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SHORT COMMUNICATION

Clinical Physiology and Functional Imaging

Changes in cardiac function in Navy divers during four days of successive dives in very cold diving conditions

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Abstract

Introduction and Methods: There is limited knowledge of cumulative effect of repetitive cold-water diving on cardiac function. Single cold dives cause some known cardiological risks, such as malign arrhythmia, due to a concurrent activation of the sympathetic and parasympathetic autonomic nervous system. A previous study from warmer water dives has shown that successive dives cause a decrease in vagal tone and a less responsive cardiovascular system. The aim of this study was to evaluate changes in cardiac function with 2D echocardiography during 4 days of diving in near-freezing water.

Results: Left ventricle systolic function measures did not show any uniform changes. E/A ratio seemed to decrease successively with the number of dives. The diastolic tissue velocity of relaxing basal septum (e′) showed a decreasing trend as well. Diastolic blood pressure seemed to increase from predive (mean: 83 RR mmHg) to postdive values (mean: 87 RR mmHg) (p=NS). Heart rate decreased significantly from predive (mean: 71 bpm, range: 56–103) to postdive values (mean: 60 bpm, range: 37–88) ($p < 0.03$).

Discussion and Conclusions: The study was conducted in very cold condition and with limited number of divers. Results of this preliminary study suggested a decreasing trend in left ventricular diastolic function in successive cold dives. Cumulative changes in cardiac function may cause health risks that need to be considered during cold water diving operations.

KEYWORDS

autonomic nervous system, blood pressure, cold water diving, diastolic function, left ventricular

1 | INTRODUCTION

Diving in very cold water is associated with well-known risks, such as a decrease in physical and psychological ability (Bridgman, 1990; Davis et al., 1975), a higher incidence of decompression illness (Gerth, 2015; Pendergast et al., 2015) and a possibility for hypothermia. At least in theory, cold water diving includes an elevated risk for malign arrhythmia: The human diving responses activate the parasympathetic nervous system (PNS) (Chouchou et al., 2009). A simultaneous activation of the PNS and the sympathetic nervous system (SNS), the latter due to the first responses to cold (Lundell et al., 2021) as well as possible physical and psychological stress at the beginning of the dive, has been shown to be a risk for arrhythmia (Buchholz et al., 2017; Kane & Davis, 2018). Navy divers and other occupational divers perform challenging underwater tasks independent of the time of the year. In certain situations, there can be a need for diving many consecutive days.

The specific cardiovascular risks of diving in consecutive days are not well understood, especially when the additionally cold water is present. Earlier studies from single breath hold dives have shown a reduction in left ventricular and overall cardiac function due to the human diving responses and due to an increase in ambient pressure (Gross et al., 1976; Marabotti et al., 2008, 2009). In contrary to those findings, studies with head out-of-water immersion have shown an increase in stroke volume and cardiac output, due to the increased ventricular preload (Grüner Sveälv et al., 2009; Löllgen et al., 1981). Earlier studies from immersion with head out of water have shown that there occurs a centralization of the blood volume from the periphery to the thorax (Arborelius et al., 1972). In addition, a shift of interstitial fluid through the capillary wall and therefore an increase in plasma volume has been described as a consequence of immersion (Greenleaf et al., 1981). Moreover, a transdiaphragmatic pressure gradient caused by the higher compressibility of the abdomen compared to the thorax and a reduction in gas volume of the lungs due to increased ambient pressure favours central venous blood return and accumulation of blood in the lungs (Castagna et al., 2017; Reid et al., 1986). In addition, cold causes vasoconstriction of the peripheral blood flow. Circulating venous gas bubbles in diving have shown to increase in postdive pulmonary systolic 15 pressure (Marabotti, Scalzini, Chiesa, 2013). Shallow depth SCUBA diving has shown to induce left ventricular enlargement and diastolic function (Marabotti, Scalzini, Menicucci, et al., 2013). Finally, heart rate variability recordings from successive day diving suggested that the cumulative effect of repeated dives causes a decrease in vagal tone and a less responsive cardiovascular system (Berry et al., 2017), which could at least in theory influence cardiac function.

The aim of this study was to evaluate changes in cardiac function with two-dimensional (2D) echocardiography on a small group of healthy Navy divers during repeated diving in 5 consecutive days in very cold water. Possible functional changes could give new views on cardiovascular risks and diving safety-related issues in successive cold-water diving.

