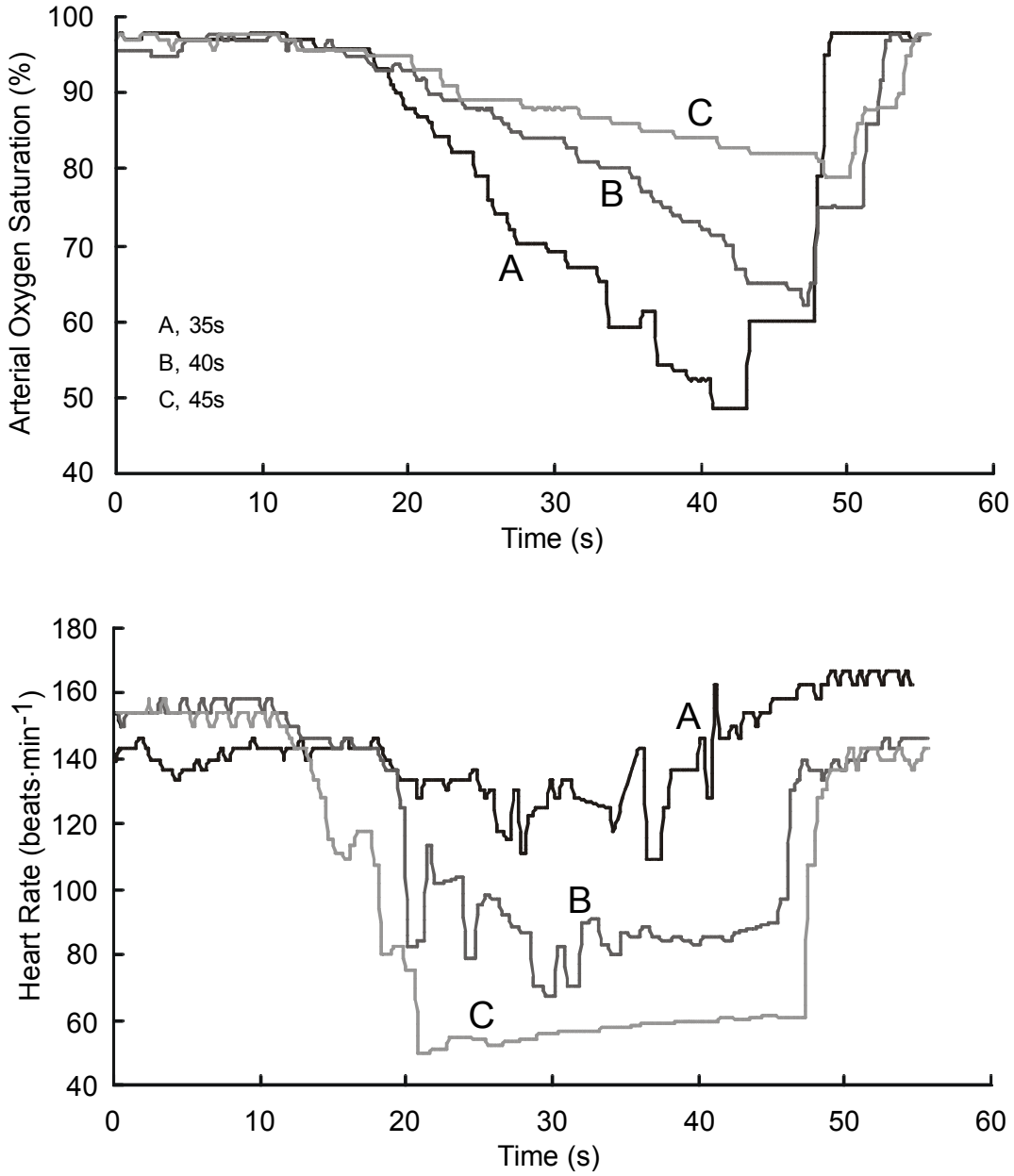

Fig 2 Upper panel: Arterial O_2 saturation as a function of time during combined apnea and leg exercise. Three subjects are shown, who have different rates of arterial desaturation. Apnea durations are shown to the left of the diagram.

Lower panel: Beat-by-beat heart rate in the same subjects as in the upper panel. The reciprocal relationship between the degree of bradycardia and the rate of desaturation is clearly visible. (from paper I and II)

Apnea starts at time zero. Steady-state work load was 120 W.

