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Diving Into Research of Biomedical Engineering in Scuba Diving

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***Abstract*—The physiologic response of the human body to different environments is a complex phenomenon to ensure survival. Immersion and compressed gas diving, together trigger a set of responses. Monitoring those responses in real-time may increase our understanding of these and help to develop safety procedures and equipment. This review outlines diving physiology and diseases and identifies physiological parameters worthy of monitoring. Subsequently, we have investigated technological approaches matched to those in order to evaluated their capability for underwater application. We focused on wearable biomedical monitoring technologies, or those which could be transformed to wearables. We have also reviewed current safety devices, including dive computers and their underlying decompression models and algorithms. The review outlines the necessity for biomedical monitoring in scuba diving and should encourage research and development of new methods to increase diving safety.**

***Index Terms*—Decompression Sickness, Decompression Algorithms, Diving Medicine, Dive Computer, Medical Engineering, Physiological Monitoring, Scuba Diving, Wearables.**

I. Introduction

Diving is practiced in many settings including recreational, commercial and military diving [1]. All variations carry physical risks related to the underwater environment and can result in negative consequences manifesting in different diving-related diseases, ranging from immediate abnormalities such as decompression illness [2], [3] to long-term or late effects such as neurological impairment [4]– [6]. Despite the rarity of lethal injuries, the risks associated with diving suggest the need to develop a device capable of real-time monitoring and analysis of bio-signals while diving and during diving injury assessment [7]. The development of underwater monitoring technology may result in safety equipment for divers that could be used for both real-time monitoring and data acquisition for later analysis, as well as increased underwater working time for commercial and military divers [1]. Evaluated data may improve the fundamental understanding of the pathophysiology in diving because physiological changes are measured as they occur.

In diving medicine, the physical effects of immersion and pressure elicit physiological responses. These responses have been well-described and are closely associated with the development of a number of diving-related diseases [8]. In relation to the preeminent physiological parameters, matching monitoring approaches are investigated. On the basis that invasive methods of monitoring are impractical for scuba diving, we assessed each technology for the ability to be adapted for the use as a wearable, including electrocardiography, blood pressure and volume shift technologies.

Common dive technologies currently in use include dive computers that calculate decompression obligations in real-time using various decompression tables, models and algorithms [9]. Diving computers are the state of the art tool for divers to monitor their depth and time in order to reduce the chance of decompression injuries [10]. The core function of any dive computer is the operating decompression models / algorithms used. These models calculate decompression schedules to step divers safely to the surface while avoiding critical supersaturation of various tissues with inert gas.

Sophisticated methods for monitoring the physiological status of divers while in the water is a topical subject. While recent articles have highlighted interest in this area [11] – [15], our aim is to comprehensively review the relationship between technical approaches to wearable monitoring during immersion and the prevention and diagnosis of diving-related pathology.

II. Diving Medicine

Diving and hyperbaric medicine [16] deals with diseases and injuries related to high ambient pressure, hyperbaric oxygen and immersion. Fatalities and injuries are reported by the Divers Alert Network (DAN) Annual Diving Reports [17]. In the latest report from 2015, DAN presents some analyses of scuba dive fatalities involving U.S. citizens, predominantly in the USA or Caribbean (Fig. 1). Most fatalities occurred in male divers aged 50-59 years. Investigations of experience level and diving activity revealed that most fatalities occurred when divers were inexperienced and the deaths occurred during recreational diving (65%). Although drowning is the most commonly attributed cause of death, this is sometimes secondary to disabling agents such as cardiac arrhythmias or myocardial infarctions, particularly in older divers. A discussion of monitoring that might prevent cardiac death in general is outside the scope of this review but may become applicable

