12-lead Holter monitoring in diving and water sports: a preliminary investigation

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Abstract

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Objective: To demonstrate the utility of 12-lead Holter monitoring underwater.

Methods: A Holter monitor, recording a 12-lead electrocardiogram (ECG) underwater, was applied to 16 pre-trained volunteer scuba divers (13 males and three females). Dive computers were synchronized with the Holter recorder to correlate the ECG tracings with diving events. Our main objective was to demonstrate the utility of recording over a period of time a good quality 12-lead ECG underwater. The ECGs were analyzed for heart rate (HR), arrhythmias, conduction abnormalities and ischaemic events in relation to various stages of diving as follows: baseline, pre diving, diving, and post diving.

Results: The ECG tracings were of good quality with minimal artefacts. Analysis of variance (ANOVA) demonstrated a significant difference in HR during the various diving stages ($P < 0.0001$). Other recorded ECG abnormalities included supraventricular ectopic beats (four cases), ventricular ectopic beats (eight cases) and ventricular couplets (two cases). Conduction abnormalities included rate-dependent right and left bundle branch block; however, these findings were previously known in these divers. No evidence of ischaemia was seen.

Conclusion: Continuous 12-lead Holter monitoring underwater can produce good quality tracings. Further studies are necessary to assess its usefulness in divers at risk for or with known coronary artery disease, and its comparison with other forms of cardiac stress tests.

Key words

Scuba diving, cardiovascular, electrocardiography, physiology, pathology, diving research, patient monitoring

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Introduction

The analysis of sudden death rates in athletes during the last 30 years in Veneto, Italy showed a significant decrease believed to be the result of implementing 12-lead electrocardiography (ECG) screening to detect silent heart disease in young athletes.[1–3] Underwater activity is a known stressor to the cardiovascular system that can lead to myocardial ischaemia in predisposed subjects, and cardiovascular disease is the third-leading cause of death during diving.[4] This highlights the potential value of implementing a valid screening tool to identify divers at risk of cardiovascular death.[5,6] Immersion in cold water, unlike warm-water immersion which is associated with peripheral vasodilatation, increased venous return and cardiac output, causes reflex peripheral vasoconstriction and bradycardia, with a resultant reduction in stroke volume and cardiac output.[7–10] Together with this left ventricular diastolic dysfunction, the postural effects of weightlessness and hydrostatic pressure force blood from the peripheries to the pulmonary circulation.[3,7] These effects occur in both breath-hold and scuba diving.[9,10] Understanding the interaction of these haemodynamic effects is crucial, particularly in divers who may suffer from ischaemic or other heart disease.[8,11]

The 12-lead ECG is valuable in detecting channelopathies, hypertrophic cardiomyopathy and the Wolff-Parkinson-White syndrome, which altogether contribute to a significant proportion of sudden deaths in athletes. Exercise testing is a tool to investigate divers with risk factors for coronary artery disease to rule out silent myocardial ischaemia and to assess their functional capacity.[12] Little attention has been paid to ECG monitoring in the aquatic environment. Since the cardiovascular stressors underwater are different from stressors during a standard exercise ECG, we thought that Holter monitoring during diving and water sports could be of value especially in divers older than 35 years who are more vulnerable to coronary atherosclerosis.[13] This presents several technical challenges such as ensuring that the instruments are water- and pressure proof and the need for electrode isolation to prevent the fall in electrical impedance with immersion in water.[14]

We hypothesized that recording a continuous 12-lead ECG underwater would detect the development of ischaemic changes that would help stratify patients at high risk for breath-hold and scuba diving. Our preliminary observations demonstrating the physiological and clinical utility of Holter monitoring underwater are reported.

Material and Methods

SUBJECTS

Sixteen Caucasian divers, 13 males and three females (age 35.1 ± 9.2 years, weight 69.6 ± 3 kg and height 172.6 ± 3.4 cm) volunteered to participate in this study. Written, informed consent was obtained and the study was approved

Figure 1
The position of the 10 electrodes in a diver using a one-piece wetsuit; a small hole in the suit at the level of the left flank allows the passage of the Holter cable