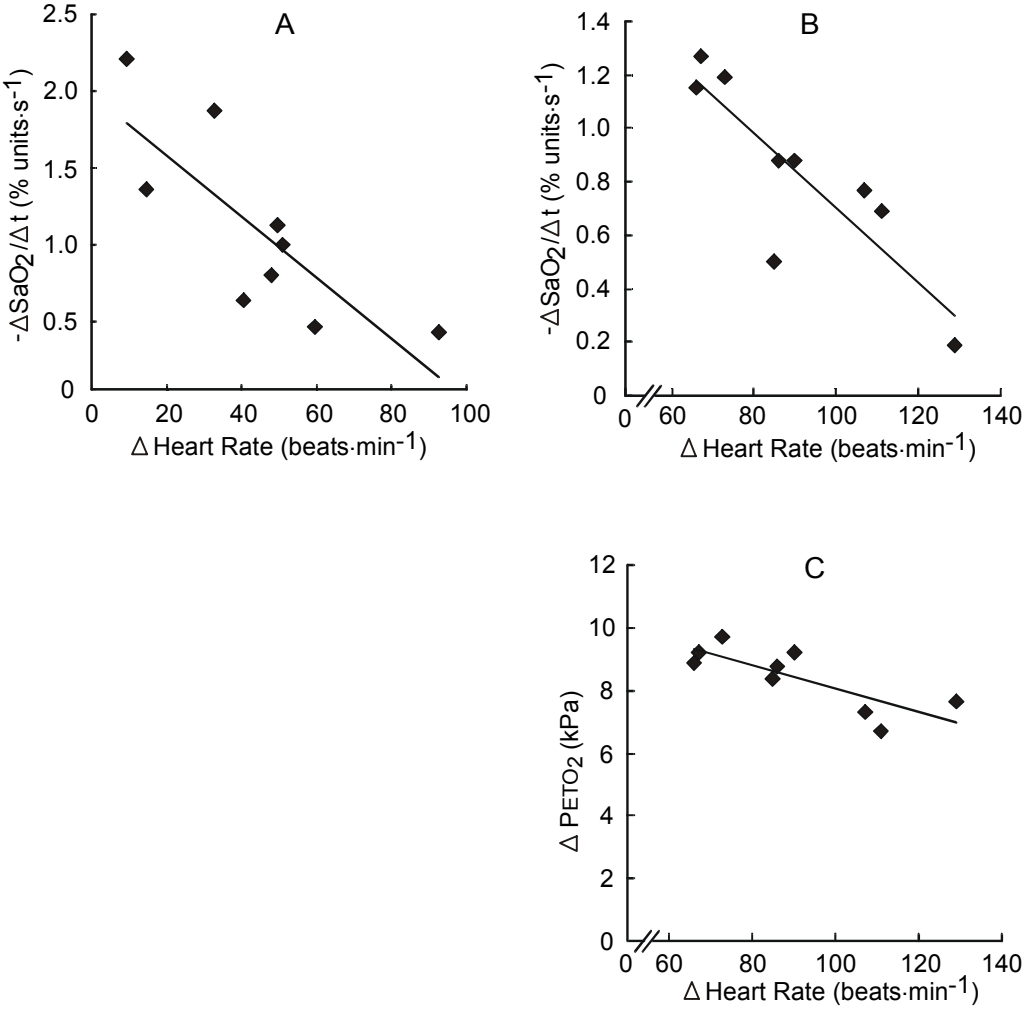

Fig 3 A: Correlation of rate of arterial desaturation and bradycardic response after 25-30 s of apnea during exercise. Data from paper I. (R=0.79, p=0.01, N=9)

B: Same correlation as in panel A but after 34-44 s of apnea. Data from paper II. (R=0.87, p<0.01, N=9)

C: Correlation between the change in $P_{ET}O_2$ at expiration to RV before and after apneas of 44 s (ordinate) and the same heart rate data as in panel B (abscissa). (R=0.79, N=9, p< 0.01)

6.2 INTER-INDIVIDUAL VARIABILITY IN THE CARDIOVASCULAR RESPONSES TO APNEA (PAPER I AND III)

The wide inter-individual variability of the bradycardic responses to apnea observed in paper I was further analyzed with determinations of stroke volume (SV), cardiac output and total peripheral resistance in an attempt to study independently the cardiac and the vasoconstrictive effects of apnea in exercising humans. The principal results are shown in Fig 4 and 5. In summary, at end-apnea there were up to 4- to 5-fold elevations of the total peripheral resistance (TPR) (Fig 4) in 4 of the 11 subjects and on the average only a doubling of TPR in the remaining 7. The subjects with the largest degree of vasoconstriction also had the largest bradycardic response (Fig 5). In both subgroups average stroke volumes were the same before and during apnea, with smaller SV values and higher control heart rate in the subgroup with the largest responses to apnea.

