Assessment of a dive incident using heart rate variability

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Abstract
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Introduction: Scuba diving likely has an impact on the autonomic nervous system (ANS). In the course of conducting trials of underwater ECG recording for measurement of heart rate variability, there was an unexpected stressful event; one participant's regulator iced and began to free-flow.
Methods: A custom-made, water- and pressure-tight aluminum housing was used to protect a portable Holter monitor. ECGs were recorded in three experienced divers who witnessed an unplanned moderately stressful incident during diving. The ECG signals were analysed for measures of heart rate variability (HRV).
Results: Analysis for different short-term HRV measures provided consistent results if periods of interest were appropriately time-aligned. There was improvement in sympatho-vagal balance. One diver unexpectedly exhibited an increase in both sympathetic and vagal activity shortly after the incident.
Conclusions: A conventional open-water dive affected the ANS of experienced recreational divers as measured by HRV which provides a global evaluation of the ANS and alterations in its two branches. The heart rate variability data gathered from several participating divers around the time of this event illustrate the potential utility of this variable in quantifying stress during diving. HRV data may be useful in addressing relevant diving related questions such as effects of cold, exercise or different breathing gases on ANS function.

Introduction

Only a few studies have addressed the effects of scuba diving on the autonomic nervous system (ANS) of recreational divers.[1–3] Given that there are as many as six million[4] to seven million[5] active scuba divers worldwide with 500,000 more training every year,[5] studies on recreational divers seem relevant.

Heart rate is characterised by an inherent variability, i.e., the healthy heart is not a metronome.[6] Heart rate variability (HRV) is the result of neuronal control by the ANS,[7,8] and HRV is of extreme importance for adaptation and flexibility, which is lost in some cardiac and non-cardiac diseases in which heart rate becomes increasingly periodic.[9–11] On the other hand, persistently high HRV in the elderly represents a predictive marker of longevity.[12] More than 160 review articles in the last five years alone forcefully underline the importance and utility of measuring HRV.

Submersion and scuba diving cause physiological stress thereby activating the sympathetic nervous system.[13,14] In turn, the diving response activates the parasympathetic nervous system,[1,3,15] which, in addition, is activated by hyperbaric hyperoxia.[16,17]

So far, several systems for collecting underwater ECG data of recreational[18] or professional[19] divers have been described but no simple ways seem to exist to collect physiological data.[2] Thus, knowledge about the effects of deep dives on the ANS is limited. We have used a custom-made system to assess ECG data for wet and dry dives down to depths of 40 m.

In the course of conducting trials of underwater ECG recording for measurement of heart rate variability, there was an unexpected stressful event; one participant's regulator iced and began to free flow. This case, along with commentary on measurement and interpretation of heart rate variability in divers is presented in this report.

Table 1
Subject characteristics. BMI = body mass index in kg·m^2

Diver	ECG system	Age years	BMI	Dives
Leader	No	28	24	600
Victim	No	36	27	300
A	Yes	42	26	650
B	Yes	38	24	26
C	Yes	48	36	1,100

Methods

PARTICIPANTS

The group consisted of five divers. All divers were experienced and familiar with the dive site. Only three wore the ECG system. Personal and dive data of all five members are presented in Table 1.

The dive was performed within the framework of a study to investigate possible different effects between breathing air and nitrox on the ANS. The protocol of this study was approved by the ethical committee of Charité – University Medicine Berlin. The divers were informed about the study via written information. Informed consent was obtained from each of the participants.

UNDERWATER ECG SYSTEM

A Holter monitor was used for ECG recording. The Holter (Lifecard CF, Spacelabs Healthcare, Nürnberg, DE) uses a 12-bit resolution system to ensure accurate recordings. Lifecard can record seven days of ECG data on removable compact flash cards with a memory of 64 GBytes. These cards can be read on personal computers.

The recorder was placed in a custom-made water- and pressure-tight aluminum cylinder. The ECG leads had a length of 1.5 m. Push buttons on their distal ends permitted connection with adhesive electrodes. They were positioned on the chest wall of each participant (subclavicular right, subclavicular left and position V6). This equipment was deployed inside a dry suit.