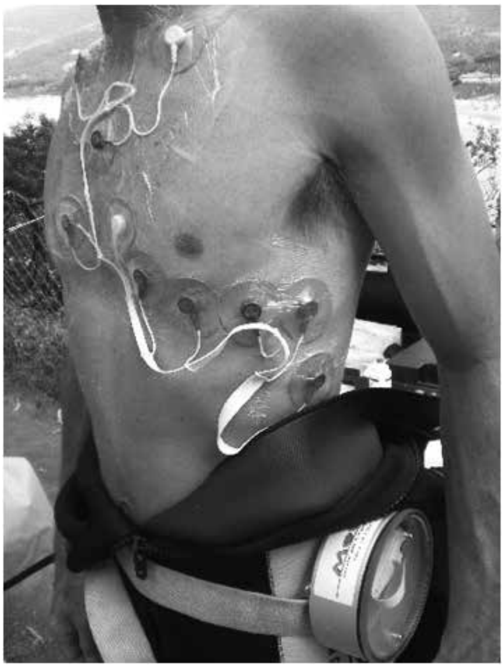


Figure 2
The Holter recorder in its pressure proof housing strapped to the diver's waist

by the University of Padova Human Research Ethics Committee (approval number 1/2014). The study followed the principles of the Declaration of Helsinki (2008 revision). The divers used their personal equipment: seven used a wetsuit, four a semi-drysuit and five wore a drysuit.

ECG MONITORING

Continuous 12-lead ECG recordings on a Holter monitor were undertaken as follows. The diver's chest was shaved, if necessary, and degreased with denatured alcohol to ensure good adhesion of the electrode patches to the skin. At the points of attachment of the self-adhesive electrodes (Kendall Arbo H34SG Tyco Healthcare and 3M Red Dot 2255), a small amount of conduction gel (Eco supergel Ceracarta, Forlì, Italy) was applied. The 10 electrodes were placed following the standard procedure used for recording 12-lead Holter as follows: slightly below the right and left clavicle, manubrium sterni, fifth intercostal space at the right and left sternal border, four electrodes along the left infra-mammary line positioned in the fifth intercostal space from parasternally to the mid-axillary line and a tenth electrode at the lower edge of the rib cage in the mid-axillary line (Figure 1). In divers using a one-piece wetsuit, a small hole at the level of the left flank was made to allow passage of the cable and the positioning of the Holter monitor (Figure 2).

After connecting the cables, the electrodes were covered with two layers of two different transparent film adhesive tapes. The first layer (Visulin, Hartmann) was used to protect the thin cables and was easily peeled off to allow the removal of the instrumentation without damaging it and to limit the discomfort during detachment from the skin. The top layer consisted of 3M Steri-Drapes; this second layer was omitted if a drysuit was used.

A digital Holter device (H12+, Mortara Instrument Europe Ltd, Milwaukee, Wisconsin) was used, weighing 125 g and capable of recording 12 channels in real time to be stored on a compact flash memory card. Its reliability in water compared to the surface was confirmed with a Bland-Alman test (unpublished data) with error < 2% of the recorded signals. The Holter recorder was placed in a pressure-proof anticorodal aluminum housing, with a Plexiglas cover (Metralabs. r.l., Padova, Italy; Figure 2), pressure tested to at least 608 kPa. There were no flooding problems and the system was well tolerated by the divers. For preliminary tests in salt water and in a swimming pool, only a single layer of Suprasorb (Lohmann and Rauscher, an analogue of Visulin) was used for better comfort. At the start of the experiment, more than one dive was performed for technical purposes until optimal quality ECGs were obtained.

MEASUREMENTS

The ECGs were recorded during scuba air dives in the sea. Dive computers were synchronized with the Holter monitor to correlate the ECG tracings with diving events. The tracings were analyzed by a cardiologist using the software H-Scribe Enterprise (Mortara Rangoni Europe, Milwaukee, Wisconsin). Heart rate (HR, beats·min^{-1}) was recorded continuously as follows: baseline before kitting up, pre dive, diving and post dive. The average HR for each individual subject during each of these four stages was then expressed as a percentage of the maximum theoretical HR for that subject, according to the formula:[18]