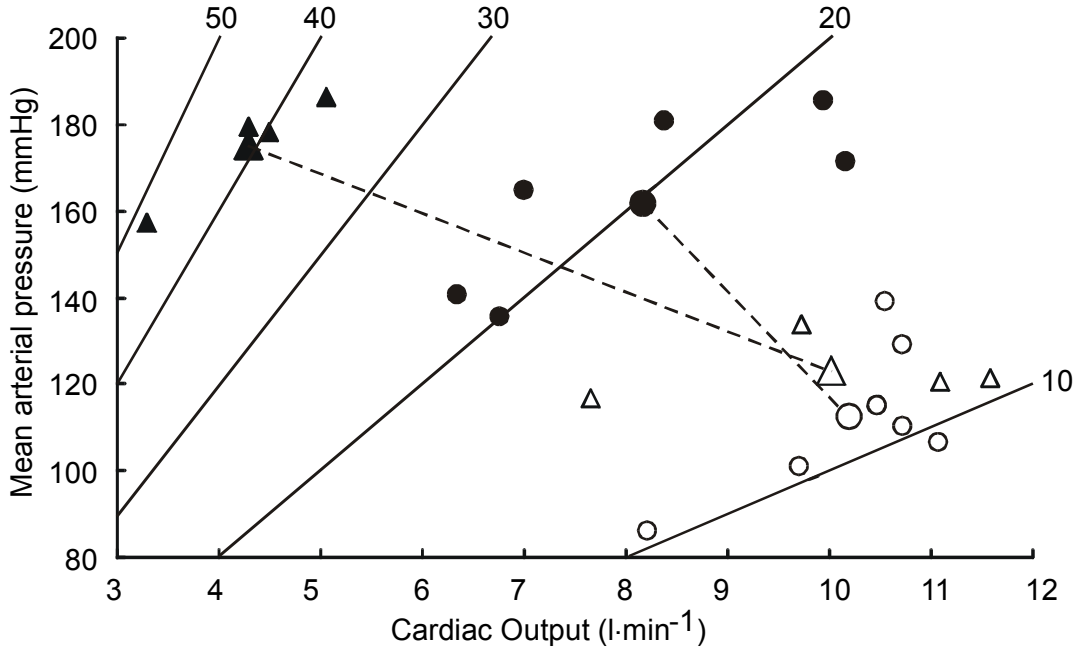

Fig 4 Mean arterial pressure (ordinate) as a function of cardiac output (abscissa) during leg exercise. Individual data from paper III. Open symbols are pre-apnea control, filled symbols are end-apnea. Also shown are isopleths for total peripheral resistance (TPR) expressed in mmHg*min*l^{-1}. Among the 11 subjects there is a subgroup of 4 subjects with a markedly higher elevation of TPR during apnea (▲) than the rest (●). Large symbols are mean values for each subgroup. All data are from air breathing.

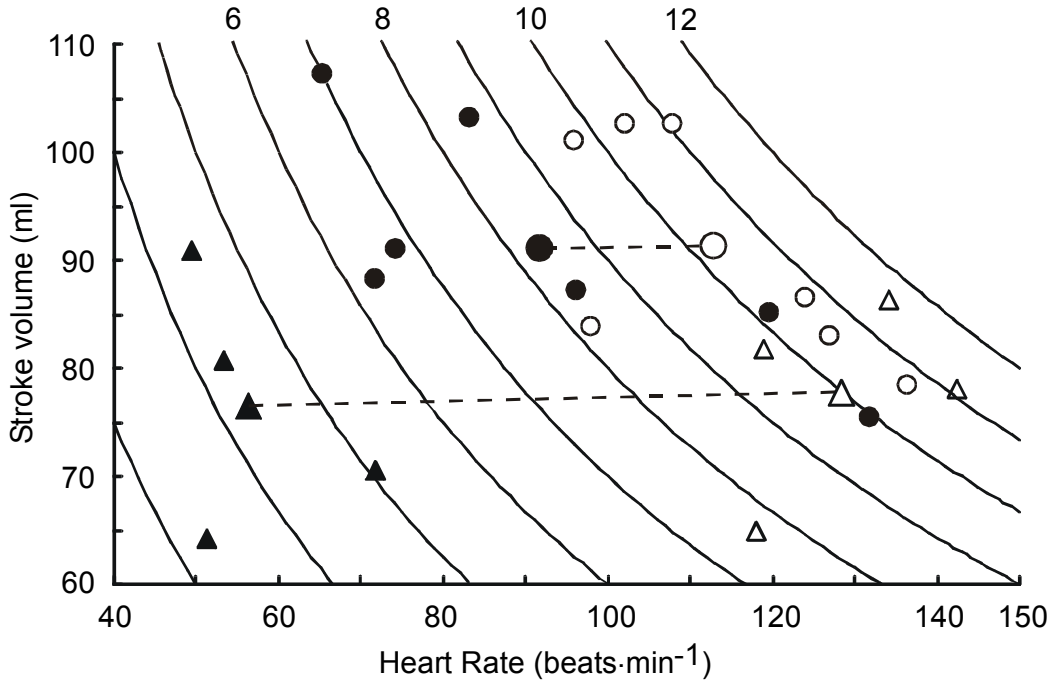

Fig 5 Same subjects and use of symbols as in Fig 4. Here stroke volume is shown as a function of heart rate together with isopleths for cardiac output. The subgroup with the largest elevation of TPR (Fig 4) also had the largest bradycardic response.