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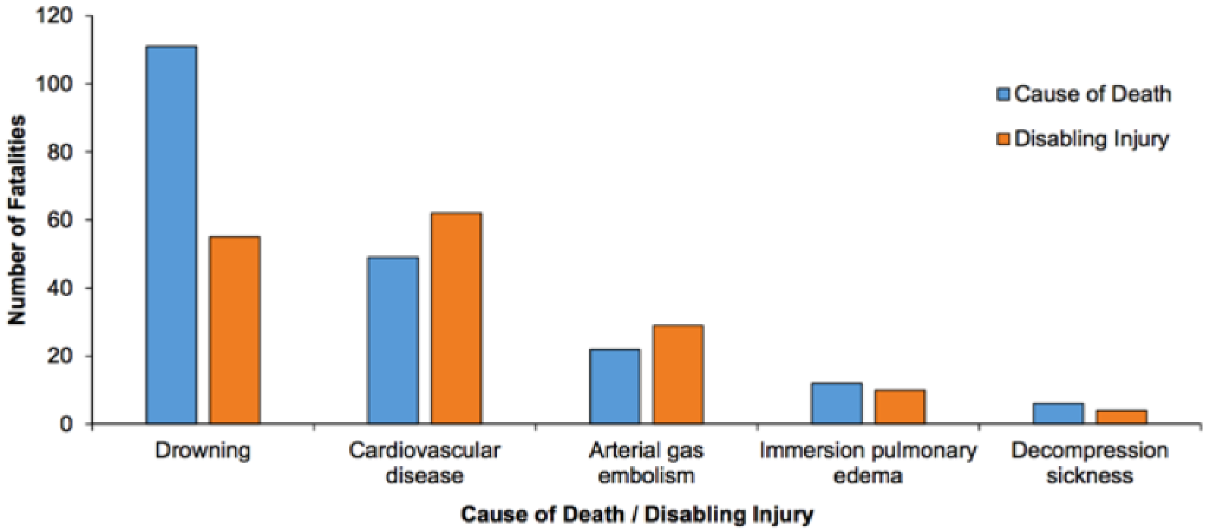

Fig. 1. Divers Alert Network investigation of diving fatalities in the USA from the Annual Diving Report 2015 [17]. Drowning and pre-existing cardiovascular diseases are the two major causes of death. However, drowning has also be considered as a result of other existing diseases or injuries.

in divers in the future. The pattern of fatality indicates the need to target injury monitoring and prevention including improved diver education.

A. *DIVING PHYSIOLOGY*

The human body is adapted to the terrestrial environment, performing best at 1 atmosphere absolute (ATM). Unsurprisingly, significant physiological changes occur when the body is immersed and subjected to increased pressure. The 'diving reflex' is the initial physiological response to immersion and is most prominent in cold water and exposure of the face [5]. Initially there is a restriction of blood flow to the peripheries (peripheral arterial vasoconstriction) and a reflex bradycardia [16]. There is also venoconstriction secondary to hydrostatic forces and combined with cooling peripheries this results in shunting of blood into central veins [18]. The net result of increased venous return, increased stroke volume and the reflex bradycardia is a modest increase in cardiac output [19]. The increased venous return also stimulates atrial receptors to release atrial natriuretic factors (ANF) in response to stretching which, in addition to an associated decrease of anti-diuretic hormone (ADH), results in unopposed diuresis [8].
High ambient pressure also impacts respiratory mechanical factors [20]. When the diver is upright (particularly head out of the water), the higher pressure on the chest wall compared to the mouth will result in compression of the thoracic structures and require an increased negative pressure generation in the lungs to achieve inspiration. This further encourages increased venous return to the heart and exacerbates the hemodynamic changes.

B. *DIVING DISEASES AND INJURIES*

1) DROWNING: Drowning, defined as a process of experiencing respiratory impairment from submersion in liquid [21], is the fourth commonest cause of injury-related death accounting about half a million deaths annually worldwide [22]. During this period the victim is unable to ventilate the lungs, resulting in oxygen depletion and carbon dioxide retention. The victim will become hypercarbic, hypoxemic and acidotic and will frequently inhale water leading to death [23]. Drowning often occurs as a consequence of a primary cause associated with a reduced level of consciousness and the loss of upper airway reflexes [24].

2) CARDIAC DISEASES: Sudden cardiac death while immersed is mostly a result of myocardial infarction or a cardiac dysrhythmia [25]. Diving induces a series of stresses (exercise, cold, breath-holding, diving reflexes) which may impact on cardiac function. These factors can be exacerbated by a reduction of blood volume secondary to the diuresis induced by immersion, tachycardia or bradycardia, hypertension and increased cardiac work [26]. Undoubtedly, pre-existing cardiac disease increases the risk of sudden death. While the presence of myocarditis, hypertrophic cardiomyopathy or genetic disorders predispose young subjects to cardiac death, cardiac disorders in older subjects are more often associated with hypertension, dysrhythmia or triggering events [27]. Minor cardiac conditions may preface major problems in divers.

