Wearable Real-Time ECG Monitoring with Emergency Alert System for Scuba Diving

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***Abstract*— Medical diagnosis is the first level for recognition and treatment of diseases. To realize fast diagnosis, we propose a concept of a basic framework for the underwater monitoring of a diver's ECG signal, including an alert system that warns the diver of predefined medical emergency situations. The framework contains QRS detection, heart rate calculation and an alert system. After performing a predefined study protocol, the algorithm's accuracy was evaluated with 10 subjects in a dry environment and with 5 subjects in an underwater environment. The results showed that, in 3 out of 5 dives as well as in dry environment, data transmission remained stable. In these cases, the subjects were able to trigger the alert system. The evaluated data showed a clear ECG signal with a QRS detection accuracy of 90 %. Thus, the proposed framework has the potential to detect and to warn of health risks. Further developments of this sample concept can imply an extension for monitoring different biomedical parameters.**

I. INTRODUCTION

Diving with a self-contained underwater breathing apparatus (SCUBA) is a modern and popular sport and practiced by a variety of people, ranging from amateurs to professionals. Although it is a well-known activity, scuba diving can be dangerous. Dangerous situations can lead to a variety of medical problems or even to death [1]. Relating to the BSAC Diving Incident Report 2014 [2], a significant number of incidents still occur and more than half of them were related to internal preexisting illnesses. The concept of an efficient diagnosis of the diver's current condition combined with an alert system could save lives. A diagnostic system could be realized by monitoring and recognizing physiological parameters, e.g. heart rate or electrocardiogram (ECG), during scuba diving.

Mobile devices are an effective option to monitor health parameters. Hence, smartphones and health applications are often used as wearable health diagnostic systems [3] [4]. In particular, the use of mobile devices for ECG analyses is an emerging field in science and telemetric medicine [5]. In addition, information obtained from ECG analyses and arrhythmia detections can be used for an alert system that warns subjects in critical situations. Applying such a system to an underwater environment opens the door to improve the safety of scuba diving.

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An approach of implementing ECG analyses on a smartphone was provided by the work of Goh et al. [6]. They proposed computer simulation models to evaluate the performance of appropriate ECG analysis techniques for smartphone devices. A study of the suitability of ECG analysis algorithms for mobile devices was performed by Elgendi et al. [7]. They examined current QRS detection algorithms for battery-operated devices. In another project, Gradl et al. [8] provided *Hearty*, an Android-based application that allowed real-time ECG monitoring and automated arrhythmia detection. Schipke and Pelzer [9] described a study of ECG recording while scuba diving. They performed an underwater ECG recording with post-diving analysis of heart rate variability. However, there is no known approach of a real-time analysis system for ECG signal during scuba diving that automatically alerts the diver and his surrounding of critical situations. In this work, we present a performance evaluation of a concept of an alert system consisting of wearable real-time ECG and smartphone technology capable to be applied and used during scuba diving. We monitored the divers' heart rates and an alert that was triggered when the heart rate exceeds a predetermined level of heart beats per minute (bpm). The heart rate was chosen as one sample application of physiological parameters that could be monitored and analyzed during scuba diving.

II. METHODS

A. Data Acquisition

1) Hardware: All data were collected with the *Shimmer 2R* (Shimmer Research Ltd., Dublin, Ireland) [10] wearable sensor for ECG recording. The sensor was placed on the middle of the subject's chest. Three ECG electrodes were placed according to the rules of Einthoven's triangle: two electrodes below the right and the left clavicle and a third electrode placed on the abdominal region above the right leg. All data from *Shimmer* were transferred wirelessly to a smartphone using *Bluetooth 2* technology. The used smartphone end device was a *Samsung Galaxy S2*. It was placed in a waterproof, professional diving bag for electric devices and attached to the subject's chest. The entire equipment setup is shown in Fig. 1.