The cylinders were equipped with a handle to allow them to be attached to the front of a belt worn around the waist within the dry suits (Figure 1A). However, they could also be worn outside the wet suits in which case the electrodes should be sealed using elastic, waterproof polyethylene plasters (Figure 1B).

ECG ANALYSIS FOR HRV

ECG signals were recorded continuously before, during and after diving. ECG analysis to evaluate dive-induced changes to the ANS was performed in the facilities of the German Naval Medical Institute (Maritime Medicine, Kronshagen, DE) using conventional software (Pathfinder SL, HRV-Tools, Spacelabs Healthcare, Feucht, DE).

Beside the heart rate (HR), two short-term HRV measures from the time domain were employed: standard deviation of NN periods (SDNN); and root mean square of successive RR interval differences (RMSSD). In addition, low frequency (LF) power, high frequency (HF) power, and their ratio (LF/HF) from the frequency domain were employed.

The ECG signals were analysed over a 5-min period shortly after the onset of the dive and another period of 5-min before surfacing. Another two 5-min periods were analysed: one before: and another after the incident. Finally, two 2-min periods were analysed: one before and the other after the incident. All employed measures were intended to reflect short-term HRV, that is, changes within a period of between 2 and 5-min.[20]

DIVE EQUIPMENT AND BREATHING GAS

The divers wore dry suits. They used 15 L cylinders, two independent, cold water-suitable regulators and a dive computer. This equipment complies with the standards of safe diving in cold water. The cylinders were filled with 3,000 L nitrox 40 (40% oxygen and 60% nitrogen).

DIVE LOCATION AND PARAMETERS

Lake Walchensee is located 805 m above sea level in the Bavarian alpine upland. Water visibility was up to 20 m and the temperature was 10°C at the surface and 5°C at a depth of 25 metres' fresh water (mfw). Dive tables of the trade associations were employed to determine the no-decompression time[21] that permitted a bottom time of 25 min at a depth of 25 mfw. However, correction for the altitude resulted in a decompression of 5 min at 3 mfw. For safety reasons, two more safety stops were to be completed: 1 min at 9 mfw and 3 min at 6 mfw. Taking the ascent rate (max. 10 m·min^{-1}) into account the total planned dive duration was 39 min.

Because of a regulator icing in one of the group, the dive was truncated at 14 min run time, but the intended stops were accurately observed (Figure 2).

Results

INCIDENT

After an uneventful descent to 25 mfw over 5 min, the dive continued for another 9 min, when the first stage of the victim's regulator iced, and there was uncontrolled free-flow from the second stage. The victim was unable to close the valve of the first regulator and swap to his second regulator. The group leader successfully closed the valve and handed the victim the second regulator permitting him to commence

Figure 1

The water- and pressure-tight cylinder contains the Holter monitor. The device can be worn inside a dry suit (**A**) or with a wetsuit by using waterproof dressing-protected electrodes (**B**)

breathing again. Because the group had performed the dive in close contact and with good visibility, the three other divers (A, B, and C) witnessed the incident straightaway. It was decided to abort the intended dive plan and to return to the entry, strictly observing the planned ascent schedule. On their way back, the victim was closely accompanied by the leader of the group on one side and by diver C on the other side. Divers A and B closely followed this trio.

ELECTROCARDIOGRAM

Physical activity associated with putting on and taking off the dive gear, as well as by entering/leaving the water, did affect the signal quality due to motion artifacts. However, during diving, the proportion of regular beats was ≥ 80%, enabling reasonable analyses for HRV measures. As a consequence, data sets from participants A, B and C could be analysed.

Heart rate

The average HR in divers A, B and C clearly decreased (in comparison to pre-dive) during the dive, from 87 to 73 min^{-1} (16%), 127 to 101 min^{-1} (20%), and 123 to 92 min^{-1} (25%), respectively. However, there were major fluctuations in rate during the dive (Figure 3).

After the incident HR quickly changed to a different degree and for a different duration. For the 5-min post-incident periods HR increased from 82 to 92 min^{-1} in diver A, from 103 to 124 min^{-1} in diver B, and from 84 to 95 min^{-1} in Diver C.