3) BAROTRAUMA: Describes injuries to the body as a result of changes in barometric pressure [8]. Rapid changes in ambient pressure can cause serious damage to several body systems where gas is contained within tissue. Most commonly barotrauma affects the middle-ear, lungs and respiratory sinuses.

4) GAS TOXICITY: Oxygen toxicity and nitrogen narcosis are hazards caused by inspired gases during scuba diving. Oxygen toxicity [28] occurs when breathing an elevated partial pressure of oxygen and depends on the pressure degree and exposure time. It is considered to result from reactive oxygen species (sometimes called 'free radicals'). When present in sufficient concentration, these species can overwhelm the available antioxidant systems and result in temporary or per-

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manent tissue injury [29]. While the lungs may be affected over a longer period of continuous exposure, the more grave danger for divers is central neurological oxygen toxicity which can manifest as a grand mal seizure without warning.

Nitrogen narcosis [30] is a result of the ability of nitrogen to produce narcotic effects similar to volatile anesthetic agents. With an increasing partial pressure of nitrogen in the central nervous system, the diver will be increasingly impaired and ultimately lose consciousness. The narcotic effect is probably due to an impairment of cell membrane function. While oxygen effects on the lungs and other tissues may persist for some time, nitrogen narcosis is completely reversible when ambient pressure decreases.

5) HYPOTHERMIA: Water conducts heat 25 times better than air. Determined divers may drop their core temperature to a point of mild hypothermia (33–35°C). This causes shivering, marked diuresis and numbness from peripheral vasoconstriction. Lethargy may cause poor decision-making with further cooling causing incoordination, unconsciousness and drowning [31].

C. DECOMPRESSION ILLNESS

Decompression illness (DCI) is the umbrella term to describe health problems caused by the effect of gas (usually nitrogen) in the blood, the tissues and organ systems as a result of exposure to changing ambient pressures. The term includes Decompression Sickness (DCS) where problems derive from gas dissolved within the tissues and later liberated on decompression and arterial gas embolism (AGE) (Fig. 2), [32]. AGE often results from pulmonary over-distension and the subsequent entry of breathing gas in pulmonary vasculature. However, it is also associated with previously dissolved inert gas from the tissues that forms bubbles in the venous blood, passes through the great veins to the right heart and crosses through an intracardiac or pulmonary vascular abnormality to the systemic arterial system [33].

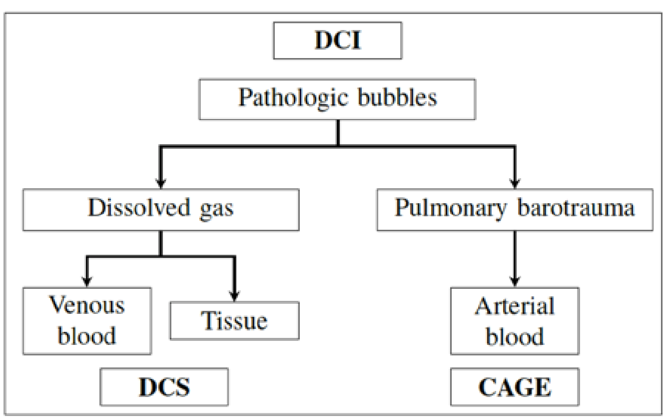

Fig. 2. Definition of bubble related diving diseases. The umbrella term Decompression Illness (DCI) includes Decompression Sickness (DCS) and Cerebral Arterial Gas Embolism (CAGE).

DCS is predominantly caused by bubble formation from dissolved gas absorbed during scuba diving. These bubbles form during or after reduction in ambient pressure on ascent. Divers absorb inert gas while breathing at an increased ambient pressure [34], [35]. During decompression the ambient pressure falls, prompting the elimination of dissolved gas down a pressure gradient. This implies the tissue will contain more dissolved gas than it would when in an equilibrium state with the ambient pressure (the tissue is 'supersaturated'). If the level of supersaturation is high enough, the gas will come out of solution and form bubbles. Bubbles can result in a wide variety of symptoms depending on the location, volume and persistence of the gas. These include cardio-pulmonary, cerebral, inner ear, spinal cutaneous and 'mild syndromes' [36].