$$HR_{max} = 208 - (0.7 \times \text{age}) \quad (1)$$

Figure 3
Ventricular extrasystole in Subject AA at 22.5 msw depth

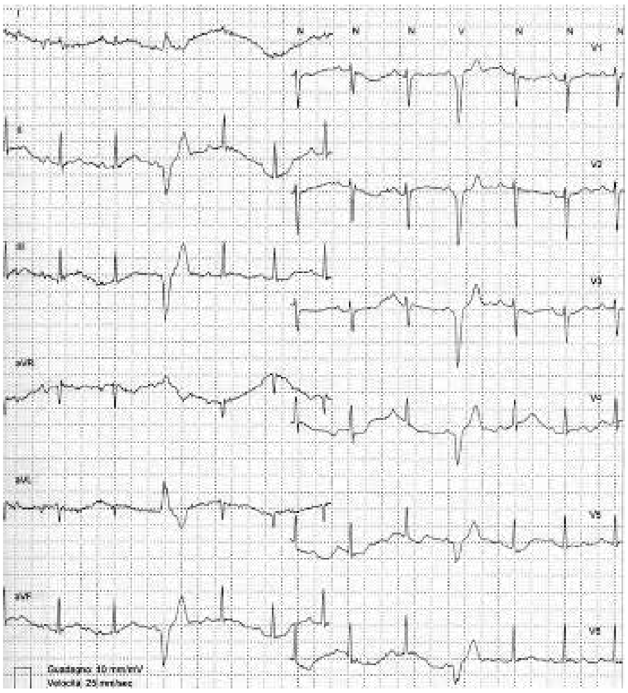
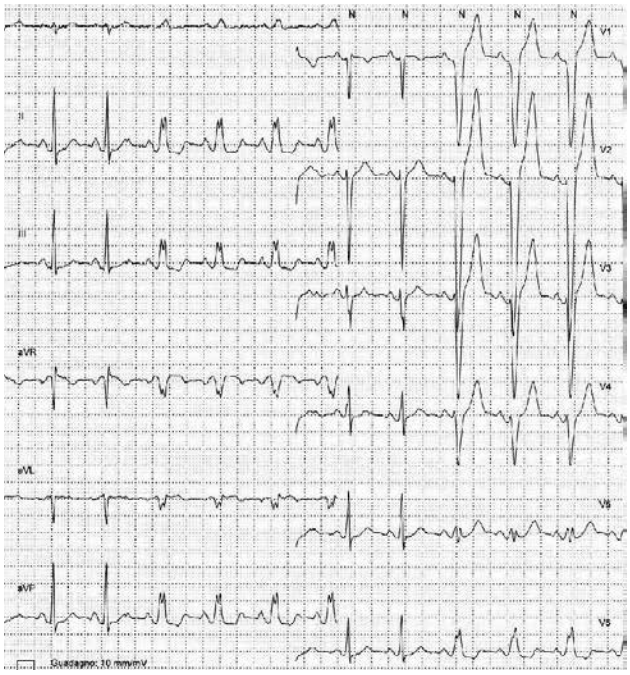


Figure 4
Left bundle branch block in Subject LS at 26 msw



As well as HR, abnormalities of conduction, such as supraventricular ectopics (SVEs), premature ventricular contractions (PVCs) and bundle branch block, as well as evidence of ischaemia, were looked for in the recordings. SVEs and PVCs were classified according to Lown's criteria.[15] Diving data included depth and duration of the dive, water temperature, air consumption and diving conditions, such as swimming against a current or low visibility.

STATISTICAL ANALYSIS

The results are expressed as mean ± standard deviation (SD). In order to determine any significant difference in HR during the various stages of diving, a one-way ANOVA was applied. Assumption of normality was verified using the Shapiro-Wilk W-test. When a significant F-value was found, the least significant difference (Bonferroni) was chosen as the post-hoc procedure. Statistical analyses were performed using the software IBM SPSS Statistic, version 15.0 (IBM Corporation, Somers, New York). The level set for significance was $P \leq 0.05$.

Results

QUALITY OF ECG RECORDINGS

All participants completed the study without any complications. The ECG tracings during diving were comparable to standard ECG tracings on dry land. There were no differences between salt and fresh water (based on the pre-trial recordings) or related to the type of diving suit worn. There were some artefacts in the recordings depending on the depth of the dive and movements of the upper limbs and trunk; however, they were insignificant and similar in extent to motion artifacts produced from athletes running on a treadmill. Generally, there was little or no loss of data.

