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# A systematic review of HRV during diving in very cold water

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**ABSTRACT**

Heart rate variability (HRV) is a useful method to study the autonomic nervous system (ANS) status. As measuring devices have developed and become smaller, many researchers have become interested in the possibilities to implement the method for diving medicine research. The aim of this study was to review human ANS responses in cold water diving (water temperature <5°C), and to comprise the current knowledge of HRV studies in diving and hyperbaric exposure into one review article. A literature search was conducted on 5 December[th] 2022, with the search terms "HRV" or "heart rate variability" and "diving" or "diver" or "divers", with search functions of the data bases PubMed and Ovid Medline. Peer reviewed original articles, review articles and case reports were accepted to this review. Twenty-six articles met the pre-defined criteria and were included in this review. Studies from very cold water conditions were rare, but suggested that cold strengthens the ANS responses of diving – especially parasympathetic nervous system (PNS) activity due to the trigeminocardiac reflex and baroreceptor and cardiac stretch receptor activity, caused cold and pressure-induced centralisation of the blood. Overall, studies showed predominant PNS activity when putting the face in water, during immersion and when ambient pressure increased.

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## The physiology of diving

When a human is immersed in water, the hydrostatic pressure causes an increase in breathing resistance and a blood shift to the central parts of the body. The body reacts to the increased central blood pressure through many complicated autonomously regulated mechanisms that ultimately lead to a decrease in blood pressure and cardiac output and an increased renal urine production [1].

Immediately when going into the cold water, peripheral vasoconstriction occurs, the heart rate (HR) increases and the cardiac output increases [2]. About 20–30 seconds later, HR starts to decrease [3]. There is great individual variation in the magnitude of the response. However, humans seem to be able to strengthen the response with training [4].

### *The diving responses or "diving reflex"*

Diving mammals, such as seals or vales have strong diving responses, often referred as the "diving reflex" [5] These responses are a series of physiological reactions of the nervous system, blood circulation and heart, and they are beneficial for preserving oxygen and for increasing the survival time under water. Humans still have the remaining responses to diving, but these are less prominent than those of diving mammals [6].

A significant proportion of the human diving responses are caused by the trigeminocardiac reflex, which is activated by wet and cold sensation of the face and the nostrils [6]. This reflex causes activation of the parasympathetic nervous system (PNS) branches of the vagus nerve (Lindholm and Lundgren, 2009). A centralisation of the blood, due to a rise in ambient pressure and cold, causes an activation of cardiac stretch receptors and baroreceptors, which in turn causes an increase in PNS activity. Breath holding strengthens these responses due to an increase in intrathoracic pressure and in freedivers due to increased acidity of the blood [7,8]. Also, hyperoxia, which may occur in many forms of SCUBA diving, increases PNS activity [9]. A centralisation of the blood to the most vital parts of the body and a dominance in PNS activity both decrease oxygen consumption and increase the survival time under water.

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### *Freediving*

Freediving or breath-hold diving is the most natural form of diving. Compared to SCUBA diving, freediving includes some additional physiological responses that can be considered to be parts of the diving responses. First, apnoea after inspiration increases the intrathoracic pressure, which activates baroreceptors and cardiac stretch receptors, which also cause PNS activation [8,10]. Second, a drop in blood CO2-levels occurs and the amount of lactate rise and carotic chemoreceptors sense a rise in acidity, which in turn causes PNS activation and a lowered heart rate (HR) [4]. Third, a contraction of the spleen, which frees red blood cells and therefore oxygen to the circulation, occurs in freediving [11]. Fourth, oxygen reserves, stored in the form of myoglobin, neuroglobin and cytoglobin are mobilised [5]. Children have a strong laryngeal chemoreflex that protects the lower airways during immersion and allows, for example, baby swimming [12]. In adults, this reflex primarily causes coughing [13].

### *The additional effects of cold*

Diving in very cold water is associated with well-known risks, such as a decrease in physical and psychological ability [14,15], a higher incidence of decompression illness [16,17] and a risk for hypothermia. The diving responses have been shown to be more prominent in cold water, most likely due to a more prominent trigeminocardiac reflex and a stronger vasoconstriction of the periphery [18]. At least in theory, diving in cold water includes an elevated risk for malign arrhythmia: The human diving responses activate the PNS [19]. A simultaneous activation of the PNS and the sympathetic nervous system (SNS), the latter due to the first responses to cold as well as possible physical and psychological stress at the beginning of the dive, leads to an “autonomic conflict” which could cause malign arrhythmia [18–20–2122].