The hypoxemia during apnea with air appeared to influence the heart directly or indirectly so that there was no increase in stroke volume despite a marked bradycardia-related increase of diastolic filling time. In contrast, during apnea with oxygen, there was an 14+/-14 % increase of SV compared to pre-apnea. In summary, the results show that both cardiac and vascular responses to apnea and the associated protective effect against hypoxemia are highly variable among individuals, rendering some individuals more fit for breath-hold diving than others.

6.3 HEMODYNAMICS AND OXYGEN EXCHANGE DURING APNEA (PAPER II AND III)

By combining data from paper II and III a hypothetical calculation can be made of central venous oxygen saturation during steady-state exercise and apnea. This quantity reflects the oxygenation in the tissues from which the venous blood is drained.
The study described in paper III showed that stroke volume at the end of apnea is similar to the stroke volume before apnea. However we have no data on the possible changes of stroke volume during the early phase of apnea. From the study in paper II we can use data on VO_2, HR and SaO_2 during the last part of the apnea. If we assume that stroke volume is the same as in study III and not significantly different during the last part of the 40 s apnea compared to baseline data, we can calculate the cardiac output and then the arteriovenous O_2 difference [(a-v)DO_2] using the Fick equation. We assume that the stroke volume during exercise at 120 W is 86 ml (different subjects and 100 W workload in paper III), and that the haemoglobin value is 160 g/l and that Hb carries 1.38 ml O_2/g. Times refer to events taking place in the lungs.

	baseline	24-34 seconds	34-44 seconds
$\dot{V}O_2$ (l/min)	1.7	0.7	0.4
HR (beats/min)	151	68	56
CO (l/min)	13	6	5
SaO_2 (%)	99	77	70
SvO_2 (%)	40	19	28
A-V diff (%)	59	58	42

Table 1 (N=6) The (a-v)DO_2 appears no different from control during the time interval 24-34 s. As shown in Fig 2, it takes some 20 seconds for the cardiovascular response to develop and there is likely another 15-20 seconds circulation time for the blood to pass from the peripheral tissues to the lungs. Together these times may account for the delay of the change in (a-v)DO_2.
During the last part of the apnea the model shows a reduction in (a-v)DO_2 and an increase in SvO_2. This probably represents blood that has circulated in the body during the part of apnea when cardiac output was low. The heart rate and cardiac output during this period are approximately the same as during rest, and although the (a-v)DO_2 is greater than during rest, it is smaller than during baseline steady-state exercise. During this period the pulmonary oxygen uptake is also very low compared to baseline values. This suggests that the recirculation of blood is mainly from tissues not involved in exercise, i.e. internal organs, brain, etc.

6.4 APNEA DURING TRAINING AND COMPETITION (PAPER IV)

The fact that apnea performance is reduced during competition is well-known among athletes; they often find that they have done their longest apneas or deepest dives during training sessions (personal observation). The apnea competitors usually reduce their depth in competition by a few meters in order to have a safety margin. There are often a few incidents of "loss of motor control" or "blackout during competitions". This can of course be explained by a stronger motivation for pushing apnea to the limit, but it is also possible that the stress of competition prevents the athlete from relaxing fully; an increase in muscle tension would consume more energy and thus increase oxygen consumption, leading to a reduction in apnea time. The higher heart rate we have shown during competitive apnea offers a plausible mechanism for explaining the high frequency of loss of motor control and blackout during competitions even though apnea times are shorter than the subjects' personal best performances.

Another possible explanation would be increased hyperventilation before competitive apneas, due to the tension of competition. This might cause a relative hypocapnia, reducing the athlete's ability to withstand a low PO_2. There is no reason that this should cause the higher heart rate seen during apnea in paper IV. It is a possible explanation, however, to the higher heart rates before competitive apneas since an increase in ventilation also increases heart rate.