HEART RATE CHANGES

The one-way ANOVA showed significant differences in HR during the various diving stages: Baseline–Pre-dive–Dive–Post-dive (F = 37.293, $P < 0.0001$; Table 1). The average baseline heart rate was 87 ± 2 beats·min^{-1} which increased significantly during the pre-diving stage to 135 ± 20 beats·min^{-1}. This was detected from a few seconds to 26 minutes (7.4 ± 7.9 min) before the start of descent and represents a mean HR increase of 48 ± 15 beats·min^{-1}. In

Table 1
Heart rate (HR) recorded during the diving stages (Baseline – Pre – During – Post) expressed as the mean of the percentages of the maximum theoretical heart rate (HR_{max} = 208 - (0.7 x age)) for each subject; i.e., the average baseline HR was 47.7 ± 9.93 % of HR_{max}. § This HR value represents the % difference in the mean HR between the four stages; * $P < 0.05$, † $P < 0.001$, (i.e., compared to baseline, the average HR pre-dive (denoted in the table as a/b increased significantly by 48%)

Condition	HR % (compared with HR max)‡	Δ% §	Δ% §
Baseline (a)	48 ± 9.93	a/b – 48†	a/c – 18 (ns)
Pre-dive (b)	71 ± 9.87	b/c – 21†	a/d – 24*
During (c)	56 ± 8.20	b/d – 49†	c/d – 35†
Post-dive (d)	36 ± 10.16		

Table 2
Demographic and dive characteristics (dive duration, air consumption, maximum depth and minimum temperature achieved) of the 16 subjects; the recorded HRs during the 4 diving stages and the occurrence of ECG abnormalities; means and standard deviation (SD) shown in the bottom row; BMI – body mass index; msw – metres' sea water; PAC – premature atrial contraction; PVC – premature ventricular contraction; BBB – bundle branch block; LBBB – left bundle branch block; RBBB – right bundle branch block

Subject	Sex	Age (yrs)	BMI ($kg \cdot m^{-2}$)	Certification	Suit	Temperature (°C)	Depth (msw)	Duration (min)	Heart rate ($beats \cdot min^{-1}$) Baseline	Pre dive	Dive	Post dive	PAC	PVC (couplets)	BBB
DE	F	32	18.2	Advanced	wet	16	30.5	43	90	132	105	69	0	1	–
BC	M	33	25.4	Rescue	semi-dry	21	24.3	53	80	135	90	59	1	0	–
DF	M	39	22.9	Open	dry	12	22.9	39	120	170	120	100	0	14 (2)	–
EF	M	35	22	Open	dry	17	22.1	34	90	130	120	80	0	0	–
ED	M	36	20.3	Dive master	dry	17	19.2	38	70	129	90	49	0	0	–
CR	M	33	24.9	Open	dry	18	21.8	46	85	135	115	74	0	0	–
PE	M	39	31.1	Advanced	dry	16	28.4	36	100	154	115	93	0	0	–
AD	M	42	24.9	Dive master	wet	18	22.9	38	70	149	95	49	0	2	–
GD	F	36	19	Advanced	semi-dry	20.5	7.2	55	80	115	85	52	0	0	–
LS	M	37	26	Tech diver	wet	10.4	33.1	45	85	150	95	68	1	2	LBBB
AA	M	45	24.2	Instructor	wet	18	37.5	50	95	120	100	50	0	10	–
BA	M	27	22	Instructor	wet	18	32.3	46	85	95	95	75	0	0	RBBB
CL	M	19	22.5	Open	semi-dry	18	21.2	45	85	130	120	70	0	1	–
CG	M	57	24.2	Rescue	wet	17.5	19	36	115	167	120	80	12	9 (1)	–
CA	M	32	21.5	Advanced	semi-dry	18	26.6	45	87	141	85	59	1	4	–
RI	F	19	19.8	Advanced	wet	18	33.4	42	55	109	90	31	0	0	–
Mean (SD)		35.1 (9.2)	23.3 (3.1)			17.1 (2.7)	25.2 (7.4)	43.2 (6.2)	87.0 (16.0)	135.1 (20.1)	102.5 (13.7)	66.1 (17.9)			

four cases, the increase in the HR was recorded immediately prior to the descent and in one case while swimming at the surface to reach the point for the descent. The two professional divers in the group showed the smallest increases in heart rate (10 and 25 beats·min^{-1} respectively).

Slowing of the HR developed during the descent and was maintained between 85 and 120 beats·min^{-1} (102 ± 13.7 beats·min^{-1}) throughout the dive, with no correlation to the depth of immersion. A decrease in HR to 66 ± 17.9 beats·min^{-1} was observed post dive which represents a significant decrease compared to the baseline HR (19 ± 7.8 beats·min^{-1} lower) and the pre-dive HR (68 ± 18.1 beats·min^{-1} lower). The lowest HR was observed between 7 min before surfacing until 20 min after surfacing.