## Heart rate variability (HRV)

HR is the number of heart beats per minute. Heart rate variability (HRV) is the variation in time intervals between heartbeats [23]. These intervals vary due to a complex brain – heart interaction controlled by the autonomic nervous system (ANS) [24]. Different branches of the ANS can be divided into the SNS that is predominant during physiologically or psychologically stressful situations, and the PNS that is predominant during rest.

### *Factors that influence HRV*

The benefit of an autonomically regulated system is the quick adaptation to a changing environment. The influences of the ANS on the cardiac sinus node are reflected as a variation of beat to beat intervals [24]. These changes can be studied with the HRV method. When interpreting short term HRV measures, especially the following factors, that directly influence HRV, must be taken into account: 1. the respiration rate (respiratory sinus arrhythmia slows and speeds HR via the vagus nerve caused by baroreceptor activity), 2. the heart and vascular tone and the blood pressure (baroreceptor activity and cardiac stretch receptor activity), 3. the central nervous system, 4. the endocrine system and 5. chemoreceptor activity [25–27].

### *Strengths and limitations of the HRV method*

The HRV method is a non-invasive way to evaluate ANS activity. Most devices, that are designed for HRV monitoring are small and portable. Battery life has developed, and the devices can be attached continuously to the study subjects for many days. Data can be retrieved from the device at any point after measuring because it is saved on the device. Most devices are very durable and have good water resistance.

Because many factors influence HRV, researchers should have a good understanding of the method so as not to draw wrong conclusions. There are many confounding factors, the most important mentioned in the previous paragraph, and therefore studies must be carefully planned. There is also great individual variation in HRV, which can confound the interpretation of results. It could be beneficial to rather study changes in HRV or to have the study subjects to act as their own controls. A common misconception is that HRV shows overall ANS activity of the body. The PNS and SNS branches of the body are not activated with an all-or-nothing principle – activity of branches can vary a lot in separate organs, and PNS and SNS branches can also be activated concurrently. HRV measures reflect the ANS output to the heart [28]. For example, as the periphery is vasoconstricted, as usually it is in diving (increase in activity of local SNS branches), a centralisation of the blood increases PNS activity to the heart, that can be measured with an HRV device.

### *The use of HRV in diving medicine research*

As the measuring devices have been enhanced and become more portable, many researchers are implementing the HRV method in diving medicine research.

The amount of research has increased in recent years. Since there is a clear growth in popularity of the method, it would be beneficial to summarise the current knowledge.

## The aim of this study

The aim of this review was to describe the human ANS responses to diving in very cold water. As already mentioned, the cold is in many ways a risk factor for divers [14,15,20] – therefore our main focus was to look at HRV findings from very cold water diving, and based on results, possibly give recommendations on how to make diving in these extreme conditions safer.

Due to a limited number of studies with HRV from very cold water diving, we decided to additionally include HRV studies from other types of dives and exposure to hyperbaric conditions. With the results from these studies, we aim to expand the understanding of the overall ANS responses to diving and give a better basis to review and discuss results from cold water conditions.

## Article search process

A literature search, following the PRISMA guidelines for systematic reviews and meta-analysis [29], was conducted on 5 December[th] 2022, with the search terms "HRV" or "heart rate variability" and "diving" or "diver" or "divers" with search functions of the databases PubMed and Ovid Medline. Peer reviewed original articles, review articles and case reports were accepted to this review. Only studies where HRV was monitored on human subjects were included. Studies where subjects did not dive or were not exposed to hyperbaric conditions were excluded.

In this research, near freezing water temperatures (<5°C) was defined as "very cold". We first aimed to present studies from very cold water dives, whereafter studies from other types of conditions were to be discussed.

## Results from the literature search

The literature search provided 185 results. The removal of non-human studies (24) and duplicates (20) reduced the number to 161. An exclusion of studies where no HRV was assessed (72) and an exclusion of studies where no diving occurred or subjects were not exposed to hyperbaric conditions (43), resulted in a final number of 26 articles in this review. The search process is shown in a separate flow chart (Figure 1).

Included articles are presented in Table 1.

The number of HRV studies in diving medicine and related research is still quite low. However, in recent years, the method has become more popular, which could be seen from the growing number of published articles in the last years. Only one systematic review and meta-analysis has been published (Ackermann et al. 2022). This work examined vagal activity with RMSSD recordings. Most studies were from SCUBA diving (12 studies) and they usually comprised only a small number of subjects and dives. A few studies from hyperbaric facilities and chambers (eight studies), also with small numbers of subjects, have been published. Studies from very cold water conditions (water temp <5°C) were rare – only two original articles [18,37] and one case report [53] met the search criteria for this review.