Tachogram

The RR intervals increased between the beginning and the end of the dive. Shortly after the onset of the incident, the average RR intervals decreased in divers A, B, and C. Figure 4 is presented as representative example (diver A). This tachogram additionally exhibits rhythmic oscillations. Before the incident their frequency was about 6 min^{-1} and was slightly increased to about 7 min^{-1} after the incident. The frequency comparably increased from 8 to 9 min^{-1} and from 6 to 7 min^{-1} in divers B and C, respectively. The amplitude of the oscillations immediately after the incident was decreased in all three divers compared with the amplitude before the incident (see diver A in Figure 4).

Heart rate variability

Because of the small sample size, only qualitative changes in the two time-domain and the three frequency-domain measures are presented. When analysed over the entire dive,

Figure 2
Planned dive profile. After 14 min runtime (arrow) the dive was terminated with observance of the planned stops as shown

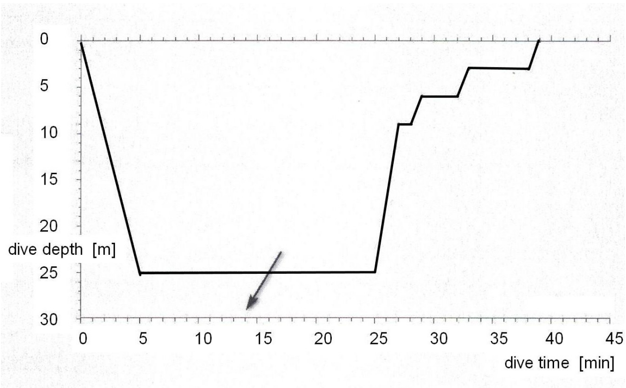
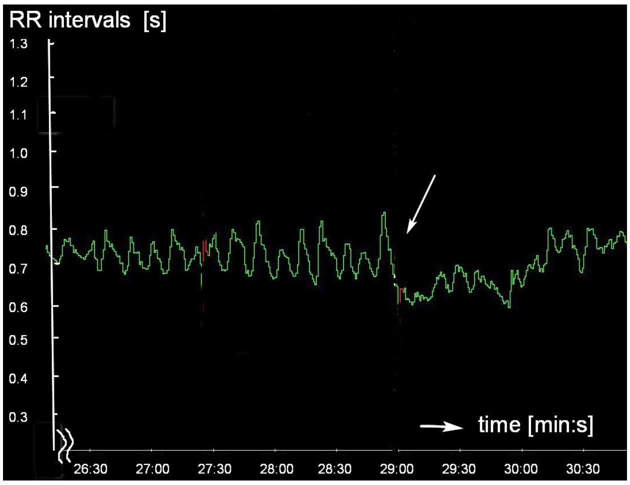


Figure 4
Tachogram of diver A. The arrow indicates the incident. Shortly after it, the RR intervals decreased together with their amplitude. Also, the frequency of the rhythmic oscillations was somewhat increased after the incident compared with before the incident



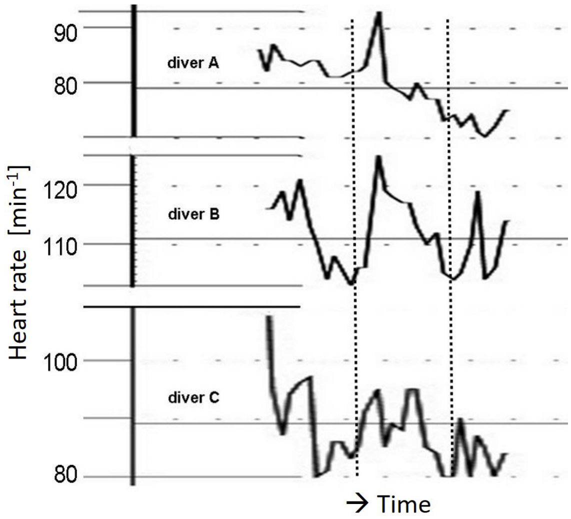
SDNN and RMSSD increased in all monitored divers. LF and HF were also increased but to differing extents such that LF/HF was decreased in all three divers (Table 2).