2 | METHODS

Four healthy male Navy divers (Table 1) performed one dive per day on 4 consecutive days (divers 2 and 3) or two dives per day on two (diver 1) and three (diver 4) consecutive days near the Arctic Circle in near-freezing water in January. Divers came to the diving site one day before the first diving day. Air temperatures outside varied from −23.0 to −3.4°C. Diving was performed as part of naval cold diving equipment development tests. Because of the extreme conditions divers were exposed to, we performed 2D echocardiography (GE Vivid i. GEMS ultrasound, Tirat Carmel, Israel. Cardiac application module H45021JM, transducer 2D 3S-RS) to detect eventual changes in cardiac dimensions and function. Moreover, we measured blood pressure and heart rate with an automatic Omron M6 AC blood pressure device before and after each dive. All divers volunteered to take part at the equipment development tests and gave their written consent. A consent was obtained from the Ethical Committee of Tampere University Hospital. A research permit was granted by the Logistic Department of the Defence Command Finland (The Logistic Department of the Defence Command Finland. Permission AO3867, 28.2.2018, 1650/12.04.01/2018.). The study adhered to the regulations of the Declaration of Helsinki.

Preparations for the dives were done indoors with a constant room temperature (19°C). Diving garment was put on with the help of assisting personnel. Divers used regular cold-water diving equipment: dry suit, thick layers of undergarment, gloves, hood and whole-face mask. Breathing gas was compressed air in all dives. After preparations, divers walked a short walk to the diving site, where a hole in the ice of the frozen river had been cut. Without further delays divers started their dives. All dives were done in a horizontal prone position at the bottom of the river with a current at 6 m depth in a constant water temperature of −0.1°C. The duration of the dives varied from 58 to 91 min (mean: 81) (divers 2 and 3) and 45 to 48 min (mean: 46) (divers 1 and 4). 2D echocardiography was performed in the morning of the first dive of the week and after each dive (divers 2 and 3) or after the second dive of the day (divers 1 and 4) by a diving physician specialized in clinical physiology. The same physician (TW) performed all the echocardiography examinations. Echocardiographic parameters were the following:

Left ventricular stroke volume (LV SV Dopp) was estimated by using the diameter of left ventricular outflow tract (LVOT) and pulsed Doppler velocity time integral trace (LVOT trace). The ejection fraction (LV EF) was evaluated from long parasternal axis projection measuring the diameter of left ventricle during diastole and systole and applying the Teicholz formula. The cardiac output (CO) was calculated as heart rate*SV.

The diameter of atria was measured by using the maximal 2D diameter in right angle to the putative axis of the atrium.

The early peak transmitral flow (MV E) was evaluated from a four-chamber view at the level of the mitral valve tips with pulse wave Doppler. Mitral annular peak diastolic velocity (MV A) was

TABLE 1 Diver demographics.

Diver (number)	Age (years)	Height (m)	Weight (kg)	BMI (kg/m^2)	Body fat mass (kg)	Body muscle mass (kg)
1	49	1.81	86.8	26.5	13	42.4
2	43	1.78	79.2	25	13.7	37.2
3	25	1.8	80.3	24.8	4.9	43.3
4	40	1.72	86.4	29.2	14.5	41.7