The most frequently used metrics were different time domain measures (most frequently reported parameters: RMSSD, SDNN) (22 studies). Frequency domain measures (most frequently reported parameters: HF power, LF power, LF/HF) were used in 18 studies, non-linear measures (most frequently reported: SD1 of a Poincaré plot) in 9 studies.

## Summary and discussion of results in different conditions

### *Systematic review and meta-analysis (1 article)*

Ackermann et al. (2023) examined the effects of face immersion or cooling, SCUBA diving, and total body immersion on vagal activity. RMSSD recordings were used as the only parameter. A significant moderate to large increase in PNS activity was seen during exposure but not after exposure. In this study, total body immersion had a significantly greater effect than forehead cooling (Ackermann et al. 2022). Because the majority of the included articles in this study were from warmer water conditions, this would indicate that the trigeminocardiac reflex is not the strongest promoter of PNS activity, if conditions are not very cold. As we know, the trigeminocardiac reflex is activated by wet and cold sensation of the face and the nostrils [6]. Cold plays a major part in the reflex and therefore, it is likely that the role of this reflex would have been more prominent if solely cold water studies would have been selected for this study.

*SCUBA diving in very cold water (<5°C) (2 articles and 1 case report)*

The number of research from very cold water conditions is limited. Only three peer-reviewed articles met the search criteria. In one of these studies, five experienced Navy divers were followed during five days of

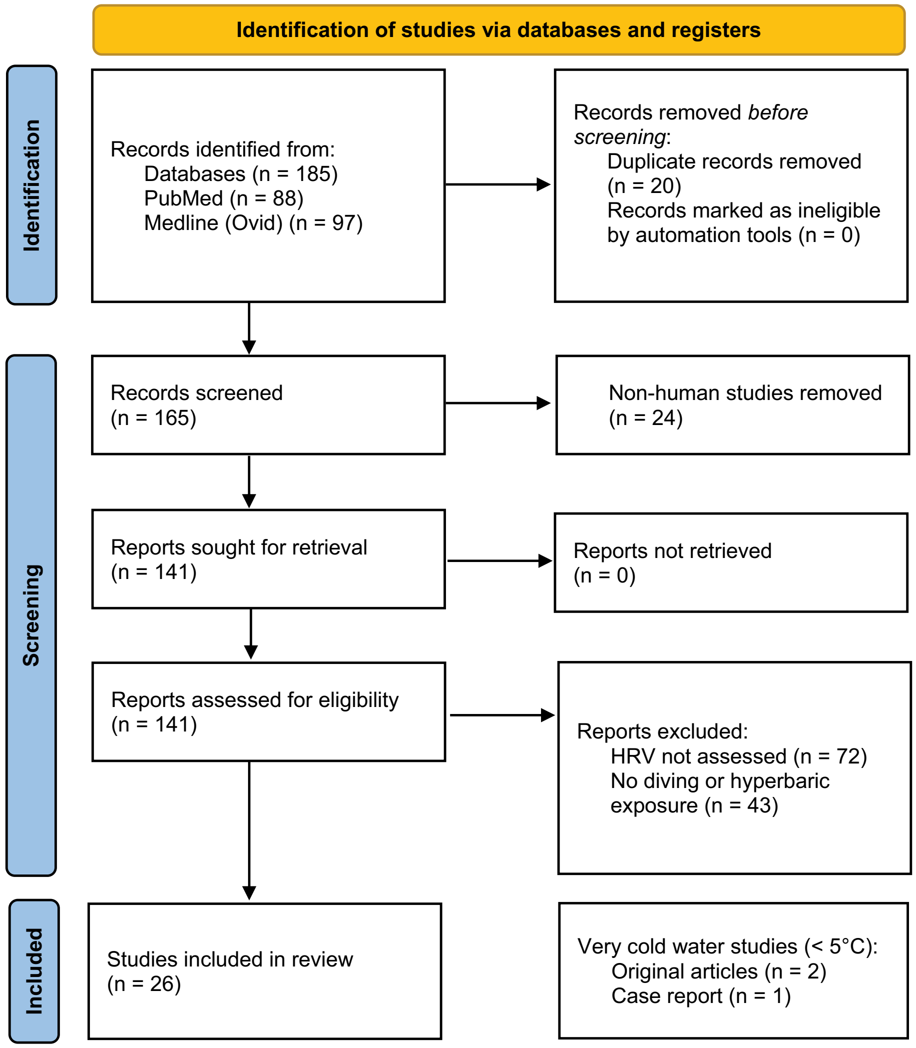


**Figure 1.** PRISMA flow chart with the article search process. After the removal of duplicates and studies that did not fulfil the pre-defined criteria for the review, a final number of 26 articles were included in the review. Of those included, only three articles met the criteria for very cold water studies (< 5°C).

diving in near freezing water. HRV measures showed a significant decrease in PNS activity after an initial activity increase at the beginning of the dives. After this, PNS activity increased linearly over time. This study suggests that the initial ANS responses to diving in very cold conditions, triggered mainly by the trigeminocardiac reflex (PNS) and cold shock (SNS), decrease quickly [37].