When analysed for the 5-min periods before and after the incident, the two time-domain and the three frequency-domain measures had changed less uniformly. When comparing these specific periods LF/HF was decreased in divers A and B and was increased in diver C (Table 2).

Finally, when analysed for the 2-min periods, the two time-domain measures were all increased after the incident, as well as LF and HF. Surprisingly, LF/HF was decreased in diver A but increased in divers B and C (Table 2).

Because the 2-min data for diver A were unexpected, an original diagram of the time course of the LF- and HF-power as well as the LF/HF ratio is provided (Figure 5). The diagram

Figure 3
Heart rate (HR) of divers A, B and C. HR clearly decreased between the start of the dive (leftmost point on the charted line) and prior to surfacing (right dotted line). The left dotted line indicates the onset of the incident following which the HR in all three divers rapidly increased. The horizontal dashes indicate five-minute intervals



shows a simultaneous increase of both the LF- and the HF-power at the time of the incident that lead to a moderate decrease in the LF/HF ratio. In both of the other divers LF/HF was increased.

Discussion

Within the framework of the underlying study, about 200 dives were performed without Holter housing failures. Moreover, the system did not impede the divers, as it was worn on a belt around the waist inside of dry suits. The unexpected recording made during a diving incident illustrated the potential for the system to detect major alterations of ANS function during diving.

HR was decreased in all three divers between the onset and the end of the dive. This result agrees with previous studies on recreational scuba diving, demonstrating an activated vagal system in experienced divers;[1,3,22] a finding also reported in children.[23]

Analysis of shorter ECG periods showed a transient increase in HR in response to the witnessed incident. Divers A, B and C witnessed all events described above, and the resulting stress lead to increases in individual HR.

The tachograms of divers A, B and C exhibited cyclic variations with a frequency between 6 min^{-1} and 9 min^{-1}. These variations are associated with breathing and are known as respiratory sinus arrhythmia.[24] The respiration rate was only moderately increased after the incident in divers A, B and C. Still, tachograms provide the respiration rate as one valuable physiological measure.

Table 2

Changes in HRV parameters over the entire dive, and when comparing the five- and two-minute periods before and after the incident in divers A, B and C. LF = low frequency power; HF = high frequency power; RMSSD = root mean square of successive RR interval differences; SDNN = standard deviation of NN periods

Measure	Periods	A	B	C
SDNN	entire	↗	↗	↗
	5-min	↘	↗	↗
	2-min	↗	↗	↔
RMSSD	entire	↗	↗	↗
	5-min	↘	↗	↘
	2-min	↗	↗	↗
LF	entire	↔	↗	↗
	5-min	↘	↗	↔
	2-min	↗	↗	↗
HF	entire	↗	↗	↗
	5-min	↘	↘	↘
	2-min	↗	↗	↔
LF/HF	entire	↘	↘	↘
	5-min	↘	↘	↗
	2-min	↘	↗	↗

HRV allows the cardiovascular system to rapidly adjust to sudden physiological and psychological challenges to homeostasis.[25] In this regard, HRV is a reliable indicator of health status and a sensitive index of autonomic stress reactivity.[26] Thus, this non-invasive tool provides information about the sympathetic and the parasympathetic (vagal) systems and the interaction of both ANS branches.