2) Study Design: The study was designed in two parts, a *General study* and a *Diving study*. The first part, the *General study*, was performed in dry environment with 10 subjects (gender: 7 male and 3 female, age [years]: 21 $\pm$ 3, height [cm]: 175.0 $\pm$ 6.5, weight [kg]: 80.0 $\pm$ 7.5). Each subject was equipped with ECG electrodes, a *Shimmer* sensor and a

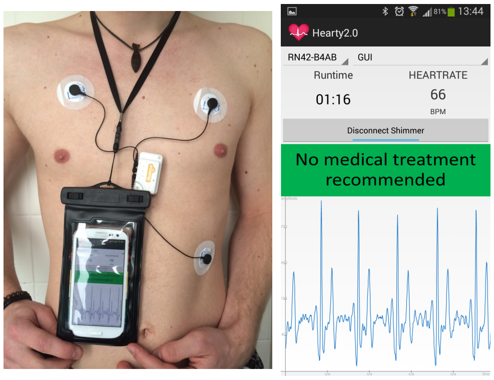

Fig. 1. **Left:** The ECG sensor was placed in the middle of the chest. The ECG electrodes were attached according to the rules of Einthoven's triangle. The smartphone was placed in a professional diving bag. **Right:** Screenshot Hearty application: The GUI contains a line plot for the raw ECG signal and two windows display the runtime and the heart rate in bpm.

smartphone. At the beginning of this study part, all subjects had to rest while the algorithm determined an average resting heart rate. Subsequently, the subjects did squats to increase their heart rate. After reaching a specified increased heart rate, the subjects had to rest to drop their heart rates below an average level. The procedure was repeated twice. This study part was used to evaluate the framework's utility and to obtain a database for further evaluation.

As a second part, the *Diving study* was performed in an indoor swimming pool (water depth of 2.7 m, water temperature of 26.0 °C) with five subjects (gender: 3 male and 2 female, age [years]: 35 ± 12, height [cm]: 180.0 ± 6.5, weight [kg]: 80.0 ± 7.5). All subjects were trained, experienced scuba divers and equipped with a drysuit to protect the electric devices of water damage. As in the first part, the subject had to rest for determining an average heart rate. All subjects had to dive for five minutes in slow pace, followed by high-speed swimming to increase the heart rate. After the exertion, the subject returned to an average heart rate level by slowing down their movements. This cycle was repeated between one and four times per diver.

The Institutional Ethnical Review Board approved the acquisition and processing of non invasive biomedical data. In addition, all divers were informed of diving-related risks and gave written consent to participate in the study and for the collected data to be published.

B. Algorithm

1) QRS detection: For QRS detection the algorithm, originally described by Gradl et al. [8] in their Android-based application *Hearty*, was implemented. As a first processing step, the raw ECG signal was detected from Einthoven's lead II. In the second processing step the raw ECG signal was filtered. All filtering steps were based on the proposed algorithm by Pan & Tompkins [11]: (i) bandpass, consisting of low-pass and high-pass filters, (ii) a five-point differentiation filter, (iii) a point-by-point squaring operation filter, (iv) a moving window integration filter. A threshold X, which was computed by a moving window average filter with a window size of 150 ms, was used to detect QRS complexes. If a processed signal value reached the threshold X, a QRS complex was detected. An average heart rate was calculated from the detected QRS complexes.

2) Alert system: A warning alert system was implemented which warned the diver of a critical condition. For the evaluation of this work, the critical condition was defined as two thresholds, T_1 and T_2. These thresholds were used to trigger an alarm if the heart rate fell below or exceeded above the limits. The lower threshold represented a bradycardia and the higher threshold represented a tachycardia. Average critical heart rates could be considered as 43 and 180 bpm [12]. To avoid dangerous situations during the data acquisition, a lower critical heart rate was defined for each subject individually. The resting heart rate, obtained from the resting phase at the beginning of each study, was calculated for each subject individually. In addition, the thresholds were set to permanent values by decreasing and increasing the resting heart rate by 40 bpm. The entire procedure was accomplished before the subjects started their activities. If either threshold was reached the alert system was triggered. Other biomedical parameters than the change of heart rate were not considered and evaluated in this study.

C. Implementation

Java^{TM} with *Android SDK* 2.3.3 (Google Inc., Mountain View, USA) was used to implement the software framework. Android provides a simple integration of external ECG sensors to the mobile device via Bluetooth.

1) Data Processing: During data acquisition, the *Shimmer* ECG sensor was connected via Bluetooth to the smartphone. In all studies, data were transferred to the mobile phone and processed by the application *Hearty* in real-time. In addition, the ECG signal data and a timestamp were written to the internal memory of the smartphone.

2) Graphical User Interface: A graphical user interface (GUI) was implemented for starting and controlling the application. Windows for the current heart rate and the runtime and a line plot of the raw ECG signal were implemented for visualization (Fig. 1).