III. DIVE COMPUTER, DECOMPRESSION TABLES AND ALGORITHMS

A. DIVE TABLES

Diving tables were developed to protect divers from DCS [37]. These tables define stepwise ascent protocols for minimizing bubble formation over a range of duration and depth exposure. All diving tables predict the uptake and elimination of inert gas during a dive and the subsequent decompression. The aim is to manipulate the decompression in order to limit the supersaturation of tissue to a level that can be tolerated without developing DCS. Tables may be entirely based on an algorithm or the result of an algorithm modified by human trial exposures, or by theoretical preferences of the designer.

B. DIVE COMPUTER

Dive computers provide real-time information about depth and duration. The primary functions of these computers are to calculate the risk of dangerous supersaturation in the tissue and avoid this point by stepping divers safely from the pressure exposure back to the surface. Many utilize a number of decompression algorithms in order to calculate a perceived amount of inert gas present in a range of theoretical tissues within the body [10]. Comparing the calculated saturation of each tissue will identify the 'critical' tissue controlling ascent. The critical tissue is that which determines when and for how long a decompression stop is required in order to avoid a dangerous supersaturation that is likely to result in clinical DCS. Some dive computers also measure physiological information, such as breathing gas consumption or heart rate [10].

The ascent schedules depend on the implemented decompression model / algorithm [38], [39]. Despite a variety of existing models and algorithms, manufacturers of dive computers often do not provide detailed information about the software. A standard method of dive computer validation has not been established, although the need has been identified [40]. In most cases, manufacturers do not have significant hard data to confidently justify claims of safety from a functional point of view, biasing their algorithms on theoretical tissue compartment behavior [40]. Several studies have nevertheless attempted to evaluate dive computers functionality from a safety perspective.

Azzopardi et al. [41] investigated the technical specifications of 47 different dive computers. They compared whether dive

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computer performance matched the technical specification described in the device manual. Some computers did not reflect the capabilities as described in their manuals. Their review emphasized the necessity for the development of standardized validation procedures.

Angelini et al. [42] investigated six dive computers during an identical set of exposures. All devices were pressurized simultaneously in a hyperbaric chamber to a maximum pressure of 8 ATM (70 msw) in three different contexts: a no-decompression stop dive, a dive requiring formal decompression stops and a set of repetitive dives. The data displayed on each computer was compared to data sets prepared in previously performed computer simulations. The results suggested all computers proposed different decompression schedules with substantial variation in decompression stop depths and durations. The authors concluded that the devices operated differently and a central data set for accurate evaluation is missing.

Most dive computer still accept a 2 % DCS probability, representing a gap between latest research and current application [36]. Dive injuries still occur, even if divers stay within the suggested schedules of their dive computers [17]. DAN Asia-Pacific records (unpublished) indicate that approximately 80 % of divers who had contacted them with symptoms of suspected DCS had been diving within the limits of their dive computers. This suggests that divers should be conservative when following the advice of their computer. Where possible, it may be wise to set the computer into a more conservative mode to reduce DCS risks.

C. DECOMPRESSION ALGORITHM

Decompression algorithms are derived from models, data and ascent schedules applied for underwater operation [45]. Complex equations delineate decompression schedules managing dissolved and free gas in blood and tissue (taking real-time depth and duration measurements into account) to stage divers as safely as possible to the surface. The equations are governed by a number of different factors [37] representing biological systems and medias and physical and chemical mechanisms [46] – [50].

In 1908, Haldane, Boycott and Damant [33] proposed that body tissues will hold gas in a supersaturated state. They determined tissue perfusion was the limiting factor in inert gas uptake and concluded tissues can tolerate a halving of ambient pressure before the onset of DCS symptoms. This approach was accepted for many years and practiced widely – resulting in a considerable reduced incidence of serious DCS. However, the overall incidence remained unacceptably high as diving techniques and equipment permitted longer and deeper exposures.