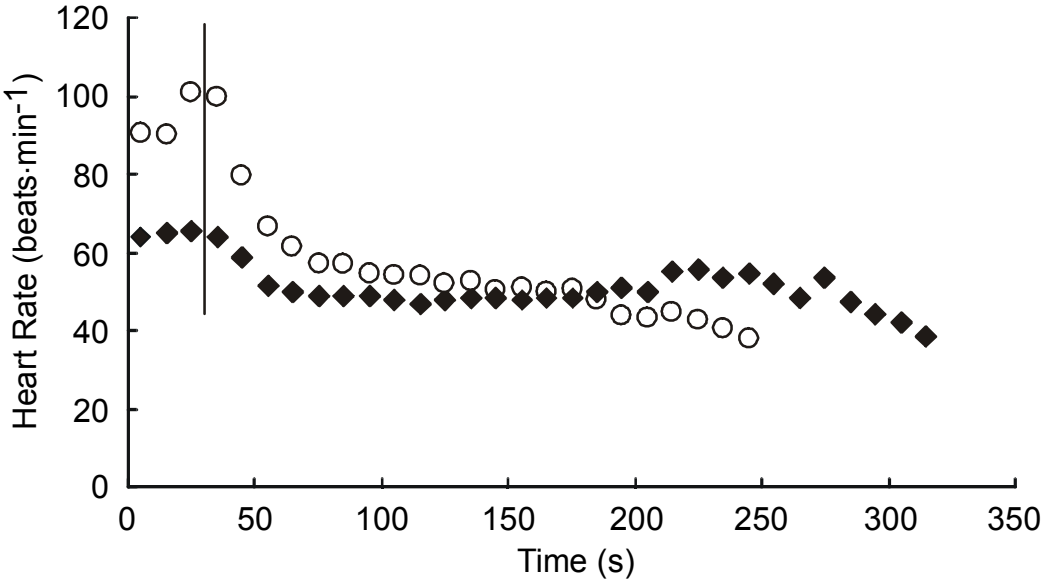

Fig 6 Heart rate of a subject performing static apnea. Heart rate was measured from 30 seconds before apnea started until apnea ended. (♦) Training, (○) competition.

We measured heart rates during static apnea in both training and competition. People practising this sport sometimes have incidents of hypoxic syncope during competitions. We found that heart rates were significantly higher both before and during competitive apnea than the corresponding control values during training. One of our subjects experienced a hypoxia-induced loss of motor control during the competition. We suggest that there is an increased risk of hypoxic syncope due to the reduced bradycardia during *competitive* apnea, compared to training.

6.5 FURTHER STUDIES ON APNEA, EXERCISE AND WATER IMMERSION

6.5.1 A comparison of bradycardia in the laboratory and in the swimming pool

Most of the experiments in this thesis have been done in dry conditions in the laboratory on an ergometer cycle. We wanted to investigate whether the large individual variations in bradycardia would persist in water during real underwater swimming.

We let the subjects swim 50 m with fins underwater in a 50 m swimming pool with a water temperature of 27°C. To measure the heart rates we used a POLAR^{tm} heart rate monitor. The fins used were short fins for scuba diving, Mares Plana Avanti 3. The heart rates were correlated with those from laboratory experiments in the same subjects, both in terms of absolute heart rate during apnea and as change in heart rate during apnea compared to baseline (see Fig 7 and 8).

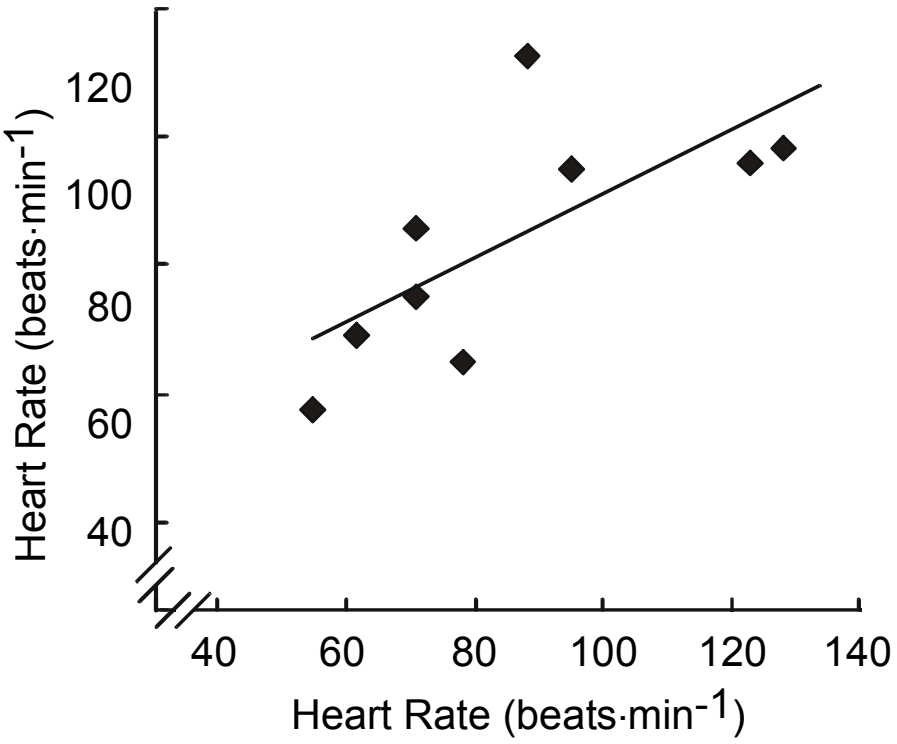

Fig 7 A comparison between absolute heart rate: during dry steady-state exercise with apnea (100 W) and dynamic apnea in a swimming pool. Heart rate was measured for 25-30 s during steady-state exercise and apnea (abscissa), and 35-40 s during dynamic apnea (ordinate). N=9, R=0.71, $p<0.05$