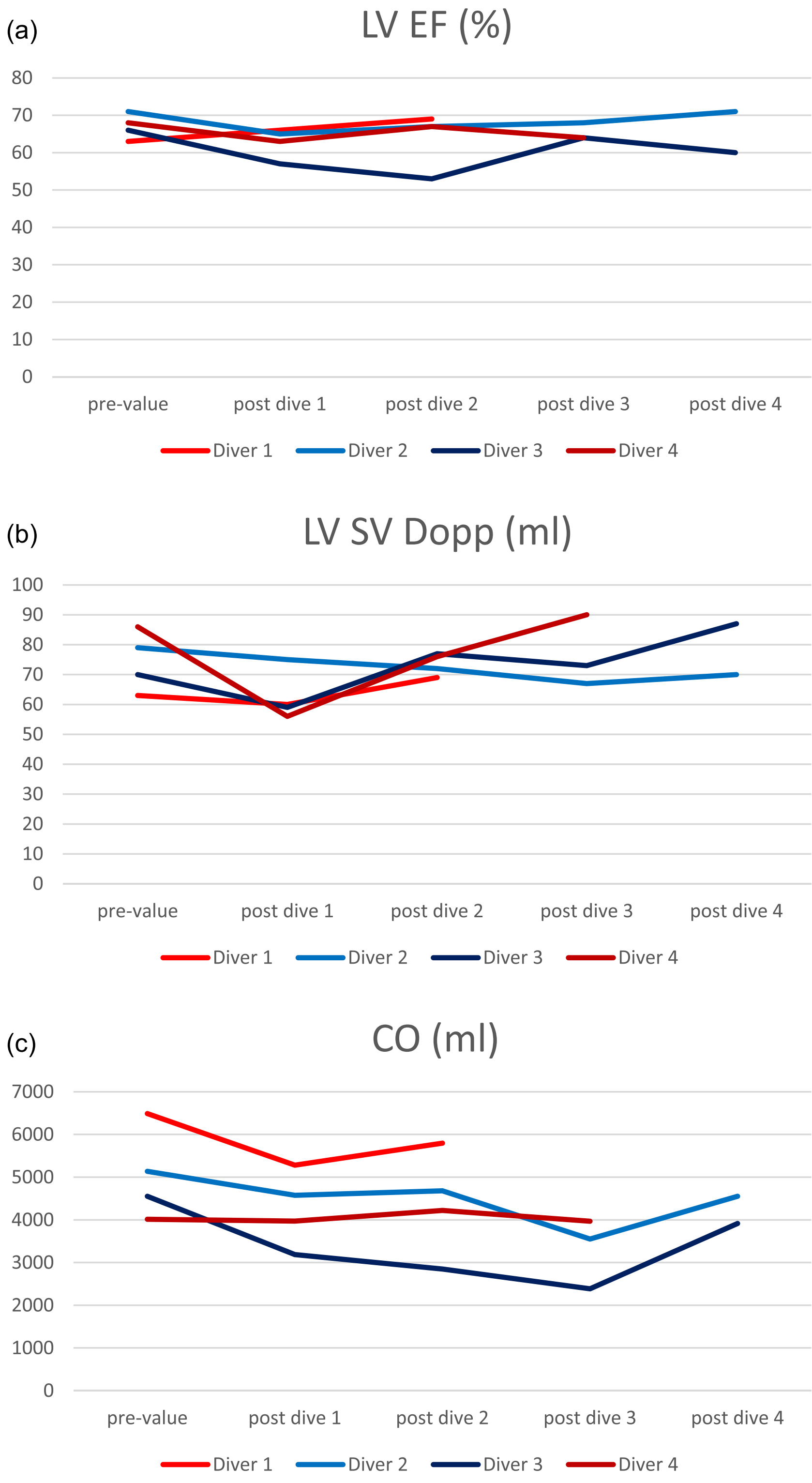

FIGURE 1 (a–c) 2D echocardiographic measures for left ventricular systolic function: (a, b) LV SV Dopp: left ventricular stroke volume and (c) cardiac output are the right parameters. Results are presented in two red tones for divers who performed two dives per day (divers 1 and 4) and in blue and dark blue for divers who performed one dive per day (divers 2 and 3). Measures were made before the first dive of the week for all divers, after each dive (divers 2 and 3) and after the second dive of the day (divers 1 and 4).

assessed from the same view. Moreover, the (E/A) ratio, the deceleration time of E velocity (MV E Dect), the mitral annular velocity (e') were measured and with the mitral annular early diastolic velocity ratio (E/e') was calculated. The mitral annular velocity was measured only in the basal part of septum wall.

On consultation of a professional biostatistician, echocardiographic measures are presented for each diver separately. Results are shown as two different groups where those who performed one dive per day (divers 2 and 3) and those who performed two dives per day (divers 1 and 4) are separated. As the number of divers and dives are small, we pooled the daily data for descriptive evaluation without further statistical evaluation.

Evaluation of possible changes in blood pressure and heart rate (from predive to postdive measures) (divers 1-3, measures on diver 4