In 1965, Goodman and Workman proposed decompression models which extended Haldanes' supersaturation concept [51], [52]. They introduced the concept of an 'M-value' – defined as the maximum value of inert gas pressure (absolute) that a hypothetical tissue compartment can tolerate without presenting overt symptoms of DCS [53]. Based on the M-values for a range of such hypothetical tissues, decompression schedules were modeled to stage divers to the surface with greater safety.

Further developments in the physics of phase separation, bubble behavior, and gas transfer mechanisms culminated in dissolved-free phase theories [46] – [56]. Unlike the supersaturation models, phase theories also consider free gas in addition to inert gas. Commonly implemented phase models are the varying permeability model (VPM) and the reduced gradient bubble model (RGBM).

The VPM was constructed using a critical bubble volume hypothesis [56]. This model assumes that microbubbles will grow after they exceed a critical cutoff radius that is dependent upon the level of supersaturation in the tissue. The VPM estimates acceptable pressure gradients that aim to minimize the total volume of bubbles. The aim of this model is to keep the total bubble volume less than a pre-defined limit volume to keep bubbles in the microbubble stage and not excite them into growth.

The RGBM approach [37] employs a phase volume constraint across a total dive profile. The model is parameterized by biological, chemical and physical factors [37]. Bubbles are assumed to expand and contract during diving. The material properties of these bubbles dictate the response to pressure changes, gas diffusion and growth. The estimation of the volume constraint is defined in terms of a bubble phase function, (Φ), dependent on the number of gas bubbles stimulated into growth by decompression, a supersaturation gradient, seed diffusion and Bolye's expansion-contraction law. The RGBM stages decompression iteratively ensuring that Φ does not exceed pre-defined limitation. It is unknown if any dive computers incorporate the full RGBM.

These are theoretical models and neither of these have been validated using human trials [43]. Possibly because of the large number of different factors, the equations are still not able to predict bubble behavior accurately [57]. As a result, the implementation of physiological parameters in decompression models has been very limited.

Gutvik et al. [58] proposed a first attempt at decompression modeling including physiological parameter in the Copernicus model [60]. They introduced a mathematical model using continuous heart rate measurements to calculate customized decompression schedules [59]. The heart rate was assumed responsive to cardiac workload and to provide information on the blood flow to body tissue, and thus to changes in the rate of uptake and elimination of inert gas. The aim was to combine this information with depth and time to control bubble growth. Despite operating on the assumption of static parameters [58], the model is designed to give a quantitative description of the physiological parameters significantly affecting decompression. The model's accuracy has yet to be validated with large data sets.

The most recent approaches in decompression research involve the potential role for changes in serum micoparticles, inflammatory markers and genetic expressions with hyperbaric exposure. The diving environment triggers a cellular stress response which results in inflammation and the generation of microparticles both of which can be linked to the appearance of intravascular bubbles [61], [62]. The analysis of gene

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activity after diving indicates that some sets of genes respond to hyperbaric stress and predispose an individual to DCS. It has been noted in the field that some individuals are more likely to suffer DCS than others, and if this is so, there may in part be some genetic predisposition. It is also possible that in the future, genetic information may be used as biomarkers for early DCS recognition [61] – [63].

IV. MEDICAL MONITORING TECHNOLOGY FOR DIVING

The consideration of diving physiology and diving-related diseases above highlights the need to monitor physiological parameters. In particular, the hemodynamic changes on diving along with the potential of assessing inert gas uptake and elimination, indicate that measuring cardiac parameters such as blood pressure, heart rate, cardiac volumes and output are of major interest. These parameters are already monitored in a wide range of application in marine mammals by sensors and data loggers transplanted into the mammals [64] – [68]. The potential to extend these measurements to humans using wearable technologies, would greatly enhance diving physiological research in general and the management of decompression in particular [68]. Monitoring physiological parameters will reflect an individual's response to diving, rather than relying on a general model, and thereby may increase diving safety [69]. To date, wearable means to measure and evaluate the onset of DCI have not emerged, although there has been some related laboratory and animal work published in recent years [67], [69], [70] – [72]. These methodologies could be converted to wearable approaches to satisfy the need for real-time monitoring [65]. For example, Evgendis et al. [73] introduced an impedance measurement concept to detect bubbles using advanced time and frequency analysis for correlation with bubble characteristics. Such an approach has the potential to determine the onset of DCS in real-time.