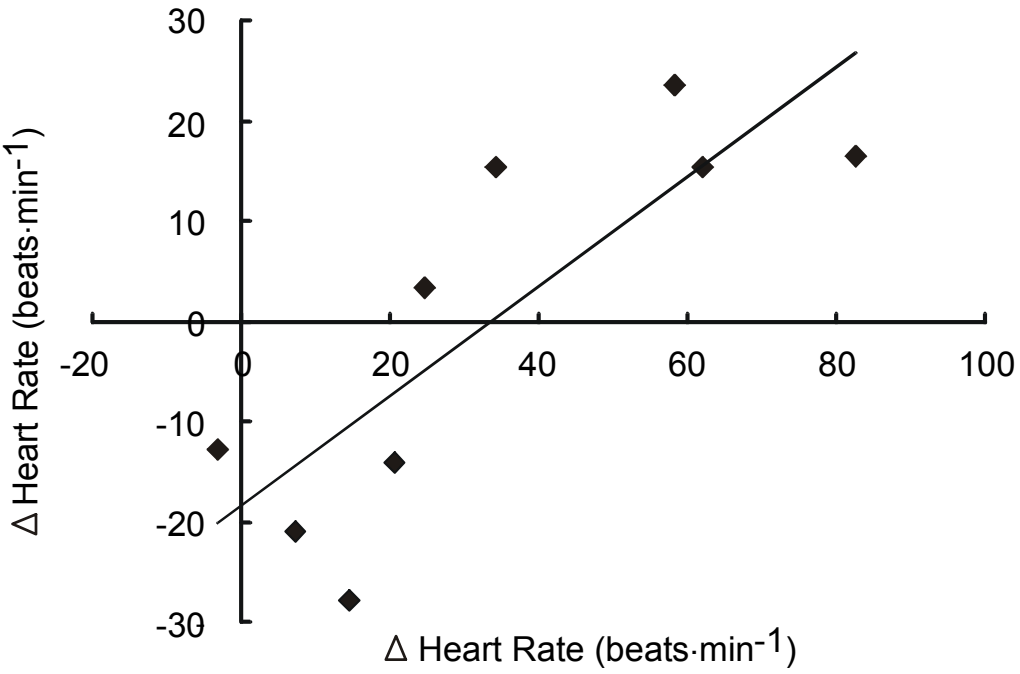

Fig 8 A comparison between bradycardia during dry steady-state exercise with apnea (100 W) and dynamic apnea in a swimming pool. Heart rate was measured for 25-30 s during steady-state exercise and apnea (abscissa), and 35-40 s during dynamic apnea (ordinate). Baseline data for calculation of ΔHR was taken during the time period 45-15 seconds before apnea started. N=9, R=0.82, $p<0.01$

As shown in the figures, subjects react similarly during both laboratory apnea and "real" underwater swimming in their heart rate responses to apnea. (Note that data for dry apnea are from the experiments of paper III and were obtained in the summer of 2000, whereas data for dynamic apnea were collected the summer and fall of 2001). We suggest that the results obtained in paper I-III during dry exercise represent physiological mechanisms that are valid also during real breath-hold diving in water.

6.5.2 Measurements of arterial oxygen saturation during simulated diving

The physical activity during underwater swimming is generally not initiated from a baseline of a steady-state exercise condition as was the case with the apneas in paper I-III. Instead underwater swimming generally starts from a resting position with initiation of exercise and apnea simultaneously. Also the face will be immersed in water. In order to determine the effects of concomitant onset of apnea and dynamic leg exercise under laboratory conditions we studied subjects on an ergometer cycle in an immersion tank. Subjects were sitting in 27^{o}C water up to the chin. They then were asked to inhale 75% of their dry vital capacity from a bag, and then dip their face into the water and start pedaling for as long as possible. This experiment thus included apnea, short lasting exercise and water immersion. The workload including water resistance was calculated to be around 60 W (25 W plus the water resistance). (Fig 9)

In summary we found that the individual differences seen during dry experiments with steady-state exercise (Fig 2) persist when short lasting exercise and apnea were initiated simultaneously during water immersion (Fig 9). This finding further supports the proposal that our results from experiments done during dry steady-state exercise and apnea are applicable to real breath-hold diving.