Another study [18] gave support to the findings described in the study by Lundell et al. [37]. In this research, HRV was measured on 26 experienced closed-circuit rebreather divers during a 45 mfw trimix dive in 2–4°C water. The dive commenced with a three-phase protocol (each lasting 5 min): 1. immersion with head out of water, 2. face in water, 3. submersion and stop at 6 mfw: Moreover, resting values were measured before and after the dive. Compared to resting values, PNS activity decreased significantly on immersion with face out of water. From immersion, it increased significantly with facial immersion, just before decompression and just before surfacing. Results suggests that the trigeminocardiac part of the diving responses decreases quickly. Cold seemed to be the most prominent promoter of later PNS activity during the dives [18].

In a case report from the Antarctic, Bruzzi et al. measured HRV at baseline-, before dives, during dives and after dives on two controls and two divers that did 10 min of diving in freezing waters (−1.7°C). In this research, diving reduced PNS activity [53]. The HRV measuring started 2 min after subjects got into the water and lasted for 10 min.

The limited amount of research from cold water conditions showed at the beginning of the dives a strong PNS activity that can be attributed to the trigeminocardiac reflex, and a later increase in PNS activity, which can be explained with pressure and

**Table 1.** Studies included in this review. The table shows the characteristics of subjects, information on the type of exposure and temperature during exposure as well as the main findings in the studies. The reported temperatures are water temperatures for in-water studies and air/gas temperatures for studies from hyperbaric chambers and facilities. Studies from very cold water are highlighted with grey background colour.

| | Subjects | Exposure and breathing gas | | | | | Temperature | Autonomic nervous system |
|---|---|---|---|---|---|---|---|---|
| | n | Subjects (as described in article) | | | | | Water/gas (°C) | Main finding(s) |
| Systematic review and meta-analysis [30] | 311 | n/a | n/a | n/a | n/a | n/a | n/a | PNS activity increased during exposure but not after exposure. Total body immersion had a greater effect than forehead cooling. |
| **Original articles** | | | | | | | | |
| *SCUBA diving* | | | | | | | | |
| [31] | 25 | sport divers | n/a | n/a | dynamic | air | n/a | PNS activity increased during diving. HRV measure length shortening to 3 min (time domain) and to 5 min (frequency domain) without loss of information possible. |
| Schipke and Pelzer, 2001[32] | 25 | trained SCUBA divers | 0–4 | 10 | static | air | 27 | The trigeminocardiac reflex did not show a significant role in warm water. Main promotor of PNS activity was head out of water immersion. |
| [19] | 10 | SCUBA divers | 19.7 | 39.5 | static | air | 16 | PNS activity increased and SNS activity decreased during dives. |
| Flouris et al. 2009[33] | 10 | healthy adults | 5 | 20 | static | air | 27 | PNS activity decreased during dives due to psychological stress. |
| [34] | 10 | navy divers | 4.6 | 360 | static | air | 32–33 | Consecutive day diving showed a successively decreasing vagal PNS responce to diving. |
| [35] | 24 | experienced SCUBA & rebreather divers | 10–61 | 40 | n/a | air/nitrox/trimix | 10–15 | PNS activity increased during diving, and it increased proportionally more with greater depth and higher oxygen partial pressure. |
| [36] | 13 | experienced divers | n/a | n/a | dynamic | air/nitrox | n/a | PNS activity increased during diving, and higher oxygen partial pressure increased PNS activity more. |
| [37] | 4 | navy divers | 6 | 80–91 | static | air | 0 | PNS activity increased during diving. PNS activity increase due to the trigeminocardiac reflex was short lived. |
| [38] | 7 | experienced rebreather divers | 90–120 | 180 | dynamic | trimix | 27 | PNS activity was increased after diving, compared to pre-dive measures. |
| [39] | 18 | experienced divers | 30 | 20–65 | dynamic | air/nitrox | 17–33 | PNS activity increased during diving, and higher oxygen partial pressure increased PNS activity more. |
| [18] | 26 | experienced rebreather divers | 45 | 66 | static/dynamic | trimix | 2–4 | PNS activity increased during diving. PNS activity increase due to the trigeminocardiac reflex is short lived. Cold seemed to be the strongest promoter of PNS activity. |
| [40] | 18 | divers from commers./priv. dive clubs | 5.7–40.1 | 35 | static | air/nitrox | 5–23 | Non-selected divers in real-world conditions showed an overall increase in ANS (SNS and PNS) activity without PNS dominace. |
| *Hyperbaric chambers and facilities* | | | | | | | | |
| [41] | 4 | experienced saturation divers | 450 | n/a | static | heliox | n/a | For unknown reasons, breath holding in increased pressure caused a progressive shortening in cardiac R-R intervals. |
| [42] | 10 | professional divers | 15 | 75 | static | air/oxygen | n/a | PNS activity increased more in a chamber with 2.5 bar when breathing 100% oxygen than when breathing air. |
| [43] | 16 | normal volunteers | 330 | n/a | static | heliox | n/a | PNS activity increased during the exposure and had a negative correlation to urinary cathecolamines. |
| [44] | 6 | volunteers | 300–400 | n/a | static | heliox | n/a | PNS and SNS activity increased concurrently after the exposure. |
| [9] | 10 | divers | 15 | 60 | static | air/oxygen | n/a | Non-linear and frequency domain measures showed a strong correlation in this study. Therefore, it is justified to report either parameter in hyperbaric experiments. |
| [45] | 10 | divers | 0–30 | 40 | static | air | n/a | PNS activity increased as pressure was elevated. |
| [46] | 10 | healthy individuals | 45 | n/a | static | trimix/nitrox/oxygen | n/a | Post-exposure PNS activity increased only for a normobaric control group, not for those exposed to elevated pressure. |
| [47] | 17 | healthy subjects | 0–40 | n/a | static | air | n/a | Self-organizing maps (artificial intelligence) could be trained to use HRV to predict different body responces during exposure to elevated pressure. |