A. WEARABLES

Wearable devices are increasingly used over a wide range of sporting and medical applications. These devices are able to analyze vital and environmental events and display the results to consumers. The usefulness of these devices is enhanced by modern processors, micro-controllers and battery technology. This innovative field offers ways to develop wearables with multiple sensors acquiring biomedical signals simultaneously, leading to a better analysis of physiological changes and the relation between different physiological effects.

Work is performed on a number of related fronts. Physiological parameter monitoring in an extreme situation has been described by Garbino et al. [13]. They investigated physiological changes during a stratospheric jump. The subject was equipped with a device capturing ECG, respiration rate and three-axis acceleration. The device stored data on a microSD card and transmitted data in real-time. Fei et al. [12] has proposed an embedded biomedical sensor system for astronauts. The system is capable of monitoring several parameters in parallel for space walks, including sensors for temperature, galvanic skin resistance, plethysmography, oxygen saturation and heart rate. They achieved parallel data analysis by developing hardware components for each sensor. Data acquisition and processing modules were applied inside the space suit and connected to the wrist display via wires. Seabrook et al. [74] investigated mobile platforms, such as Apple iOS and Android, for their capacity for medical applications while Laurino et al. [75] have developed a telemonitoring system for commercial divers that is applicable in hyperbaric chambers. The system acquires vital parameters and communicates via internet connection with external monitors outside the chamber. Sieber et al. [11] has presented instrumentation for physiological monitoring during scuba diving using an underwater data controller, containing an 8-bit micro-controller and a 3x16 character display.

Companies are continually developing smaller, faster and more powerful components with capabilities for measuring different scenarios simultaneously. At the time of writing however, multi-sensor platforms with real-time processing capability during scuba diving are not available.

B. IMPEDANCEMETRY

Electrodes typically acquire high input impedances in biomedical measurements. During submersion, however, electrodes are exposed to a high conductivity medium water, compared to the poorly conductive air. Water is assumed as a low-impedance $Z_0(= 10\,\Omega)$ parallel to a high electrode-skininterface impedance $Z_{IF}(= 10\,k\Omega)$. The water impedance significantly reduces the interface-input impedance of the amplifier from kilo-ohms to ohms, making biopotential measurements impossible using standard equipment. To solve this problem, hydrophobic-sealed electrodes are needed.

The current practice is to seal standard Ag/AgCl electrodes with adhesive material. However, this approach has many limitations, such as skin irritations due to the adhesive insulators, gel hydration over time and water leakage [78]. Although, biosignals can be observed as long as water does not penetrate the sealed electrodes, the quality of the acquired signal degrades over time. Further developments of electrodes for underwater use is required [76]. One method for facilitating underwater biopotential measurement without adhesive waterproofing was proposed by Ohtsu et al. [78]. This method employs a waterproof-designed electrode with a high-input impedance amplifier. The insulated electrodes are coated with a non-conductive, water resistant material which served as the electrode-skin interface. Electrode, insulator and skin created a capacitive coupling that permitted signal measurement on the body surface. Water resistance was ensured by using a five layers' electrode design covered with antistatic silicone. A driven-shield-technique was implemented to prevent gain loss in the high-frequency range when the signal was sent through an extended wire to the amplifier.

Another water-resistant electrode was designed by Reyes et al. [78]. This electrode consists of two active components with hydrophobic properties. The first component, Polydimethylsiloxane (PDMS), provides an elastomeric, hydrophobic matrix. The second component, Carbon Black (CB) was used as a conductive material uniformly distributed inside the PDMS polymer matrix to facilitate the transport of electrons [80].

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TABLE I
OVERVIEW AND EVALUATION OF MEASUREMENT APPROACHES OF ELECTROCARDIOGRAPHY, BLOOD PRESSURE AND STROKE AND CARDIAC OUTPUT IN ORDER TO VALIDATE USABILITY FOR SCUBA DIVING.