3) Alert System: The warning was realized by vibration and alarm noise. Those measures were chosen to warn the diver in multiple ways, by the smartphone vibration pattern movement and loud noise sound effects.

D. Evaluation

The data transmission was evaluated in order to verify a stable *Bluetooth* connection. Therefore, the data visualization was observed and analyzed for outages during the entire data acquisition in the *General study*. In contrast, a continuous observation was not possible in the *Diving study* due to fact that the smartphone was placed inside the drysuit. The framework was programmed that if the *Bluetooth* connection broke, it would not reconnect. Therefore, a stable connection after the dive was taken as evidence for a stable connection throughout the entire dive. Both studies were also evaluated offline in order to detect transmission outages that could not be noticed during the acquisitions.

The quality of the ECG recording was evaluated to confirm the reliability of the ECG analysis. This evaluation was only performed on the records obtained from the *Diving study*, as the application is intended for use during scuba diving. The ECG behavior was defined as frequent QRS complex appearance, the length and amplitude of QRS complexes, and the interval length between QRS complexes. In addition, the total number of heart beats during a dive was recounted in the offline analysis. This was compared with the total number of heart beats detected by the real-time algorithm. For both the quality evaluation and heart beat detection, *Matlab* R2013a (The MathWorks Inc., Massachusetts, USA) was used.

The alert system was evaluated in both studies to determine if it was triggered correctly. During the data acquisition, a warning was expected when the heart rate reached one of the thresholds, T_1 or T_2. In the *General study*, the interval between the resting heart rate and the threshold value was evaluated weather or not the interval equals the set 40 heart beats by the algorithm. During the *Diving study*, the evaluation only relied on the diver's feedback as to whether or not the alert system was noticeable and how often the alert occurred.

III. Results

During the *General study*, a continuous data transmission was observed in all cases on the smartphone display. In the offline evaluation, it was noted that no data points were missing in the signals. However, in the *Diving study* only three out of five data transmissions remained streaming after the dive. The offline evaluation showed that in the remaining two cases the connection broke after a few seconds (Tab. I). The data of these two subjects were not used for further evaluation.

An example of the recorded ECG signal's quality is given in Fig. 2. The characteristic behavior was observable in the frequency and continuously stable interval lengths of the QRS complexes. The evaluated QRS complexes showed typical amplitudes and lengths which can be seen in Fig. 3. Offline evaluation of the total number of heart beats showed that on average the algorithm detected 90 % of all heart beats correctly (5531 out of 6085).

The observation of the alert system during the *General study* revealed that the alert was triggered correctly as soon as the subject exceeded its heart rate above the threshold T_2. The relative number of heart beats between the resting heart rate and threshold limit was observed to be similar for all subjects. In the *Diving study*, the three divers with stable *Bluetooth* connection noticed the smartphone vibration but not the sound effect.

IV. Discussion

With the provided concept, real-time monitoring of divers' ECG signals was observable during the *General study*. The monitoring was also available during scuba diving. However,

TABLE I

Evaluation Alert System Visualization of the transmitted data during the study and the offline analysis. 'G' represents the General study and 'D' the Diving study. The number of triggered alarms by each subject is shown as well.

Subject	Stream	Signal analysis	Alerts triggered
Subject 1-10 G	√	√	23
Subject 1 D	√	√	4
Subject 2 D	√	√	2
Subject 3 D	√	√	1
Subject 4,5 D	X	for a few seconds	-

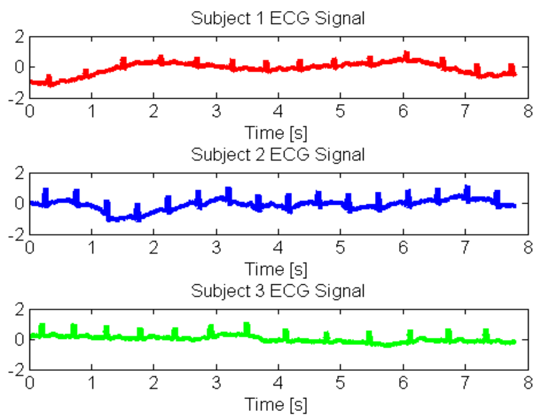

Fig. 2. **Recorded ECG signals during scuba diving**. ECG signals were recorded from three different subjects. All signals show typical behavior for an underwater ECG, as the curved trend, which represents the heavy breathing movement of the chest during diving.