(*Continued*)

**Table 1.** (Continued).

| | Subjects | | Exposure and breathing gas | | | | Temperature | Autonomic nervous system |
|---|---|---|---|---|---|---|---|---|
| *Static apnea and breath hold diving* | | | | | | | | |
| [48] | 9 | elite breath-hold divers | n/a | n/a | static/ dynamic | air | 26.9 | PNS activity increased in both static and in dynamic apnea. In dynamic apnea, the PNS response blunts the effects of exercise induced SNS activity. |
| [49] | 11 | trained breath-hold divers | n/a | n/a | static | air | 26–27 | Breathholding under water and in air caused a triphasic heart rate kinetics: first a strong decrease, then a short linear increase and finally a decrease. |
| *Immersed subjects* | | | | | | | | |
| [50] | 10 | healthy subjects | 0 | 360 | static | air | 32–33 | Estimated with HRV measures, a differential activation-depression path was seen in the cold pressure and handgrip test compared to the head-up-tilt test. |
| *Elite synchr. swimmers (incl. immersion)* | | | | | | | | |
| Solana-Tramunt 2019 [51] | 12 | elite synchonized swimmers | n/a | n/a | dynamic | air | n/a | Pronounced bradycardia was observed during training sessions corresponding to apneic exercise, but no clinically meaningful changes in HRV measures occured. |
| **Case reports** | | | | | | | | |
| [52] | 3 | experienced divers | 25 | 39 | dynamic | nitrox | 5–10 | Both PNS and SNS activity increased shortly after a stressufull incident in diving. |
| [53] | 4 | military divers | n/a | 10 | n/a | air | −1.7 | PNS activity decreased from baseline during diving, when measured 10 min starting from 2 min after the beginning of the dives. |

cold-induced blood centralisation. A centralisation of blood activated cardiac stretch receptors and baroreceptors causing an increase in vagal PNS activity [18]. A strong trigeminocardiac reflex at the beginning of dives seemed to decrease quickly in cold water conditions [18,37].

In cold water, the trigeminocardiac reflex seems to play a major role in PNS dominance at the beginning of the dive [18,37], whereas in warmer water, at least in current studies, the reflex does not seem to contribute as much (Ackermann et al. 2022 [32].

Case reports from the Antarctic did not show PNS dominance during dives. This is not surprising since in this study HRV was reported for a 10 min time span, starting from 2 min after the beginning of the dive [53]. In theory, an increase in PNS activity at the beginning of the dives, due to the trigeminocardiac reflex, could have occurred but was not seen because of the measuring protocol. As seen in the other two studies from very cold water, the PNS response due to the trigeminocardiac reflex diminishes quickly [37]and 2021). If the dives would have lasted for longer than 10 min, later PNS activity increase, caused by centralisation of the blood volume, could also have occurred.