	Method	**Commercial Device / Study**	**Invasive / Non-invsive**	**Application in Scuba Diving**
Electrocardiography	Smart Wearable Systems	Textile based [83], T-Shirt [84], Belt [85], Vest [86]	Non-invsive	Application in wet and dry suits
	Wireless Wearable ECG Sensors	ECG wireless sensor board [90]	Non-invasice	Successful application [88]
	Mobile based ECG	Variety of mobile phone implementation [98], [101]	Non-invasive	Successful application [101], (Fig. 3)
Blood pressure	Krotkoff Method	Brachial artery cuff [115]	Non-invasive	Only when operated manually
	Oscillometric Method	Oscillometric cuff based device [119]	Non-invasive	Successful trials [119]
	Finger cuff Method	Penaz et al [117]	Non-invsive	Doubtful
Cardiac Output & Stroke Volume	Thermodilution	Ganz et al. [122]	Invasive	No
	Thoracic Electrical Bioimpedance (TEB)	Newman [124], Marik [128] and Guijar [129]	Non-invasive	Possible with limitations
	Bioreactance (phase shift)	Kere [132] and Raval [133]	Non-invasive	Possible
	Photoplethysmography	Kuch [138]	Non-invasive	Successful trials [138]

ECG signal acquisition of the PDMS/CB electrodes were tested in three conditions (dry, wet, full immersion) and compared to the performance of sealed Ag/AgCl electrodes [75] – [77]. The signal quality of both electrodes was highly correlated during dry and wet conditions. In immersed conditions, the PDMS/CB electrodes, however, maintained or in some cases even amplified the ECG signal, whereas the Ag/AgCl electrodes failed to record the signal accurately. Noh et al. performed trials with varying pressure fixations of the PDMS/CB electrodes. They revealed that increasing pressure levels on the electrodes resulted in a decrease of input impedance.

To date, these are the only promising approaches for underwater bioimpedance measurement. The evaluation work performed by Reyes [79] and Noh [80] showed the potential for bioimpedance measurements during immersion. However, there is no evidence of accurate performance in scuba diving.

C. ELECTROCARDIOGRAM

The electrocardiogram (ECG) is the best known and most widely used bio-signal in medicine. Acquired information about cardiac response in divers may help determine if divers with pre-existing cardiovascular illness should be allowed to dive [8]. Real-time ECG monitoring with an alert system triggered by cardiac abnormalities may increase diving safety (Tab. I).

Wearable ECG monitoring systems have been described for domestic, fitness and diagnostic applications. The American Heart Association [81] published guidelines for ambulatory ECG measurement including information about recording techniques, risk assessment and efficiency advises for monitoring and therapy. Baig et al. [82] classified wearable ECG devices into three categories: smart wearables, wireless and mobile ECG systems.

Smart wearable monitoring systems are wearable textile and garment based technologies. These embedded wearable systems, collect and/or process acquired ECG data in textile and planar-fashionable systems, such as T-Shirts [83], [84], belts [85] or smart vests [86]. They consist of sensor boards for long-term monitoring in a non-invasive and unobstructed way. Wireless monitoring systems are based on body network areas [87]. These networks allow the integration of intelligent monitoring systems, minimized components and low-power sensors attached directly to a patients' body. Holter monitors are the state of the art device for wireless, long-term ECG monitoring and storage. Bosco et al [88] performed a study on divers using a 12-lead Holter monitor and concluded that the device produces accurate ECG tracing. An example of an ECG board with data processing is the ECG-Micro-Board (Corscience, Erlangen, GER) [89]. In addition to acquisition and storage, the board includes heart rate variability evaluation. More advanced wireless technologies can include contactless or leadless ECG monitoring [90], [91].

Mobile ECG monitoring exploits the technology in mobile phones [92] – [100]. The set-up contains a mobile phone as a processing and display unit and an ECG sensor, attached directly to a patients' thorax. The mobile device and sensor, communicate wirelessly via Bluetooth or Wifi [94]. Gradl et al. [98] developed an Android based application, capable of QRS and arrhythmia detection. Acquired data was stored on a mobile phones internal memory and simultaneously displayed in real-time. Mobile tele-monitoring is considered one of the most promising means for daily vital sign monitoring [102]. Despite facing common delay issues, this technology provides a high level of accuracy regarding long term application and cardiac event detection [95], [98] – [100].