DYSRHYTHMIAS AND CONDUCTION ABNORMALITIES

Supraventricular ectopic beats were identified in four subjects, ventricular ectopic beats in eight subjects and ventricular couplets in two subjects. Two divers had one PVC during the ascent and after emergence (Figure 3), two divers had two PVCs both during the descent, one diver had four PVCs, one nine PVCs, one had 10 PVCs and one diver who was already known to suffer from PVCs had 14 (all Lown class 1). Two divers had two consecutive PVCs (couplets, Lown class 4a which carries a higher risk of degenerating into ventricular arrhythmia). The ventricular couplets were recorded 10 min before descent in one case and 2 min after surfacing in another case. Conduction abnormalities, including right bundle branch block and rate-dependent left bundle branch block (LBBB, Figure 4), were recorded; however, this diagnosis was not new for either of these divers.

None of the divers experienced chest pain during diving. There were no observed ST-segment shifts to suggest ischaemia in any of the recorded ECGs. Table 2 represents a compilation of the demographics, dive characteristics, the recorded HR during the four diving stages and the occurrence of arrhythmias in the 16 study subjects.

Discussion

The first underwater Holter studies, carried out in 1970 on breath-hold divers using magnetic tape recordings, correlated the breath-hold immersion-induced bradycardia with the duration of the apnea and the speed and depth of descent. Increased parasympathetic activity was demonstrated in healthy subjects during scuba diving and heart rate variability (HRV) assessed using 2-lead Holter monitoring.[15,17–19] Unlike patients with heart disease where a decrease in the HRV is associated with a higher risk of cardiac death, the significance of a reduced HRV in a healthy person is unknown. Despite the technical limitations, the occurrence of arrhythmias in elite breath-hold divers during deep diving in the sea has been recorded using 3-lead ECG monitoring.[8] Others have recorded ECG and depth simultaneously using an ECG device with an integrated pressure sensor.[18] There are also reports of simultaneous recording of a 2-lead ECG, oxygen saturation, depth and temperature underwater up to a depth of 10.5 metres.[20]

The current study demonstrated the feasibility of recording 12-lead ECG underwater, with good quality tracings similar to those during exercise treadmill testing. We found a maximum increase in HR in the pre-diving stage, slowing at the end of the dive. This increase in the pre-dive HR was unrelated to physical effort and was mostly detected at rest during the waiting period prior to the descent. The two professional divers showed only minor HR increases before descent, confirming that this HR rise is likely linked to an emotional phenomenon causing sympathetic stimulation.[21] This emotional origin of tachycardia prior to performance is well known and correlates with the type of sport, being most significant with high-risk activities, such as motor racing, downhill skiing or skydiving.[22]

During the dive, HR was constantly maintained higher than baseline with minimal variability. An important finding was the bradycardia recorded at the end of the dive, a phenomenon reported previously after recreational scuba diving.[6] Hypothermia-induced bradycardia during cold-water immersion is a possible explanation for this phenomenon; bradycardia is a recognized haemodynamic finding in hypothermia.[23] Also, the shift of blood volume into the thoracic vasculature with immersion stimulates cardiopulmonary baroreflexes with a resultant parasympathetic effect and bradycardia. [8]

The occurrence of PVCs did not correlate with any particular stage of the dives, although they were most commonly seen immediately pre dive and post dive. The development of rate-dependent LBBB provoked a complete re-evaluation of this diver, confirming his unsuitability for diving. In the absence of underlying heart disease, the presence of PVCs usually has no impact on limiting activity and their numbers usually decrease during exercise owing to overdrive suppression of ectopic pacemakers by the fast sinus rhythm. An increase in PVC frequency during exercise should therefore prompt evaluation of the cardiac status of the diver.[24]

The main limitation of the study is that these dives were not standardized for immersion times and depth of exposure, as our main purpose was to demonstrate the feasibility of recording 12-lead ECG underwater. The need for meticulous placement of the electrodes and proper insulation for ideal signal transmission cannot be over-emphasized. We have demonstrated the feasibility of dynamic 12-lead ECG recording underwater producing good quality tracings, with no reduction in voltage, and minimal motion artifacts. Since Holter monitoring is the gold standard for detailed diagnosis of acute ischaemia and arrhythmias, it will be useful particularly for assessing the older diver, those with risk factors for coronary artery disease and those starting a professional water sports career. Its advantage over standard exercise testing (e.g., Bruce protocol) is that it directly reflects the interaction between the underwater environment with its unique stressors and the cardiovascular system. Based on this experience, further studies under more strictly controlled conditions should be undertaken to assess the value of underwater Holter monitoring compared to other forms of cardiac stress tests.

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