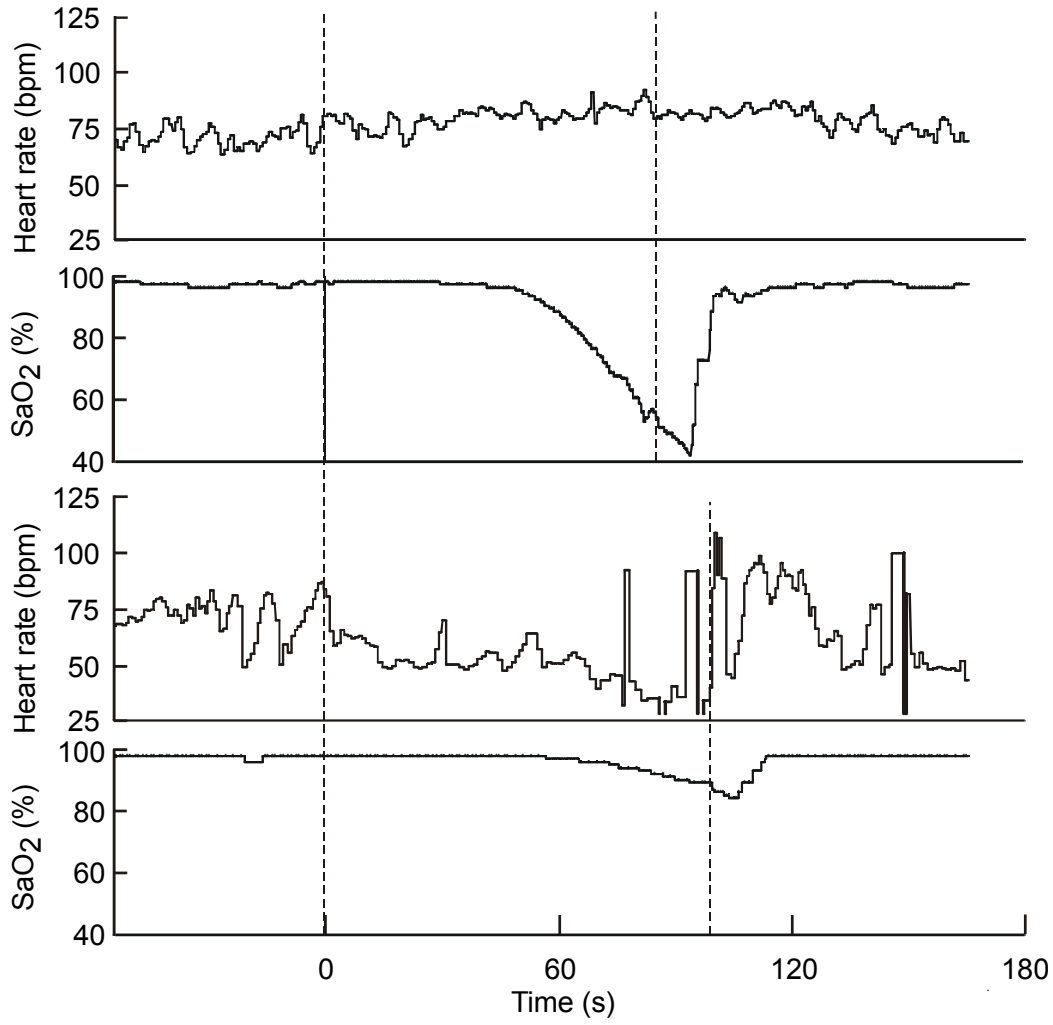

Fig 9 shows 2 subjects; one with bradycardia (bottom panels), and one without, (top panels) before and during simultaneously initiated apnea and underwater exercise. Subjects exhaled to residual volume and inhaled an air volume equivalent to 75% of dry vital capacity before starting apnea and exercise. Lines represent start and end of apnea and exercise.
The subject with bradycardia inhaled 4,3 liters while the other subject inhaled 4,1 liters. Water temperature during the experiments was 27-28^{o}C.

6.5.3 ECG during constant weight diving

Many of our subjects breath-hold dive with fins in Swedish waters to depths below 40 meters. We measured ECG of the subjects during this type of dive. The water temperature was 18^{o}C at the surface and 4^{o}C at the bottom (43 m).
The heart rate before diving during hyperventilation ranged 93-130 bpm. During diving heart rates dropped to about 40-60 bpm in most subjects. This type of diving by swimming has never been studied to these depths. During dives assisted by weights ("no limits") or in a compression chamber, and thus without any exercise, heart rates as low as 20 beats/min have been reported in champion divers (Ferrigno et al. 1991; Ferrigno et al. 1997). These results show that the heart rates measured under the present

laboratory conditions fairly well represent those occurring during constant weight breath-hold diving.