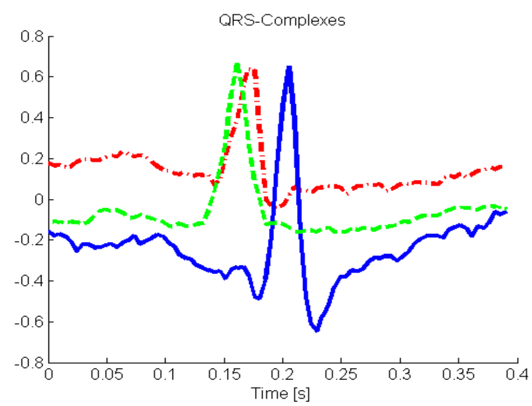

Fig. 3. **QRS complexes**. All QRS-Complexes were selected randomly from three different subjects (subject 1 - red; subject 2 - blue; subject 3 - green). Each QRS complex was evaluated by its length and amplitude.

due to the limitation of the dry suit, a direct view to the screen was not possible during the *Diving study*.

The results showed that the connection broke twice during underwater data acquisition. This could be caused by the surrounding water, which interfered with the *Bluetooth* connection. Another possibility is that the connection got lost because of the moving breathing equipment that pressed against the framework. Due to the known connection problem of *Bluetooth* in water, the pumped air in the dry suit was considered as an environment good enough for short range Bluetooth connection. However, it would be beneficial to investigate an alternative route for underwater data transmission. Another possibility could be specialized electromagnetic waves for short range communication as suggested in [13]. Furthermore, a wider range of signal transfer would allow biomedical parameters to be transmitted to the diver, their diving partner or an external observer on land, who could react immediately in case of emergency.

Evaluation of the ECG signals demonstrated that the signals were clear with little noise and showed detailed, diving-specific events. For example, the curved trend of the ECG signals represented the strong breathing of the divers (Fig. 2). All information provided by the offline plotted signals could be used for intense medical monitoring and diagnosis. This could lead to better and more detailed knowledge of how diving diseases occur. With this knowledge, new treatments, especially for emergency medicine, could be developed. Despite the quality of the ECG signals, the real-time algorithm detected less heart beats than counted in the offline study, caused by artifacts in the signal. One source of artifacts was the diver's heavy movement in combination with the pressure of the tightly equipped diving apparatus on the framework. Due to the used ECG electrodes, sweat was not considered as a source of artifacts. Only the total number of heart beats was evaluated, due to the fact that the real-time detected beats were not observable after the study. The equality of both real-time and post-study detected heart beats was assumed. Installing the framework in a more compact form on the diver's chest, the susceptibility of the system to these artifacts can be reduced.

Evaluating the results of the alert system showed that the smartphone vibration was effective but the sound effect was not loud enough. The sound effect would need to be louder in order to improve the system. This could be achieved by using a louder speaker or playing a tune with different frequency spectrums. The alert system was only evaluated by increasing the heart rate to threshold T_2. Attempting to decrease the heart rate to the threshold T_1 was not feasible to simulate in a safe manner. The heart rate alert system was used to prove the utility of the system. However, the alert system should be extended with several arrhythmia detections and evaluated in a clinical study. The used Android application already contains an ECG arrhythmia detection, as it was proposed in the work of Gradl et al. [8]. In this work, the arrhythmia detection was not involved and evaluated in the alert system, due to the fact that only healthy divers participated in the study. The accuracy of the alert system could not be proved by using another reference system during diving. Therefore, the *General study* was performed to obtain a data base to prove the accuracy.

Ideally, the entire framework can be waterproofed to improve the ease of use. To accomplish this, all framework components would need to be developed for underwater use. An example is given by Reyes et al. [14] who suggested waterproof ECG electrodes.

V. Conclusion

In this work, we present the concept of a basic real-time ECG analysis system with alert function capable for scuba diving. All obtained results show the good accuracy of the analysis system as well as the alert system. Thus, we recommend the concept of the framework for further developments and improvements of the alert system.

Applications of the described system can be used to increase diving safety by providing real-time monitoring for early detection of medically dangerous conditions. Especially for elderly people, a feedback system of the body's reaction to diving could lower diving incidents. For further studies and developments, the provided framework offers the opportunity for clinical monitoring of a person's biomedical signals under diving conditions. This could lead to better medical differentiation between actual diving incidents, like arterial gas embolism or decompression sickness, and internal illness related incidents, like heart attacks or arrhythmia, because a physiological change can be monitored when it actually occurs.

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