Cold causes a stronger trigemionocardiac reflex, but it also strengthens peripheral vasoconstriction, that in warmer conditions mainly occurs due to hydrostatic pressure. At later stages of dives, cold – not pressure – was the major contributor to PNS activity. PNS activity increased successively even if the pressure was constant for the whole dive [37], and also while the pressure decreased due to ascent at the end of dives [18].

SNS activity increased at the beginning of the dives [18,37] and was predominant in short dives (10 min) [53]. Strong SNS activity can be attributed to the first responses to cold "cold shock" as well as possible physical and psychological stress at the beginning of the dive [20]. After the first reactions to cold, later measures showed a significant decrease in SNS activity over time [18,37], with the exception of one measure during which divers had to do minor physical activity [18].

### *Other SCUBA diving articles (10 articles and 1 case report)*

Even from warmer water conditions, studies were rare. Ten original articles and one case report met the search criteria. In one study, Pelzer et al. [31] studied 25 recreational divers by using different HRV measures during the dives, as well as evaluating how much the ECG measure length could be shortened without losing significant information. This study showed a significant increase in PNS activity during diving compared to control conditions. Moreover, the ECG measure length could be shortened to 3 min for time domain measures and to 5 min for frequency domain measures, without a significant loss of information compared to longer recording lengths. This study supports the use of short measure HRV in diving medical research [31].

Schipke and Pelzer [32], showed that in warm water (27°C) the trigeminocardiac part of the diving responses does not seem to play a significant role. In this study, head out of water immersion was a powerful stimulus on the ANS, mainly on the PNS part in warm pool conditions [32]. A study on experienced recreational SCUBA divers showed that diving induced vagal PNS activity and decreased SNS activity. After the dive, conversely SNS activity increased [19]. A study with 10 subjects performing a challenging task in a 20-min dive at 5-m depth in warm water (27°C) showed a significant decrease in PNS activity during the dives compared to pre- and post-dive measurements, most likely due to psychological stress [33].

In a study by Berry et al. [34] 10 US Navy divers who performed resting dives for 6 h on five consecutive days showed that repeated diving caused a daily increase in vagal PNS activity due to diving, but a successive decrease in vagal PNS activity from day-to-day, which indicates a less responsive cardiovascular system in successive day diving [34]. Noh et al. [35] studied ANS behaviour in different depths (10.05, 20.10, 30.17, 45.72 and 60.96 m of salt water) and with different breathing gas mixtures (air, nitrox and trimix). For all depths and gas mixtures, there was a consistent dominance in PNS activity, and an increase in PNS activity with an increase in time and depth [35].

Zenske et al. [36] studied 13 experienced divers who dove one time with air and one time with the breathing gas nitrox. Both dives increased the PNS activity but when diving with nitrox (higher oxygen partial pressure) PNS activity increased more (Zenske et al. [36]). A field study by Dugrenot et al. [38] measured HRV before and after diving on seven closed-circuit rebreather divers that performed 16 open sea bounces dives to 90–120-m seawater (msw). Compared to the baseline, there was a post-dive increase in PNS activity [38].

Lafère et al. [39] studied HRV changes on 12 open-circuit air breathing divers (variable hyperoxia) and six closed-circuit rebreather divers (constant hyperoxia) during 30-m freshwater (mfw) dives. Both groups showed an increase in the PNS activity during dives. HRV parameters indicated stronger PNS activity for the open-circuit breathing divers. This could be explained with higher oxygen partial pressure, which is known to be a promoter of PNS activity, in this group [39].

Schaller et al. [40] studied HRV from 18 real-world conditions dives performed by non-selected divers of different ages. In this study, HR just before diving was surprisingly high. Diving induced a remarkable increase in ANS activity without a predominance of PNS parameters. This suggests that in non-selected divers in real-world conditions, diving causes an immediate and sustained concurrent PNS and SNS activation [40]. A case report where an unexpected stressful situation occurred during HRV recording during diving, showed that shortly after the incident the divers' both PNS and SNS activity increased [52].

Results in the studies were surprisingly coherent and showed a predominant activation of the PNS during immersion and when ambient pressure increased. When putting the face in water, the trigeminocardiac reflex is known to be activated and to cause an increase in PNS activity [54]. Compared to the few studies from cold water conditions, the trigeminocardiac reflex did not seem to play an as significant role in these studies from warmer water conditions. Pressure elevation induced a centralisation of peripheral blood, which activated cardiac stretch receptors and baroreceptors [55], which in turn caused an increase in PNS activity. Also, an increase in oxygen partial pressure showed to increase PNS activity in these studies.