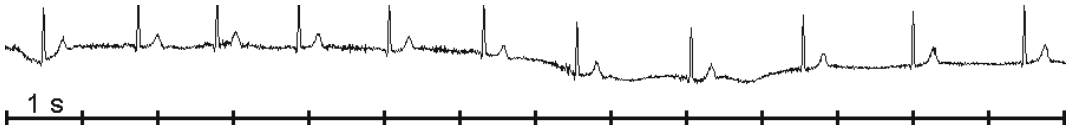

Fig 10 ECG from a subject while swimming up from a dive to 42 m. Data were obtained in the depth range 39.9 to 28.7 m. He was using a monofin with a dolphin kick. Lowest heart rate in this figure is 40 beats/minute.

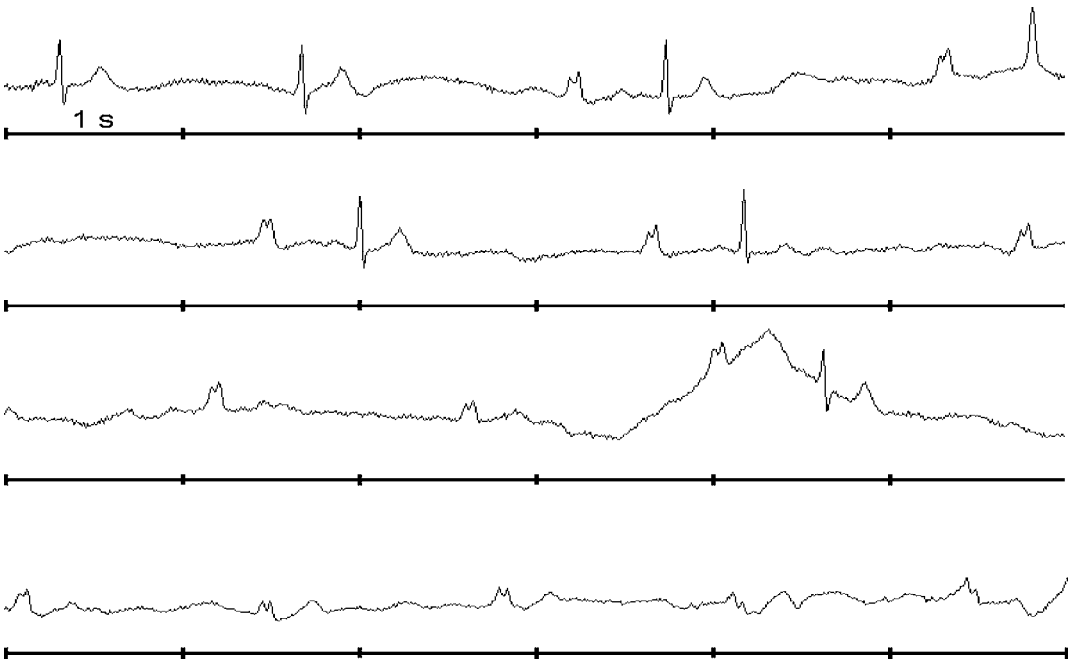

Fig 11 ECG from another subject. The interval between the two supraventricular heart beats on line 2 and 3 is 6.7 seconds. During the long interval there is a ventricular rhythm of around 40 beats/min. The measured interval corresponds to 23–43 m depth during descent. Due to increasingly negative buoyancy the subject swims slower and slower and was descending motionless the last 10-15 seconds, to keep an even rate of descent.

7 CONCLUSIONS

"*Research is endlessly seductive. Writing is hard work.*" Barbara W. Tuchman

The overall conclusions of this thesis are

-That the individual degree of bradycardia during apnea correlates significantly with higher levels (= better conservation) of arterial oxygen saturation. Thus, the subjects with the lowest heart rates during exercise and apnea had the best preserved saturation measured with earlobe pulse oximetry.

-That the cardiovascular responses to apnea in exercising humans clearly delay the development of hypoxemia by reducing the rate of uptake from the main oxygen store, i.e. the lungs.

-That stroke volume at the end of apneas with air was not significantly different from baseline before apnea. During apneas with oxygen, however, there was an increase in stroke volume at end-apnea. Under both conditions there was a marked elevation of total peripheral resistance, but more so in some individuals.

-That there is a significant correlation between the degree of vasoconstriction and the intensity of the bradycardia in the group of subjects, so that subjects with the largest degree of vasoconstriction also had the largest degree of bradycardia.

-That hypoxemia when occurring together with respiratory arrest appears to provide an additional but not principal stimulus for bradycardia and to some extent hypertension. We also conclude that the inter-individual variation in bradycardia was independent of hypoxia and thus cannot be explained by individual sensitivity to hypoxia.

-That during competition, heart rates were higher both before and during static apnea, compared to a control situation.

-That the heart rate responses to apnea observed under the present laboratory conditions fairly well represent those occurring during actual breath-hold diving.

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