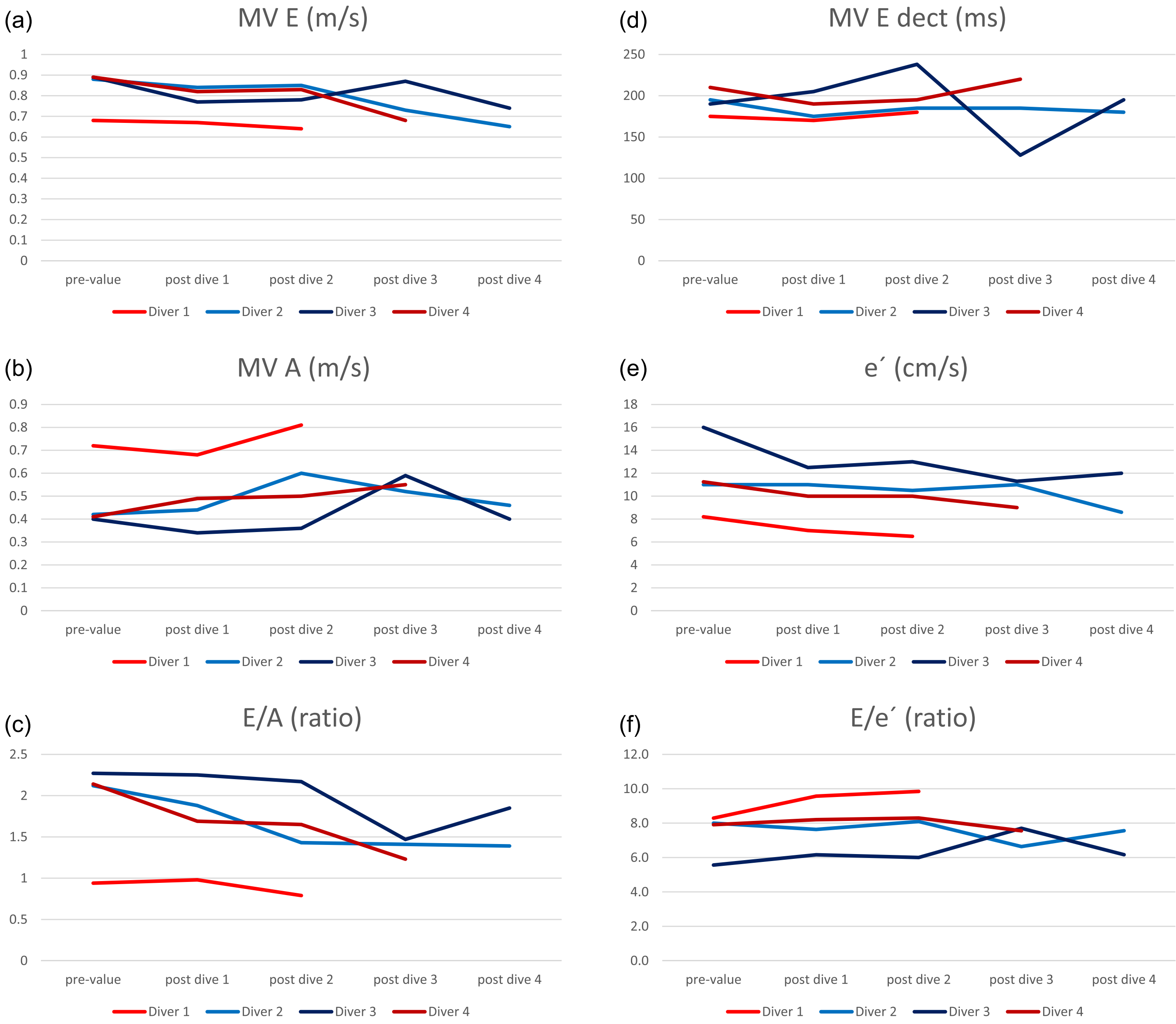

FIGURE 2 (a–f) 2D echocardiographic measures for left ventricular diastolic function: (a) MV E (m/s), (b) MV A (m/s), (c) E/A (ratio), (d) MV E dect (ms), (e) e′ (cm/s), and (f) E/e′ (ratio). Results are presented in two red tones for divers who performed two dives per day (divers 1 and 4) and in blue and dark blue for divers who performed one dive per day (divers 2 and 3). Measures were made before the first dive of the week for all divers, after each dive (divers 2 and 3) and after the second dive of the day (divers 1 and 4).

not applicable) was done by using the Student's *t* test. A significance level was set to 0.05.

3 | RESULTS

LV SV Dopp, LV EF as well as other left ventricle systolic and diastolic diameters stayed constant during the week (Figures 1 and 2). There was a trend in decrease in MV E velocity and increase in MV A velocity leading to decreased E/A ratio. Similarly, diastolic tissue velocity e′ of basal septum showed a decreasing trend while E/e′ ratio stayed almost constant. No change in the diameter of the left atria maximum diameter occurred.