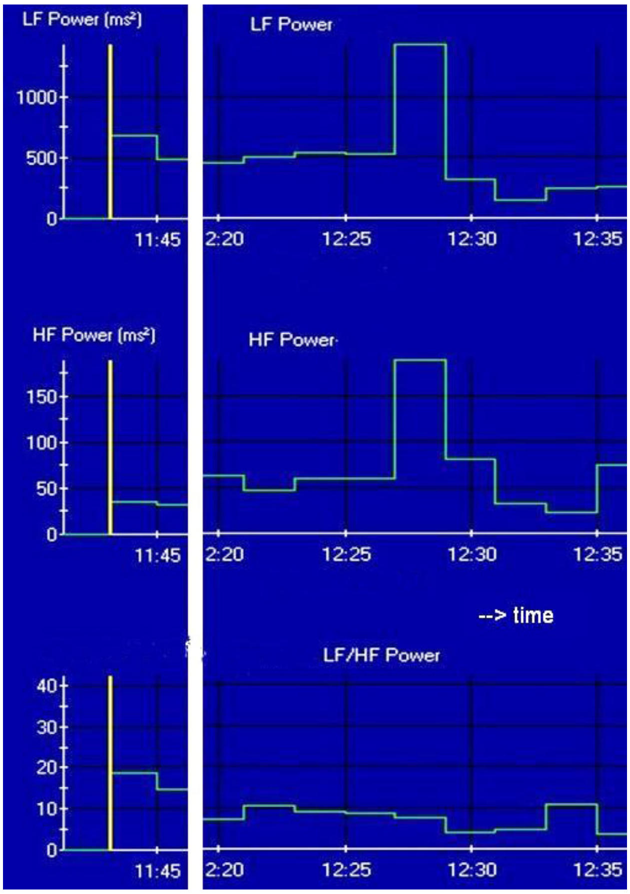
Submersing the face into water elicits the 'dive response'[15,27] including a bradycardia as the best-known manifestation.[28,29] On the other hand, as man is not made to live under water, submersion and diving will likely present stress. Thus, both the vagal and the sympathetic nervous system should be activated during diving.[3] Stress will further increase if the face is submersed into cold water. The strong and simultaneous activation of the two ANS branches has been termed autonomic conflict and may account for arrhythmias and (potentially) death in some vulnerable individuals.[14]

We chose two measures from the time domain and three measures from the frequency domain to assess ANS activity resulting from the incident: The mean SDNN reflects all cyclic components responsible for variability during the interval of recording. In contrast, the RMSSD is a measure of vagal activity.

The low frequency power spectrum (LF: 0.04 to 0.15 Hz) overwhelmingly reflects sympathetic activity. However, vagal modulations are also involved, although at a much lower power. The high frequency power spectrum (HF: 0.15 to 0.40 Hz) is considered to reflect vagal activity. HF components are associated with the respiratory sinus

Figure 5

Left panel: LF Power, HF Power and LF/HF ratio for diver A with frequency domain measures starting after correct placement of the ECG-electrodes, i.e., in a dry environment. Right panel: Tracings start approximately seven minutes before the incident. The drastic and simultaneous increase in both LF and HF after the incident are of surprise. The resulting decrease in the LF/HF ratio is suggestive for an improved sympatho-vagal balance



arrhythmia where respiration is normal and varying between 9 and 24 breaths·min^{-1}.[30] In our three divers, maximum rate was 9 min^{-1} (0.15 Hz) and was thus located in the LF power spectrum. It had been previously reported that scuba diving is associated with surprisingly low respiration rates.[31] The LF/HF ratio is considered to present the sympatho-vagal balance.[32,33]

Not only can HRV describe overall changes in the ANS activity, but it also can differentiate which of the two ANS branches is activated and to what degree. HRV also permits measurement of the breathing rate.[24] Because of these advantages, the HRV has established its usefulness in describing health status.[26] HRV is also suited to assess stresses like noise, time constraints or shift work in the occupational environment.[34,35] Use of HRV should therefore, permit physiologists and other scientists to assess the effects of various stressors associated with scuba diving such as varying depths, exercise, different breathing gases, fast environmental changes (e.g., visibility, current), or equipment-related problems. Normal values for HRV measures exist,[36–38] such that deviations from the standards can be detected.

Either a reduced HRV at rest or a non-physiological response during submersion could be used to identify scuba diving candidates who merit closer scrutiny to prevent events like ventricular arrhythmias,[39] or sudden cardiac death,[40] and parameters may help identify older divers at greater risk.[41] Stressful elements of training could be identified in novice divers enabling adjustment of a teaching schedule. This possibility holds for professional divers such as police, firefighters, and armed forces. HRV analyses could help identify stressing conditions for individual divers. If HRV analyses were available during accident investigation, they could contribute to identifying causes of fatal dive accidents.

We have the impression that assessment of HRV measures might support diver training, contribute to medical decisions, and foster scuba diving-related science.

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