An increase in SNS activity was seen at the beginning of dives and during stressful events [33,46,52]. Also, the level of training seemed to have an influence on SNS activity – beginners tended to show high SNS activity already before and during dives, most likely due to the psychological stress that going into water caused [40]. The case report by Zenske et al. [52] showed that in stressful situations a significant concurrent increase in PNS and SNS activity can occur. As described previously in this article, this could cause malign arrhythmia and therefore hazardous underwater events.

## *Hyperbaric chambers and hyperbaric facilities (8 articles)*

HRV studies from hyperbaric chambers and facilities are rare as well. One study from a saturation dive to 450 msw, the effects of hyperbaric conditions on HRV during breath holding were examined. Compared to normobaric conditions, elevated pressure caused a significant progressive shortening in cardiac intervals. However, the cause for the difference in interval length is unclear [41]. In another study, Lund et al. showed that 100% oxygen increases PNS activity more than air in a chamber with 2.5 bar pressures [42].

A study from a submarine training facility, where subjects were exposed for days to high pressure simulating extreme depth (pressures equalling 330 msw), showed an increase in PNS activity, estimated with HRV, and a negative correlation in HRV PNS parameters and urine catecholamines, indicating that in extreme depth the HRV method can be used to evaluate ANS function [43]. Hirayanagi et al. [44] did a hyperbaric saturation dive study, where HRV indicated increased PNS activity shortly after the dive. A concurrent SNS activity was estimated from an increase in plasma epinephrine levels [44].

Another study, also from a chamber with 2.5 bar pressure, showed a strong correlation between SD1 of a Poincaré plot analysis (non-linear measure) and the HF power (frequency domain measure), which supports the use of SD1 as a measure in diving medicine-related research [9]. The use of SD1 could be beneficial in future diving medicine research since HF power is more sensitive to breathing frequency, which may vary a lot during diving [28]. In a study by Barbosa et al. [45], chamber experiments as well as experiments from hyperbaric facilities showed that PNS activity increased as the pressure was elevated [45].

Schirato et al. [46] did a study where HRV was measured in two groups (one group exposed to a hyperbaric environment equalling 45 msw with the other group acting as a control) before and after a simulated dive in a hyperbaric chamber. Compared to pre-dive measures, the hyperbaric group did not show major changes in PNS nor SNS activity in post-dive measures, while the controls showed increase in many HRV measures that indicate PNS activity. This finding was estimated to be related to the physiological stress of being exposed to the hyperbaric environment [46].

Perez-Martinez et al. [47] studied ECG signals on 17 subjects in a hyperbaric chamber with pressures equalling depths from 0 to 40 msw, compared HRV measures with biophysical variables and depth using artificial neural networks. Especially, self-organising maps were trained in modelling and clustering the data. This study showed that further developing such models could be useful in predicting possible abnormal body responses during diving in advance, and thus improving diving safety [47].

The strength of studies from hyperbaric chambers and facilities are that they provide controlled conditions. On the other hand, results from chambers cannot automatically be transferred to diving since many other factors play a role during dives. When comparing HRV studies from non-diving hyperbaric experiments, with those from real in-water diving, results were overall in line with each other: First, an increase in ambient pressure caused an increase in PNS activity. Second, an increase in oxygen partial pressure in the breathing gas, caused an increase in PNS activity. Third, stressful situations caused logically an increase in SNS activity, as is the case in any conditions.

The research by Perez-Martinez et al. [47] combined HRV parameter analysis with artificial intelligence. Further development of the described method could give new tools for predicting possible hazardous events in advance, and thus to avoid them from happening underwater.

### *Static apnoea and breath hold diving (2 articles)*

Two HRV studies with static apnoea and breath hold diving met the search criteria. In the first one, Kiviniemi et al. studied cardiac autonomic modulation during static (mean duration: 78 min) and dynamic (mean duration: 225 min) underwater apnoea on elite breath hold divers. Both static and dynamic apnoea caused an increase in vagal PNS activity, estimated from HR and HRV measures. An initial increase in HR during dynamic apnoea was followed by a decrease below baseline. This study suggests that the response to underwater apnoea blunts the effects of exercise induced SNS activity in dynamic apnoea [48].

Another study by Costalat et al. [49] observed 11 trained breath hold divers during prolonged static apnoea in both air and immersed conditions. HR kinetics showed in both conditions a triphasic model with first a sharp drop in HR, whereafter HR increased linearly until a second breaking point, after which it decreased again. The second decrease in HR could be interpreted as a “oxygen conserving breaking point” – an adaptive physiological feature that improves oxygen conservation [49].