Diastolic blood pressure seemed to increase from predive (mean: 83 RR mmHg, range: 66–105) to postdive values (mean: 87 RR mmHg, range: 73–111) (p=NS), but no change could be seen on the systolic blood pressure values. Heart rate decreased significantly from predive (mean: 71 bpm, range: 56–103) to postdive values (mean: 60 bpm, range: 37–88) ($p < 0.03$) (Table 2).

4 | DISCUSSION

Our small study on healthy male navy divers seemed to show a decreasing trend in left ventricular diastolic function over time during 4 days of diving in near-freezing temperature water. The measured

TABLE 2 Mean predive and postdive measures of heart rate and systolic and diastolic blood pressure values for divers 1–3 (measures on diver 4 not applicable).

Diver (number)	Heart rate (bpm) Predive	Postdive	difference	*p* (*t*-test)	Systolic BP (RR mmHg) Predive	Postdive	difference	*p* (*t*-test)	Diastolic BP (RR mmHg) Predive	Postdive	difference	*p* (*t*-test)
1	86	103.5	17.5		165	160.5	−4.5		107.5	103.5	−4	
2	61	70.5	9.5	0.03	133.25	137.5	4.25	0.58	86	83.5	−2.5	0.12
3	45.25	60	14.75		126.75	120.75	−6		77.25	68.25	−9	
4	59	63	4									

Note: Comparisons were done by using the Student's *t* test for normally distributed variables.

values remained within physiologically normal limits, and no significant deteriorating of left ventricular systolic or diastolic function occurred. As left ventricular diastolic function decreased, it was compensated with strengthening atrial systolic function. These findings were indicated by decreasing early diastolic mitral inflow, increased atrial systolic flow, decreasing E/A ratio and decreasing basal septum relaxation tissue velocity (e′) (Figure 2). A new finding—a successive change in cardiac function during several days of diving in cold water has not been described earlier.

Possible explanations for this change could be a less responsive autonomic nervous system due to repetitive diving (Berry et al., 2017) or effects of acclimatization to cold. Research on rats has shown that cold acclimatization causes volume-overload hypertrophy with increased end-diastolic volume of the left ventricle (Cheng & Hauton, 2008). An increased end-diastolic volume would at least in theory decrease the diastolic function of the ventricle. Moreover, breathing cold air during the diving days and very cold air during the dives would decrease coronary perfusion (Williams et al., 2018), which in turn could influence the responsiveness of the heart muscle. On the other hand, the last described phenomenon does not fully describe a successive change in diastolic function.

Predive and postdive blood pressure measurements showed a significant increase in diastolic pressure but not in systolic pressure. Earlier studies from immersion in cold water have shown an increase in both values, but a rapid recover to baseline values after immersion (Zenner et al., 1980). Our finding could possibly be explained with the divers' long exposure to cold and hydrostatic pressure. Both cold and hydrostatic pressure cause a centralization the peripheral blood by causing vasoconstriction of the peripheral venous system (Alba et al., 2019; Arborelius et al., 1972).

A long exposure in turn causes activation of the carotid baroreceptors and the cardiac stretch receptors, which leads to parasympathetic activation and reduced heart rate (Armstrong et al., 2021). It is possible that these later described mechanisms influenced the systolic blood pressure and therefore that value did not change. Heart rate decreased significantly during dives, estimated from predive and postdive measurements. This is in line with earlier studies from cold diving (Lundell et al., 2020).

Our study has some limitations. First, the number of divers and dives was small. This is usual in experimental field studies from extreme outside conditions. For practical reasons in harsh environment, the number of study individuals remains usually low, as was the case in our study. Therefore, the results should be interpreted with caution and with the understanding that they are only descriptive. Second, the study was not performed in stable laboratory conditions, as in a wet chamber. On the other hand, diving conditions and water temperature was constant during the week of diving. Therefore, diving conditions should not have influenced the results. Thirdly, possible acclimatization to cold during the diving week was not taken into account. Acclimatization has been described in humans, who are exposed longer times to cold (Castellani & Young, 2016).

5 | CONCLUSIONS

Our study indicated a decreasing and possibly a cumulative trend in left ventricular diastolic function in successive cold dives on a small group of healthy Navy divers. Successive changes in cardiac function could possibly cause health risks that need to be considered during cold water diving operations. Because of the limited number of divers and dives we would recommend more research on this topic, especially on possible changes to the left ventricle diastolic function, with a larger and a more balanced group of divers.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data is owned by the Finnish Defence Forces. On request, the authors can apply for permission to hand over the data for scientific purposes.

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