Both studies showed a dominance in PNS activity. During dynamic apnoea, strong PNS activity blunted the effects of physical activity. In addition to the promotors of PNS activity in SCUBA diving, apnoea promotes PNS activity via intrathoracic pressure increase [8,10], via a drop in blood CO2-levels and via lactate rise that is sensed by carotic chemoreseptors [4]. It is likely that the “oxygen conserving point”, observed in the study by Costalat et al. [49], is caused by chemoreceptor activity.

### *Immersed subjects (1 article)*

In a study by Florian et al. [50], 10 healthy subjects were immersed in warm water (32–33°C) for 6 hours. A 2 min cold pressor test, a static handgrip fatigue test, and 15 min 70° head-up-tilt test were performed pre- and post-immersion. Results suggested a differential activation-depression path during cold pressor and handgrip (a reduced SNS and an elevated PNS) and a head-up-tilt test (an elevated SNS and a reduced PNS) following immersion [50].

This study shows that the branches of the PNS and SNS are differentially activated in diving. The specific physiological responses that immersion causes are important, for example, when we aim to understand blood pressure-related issues and cardiovascular risk factors. More research is still needed on this area.

### *Training activity of elite synchronised swimmers (including immersion) (1 article)*

A study where elite-synchronised swimmers were observed prior to the 2015 World Championships, showed periods of pronounced bradycardia during training sessions corresponding to apnoeic exercise, but no clinically meaningful changes in HRV measures. Simultaneously measured salivary cortisol, capillary blood lactate and self-assessment of exertion all indicated reduced SNS activity and adaptation to long-term stress. The authors concluded that due to the “diving reflex” an isolated HRV assessment could reveal a controversial interpretation of the ANS status [51].

It is always better to study specific physiological responses with more than one method. Therefore, the design of this study is well justified. Still, one could argue that actually the “diving reflex” should not have blunted a possible decrease in SNS activity during the training period. Even if the stress hormone levels would have decreased for the measuring time points, an intensive training period may overall not have changed in the level of physiological stress and ANS status.

## Limitations and recommendations for future projects

The amount of research from this field is still low, and majority of studies were done with small numbers of subjects and dives. Studies had used different HRV parameters and the methodology differed considerably. Only one systematic review and meta-analyses met the inclusion criteria for this study. Especially, the research from very cold water conditions is rare – only two original articles and one case report have been published.

The use of the HRV method in diving medicine research has in recent years become more popular. Therefore, it is likely that the knowledge in this field will grow rapidly. The number of subjects in the studies, for practical and logistic reasons, are usually small in experimental studies in extreme conditions. However, results from these studies are surprisingly coherent, which strengthens the reliability of the results: Studies showed an increase in PNS activity on elevation of ambient pressure and increased oxygen partial pressure in the breathing gas. In cold water conditions, the trigeminocardiac reflex seems to play a greater role than in warmer water, where its overall significance is less significant. Also, cold per se showed to be the most significant promotor of PNS activity over time in cold dives, most likely due to vasoconstriction of the periphery.

In future projects, it could be useful to more frequently compare different HRV parameters, to evaluate different length measures in diving conditions, and to possibly come up with gold standard recommendations for more comparable studies in the future. Moreover, as breathing pattern and frequency is known to influence HRV [25], it would be useful to measure breathing frequency in future research. The use of non-linear measures (for example, SD1 of a Poincaré plot) could also be beneficial in future diving medicine research since they are not that sensitive to breathing frequency (Shaffer et al. 2017).

To minimise the risk for controversial interpretation of the ANS status, especially in long term HRV measures, it could be useful to confirm findings with other methods than solely HRV [51]. Many researchers did also evaluate autonomic functions with the help of other methods than only HRV, for example by measuring stress hormone levels [43,44,50,51,53].

## Conclusions

HRV is a useful method to study divers, because it is an easily applicable method that provides a great amount of information on the ANS status. More research is needed to confirm how the human ANS responds to diving in different conditions. Especially when it comes to very cold water, the knowledge is limited. However, results in published studies are surprisingly coherent and show a predominant activation of the parasympathetic nervous system during exposure. The cold seems to strengthen the PNS responses of diving.

In cold water conditions, to minimise the risks of a strong concurrent PNS and SNS activation caused by the trigeminocardiac reflex and "cold shock", which is known to increase the risk for arrhythmia, whole face masks should be preferred, and a short adaptation phase before physical activity would be beneficial at the beginning cold water dives. For military and occupational cold water divers, special attention should be given to cardiovascular risk factors.

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