The application of mobile ECG monitoring in scuba diving has been successfully demonstrated by Cibis et al. [101], (Fig. 3). Heart rates were detected and an alert system was triggered when the heart rate exceeded or dropped below pre-defined critical limits. Any further application in scuba diving has yet to be evaluated.

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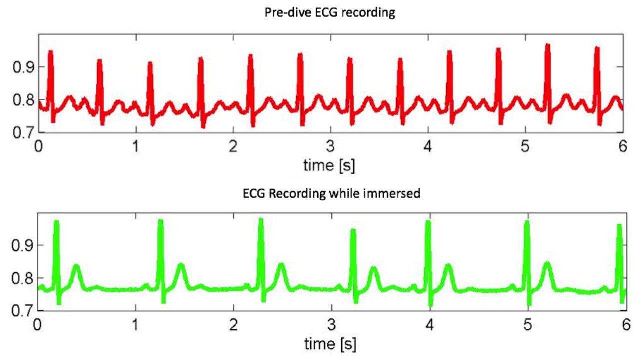

Fig. 3. ECG recodrings of the same subject, taken prior and during a dive [101]. The immersed recoding displays the onset of the diving reflex (bradycardia).

Von Tscharner et al. [102] recently proposed a novel current amplifier-based method to measure subcutaneous current flow, instead of surface potentials which become equipotential when immersed conditions. A current amplifier extracts current arising at the skin surface and thereby actively grounds the area beneath the electrodes enabling physiological measurements underwater without further electrode insulation [76]. In underwater trails, the information obtained in dry and wet environments was comparable [102].

For scuba diving, several of the listed ECG (Tab. I) measurement system seem applicable. Limitations are the ability to waterproof the system and the electrode-device connection [102]. The effects of body and water movement on the signal quality are unknown. A useful system has to operate accurately and be robust in the face of movement [103], [104].

D. BLOOD PRESSURE

Any changes in blood pressure (BP) over the course of a dive remains to be defined [11]. Accurate BP measurement is essential to understand hemodynamic effects and to classify cardio-vascular health risks [105] – [110]. Invasive methods are impractical for safety reasons [110] but have been used as the 'gold-standard' against which to validate non-invasive methods [111] – [114]. Non-invasive, automated methods include the oscillometric and the finger cuff based method (Tab. I).

The automated oscillometric method is derived from the manual Korotkoffs' BP method where the operator hears changes in arterial flow underneath a stethoscope during slow cuff deflation [115]. Oscillometry detects pressure oscillations under cuff rather than sound [105], [108]. The maximum oscillation corresponds to the mean arterial pressure [110], [112]. Because oscillations occur above the points of systolic and diastolic pressure, these values are only estimated indirectly by defined algorithms [116]. This method fails during physical activity because of movement artifacts, and this may make use during diving problematic [116]. Another method was first proposed by Penaz et al. in the 1970s [117], [118]. Penaz developed a finger cuff method, based on an 'unloaded arterial wall' principle. Arterial pulsation in the finger is detected using a photo-plethysmograph, obtaining pressure oscillation from the measured pressure curve [105]. Trials demonstrated that the finger cuff method fails to measure absolute levels of blood pressure accurately, but does reflect changes over time accurately [118]. Because immersion at pressure tends to minimize blood flow in the peripheries, the use of this method is also problematic during diving.

Recently, a sphygmomanometer BP measurement device for underwater application was developed by Sieber et al. [119]. The aim was to obtain real-time BP measurements to evaluate BP response during breath-hold dives. The device was designed to fit in a waterproof housing, directly mounted to the cuff containing a microcontroller board, differential pressure sensor and display. The first trials were performed in a swimming pool at varying depths and in dry hyperbaric environments with good results.

The challenges for BP measurements in divers are to waterproof the control boards and the cuff operation (Tab. I). The impact of ambient pressure on the cuff must be considered [120]. Movement may compromise BP detection and have yet to be addressed in literature. The oscillometric method seems most likely to reach the exacting requirements [117].

E. STROKE VOLUME & CARDIAC OUTPUT

During scuba diving, increased ambient pressure causes a blood shift to the central compartment [5]. Measuring cardiac output (CO) and stroke volume (SV) will provide information about blood volume changes and cardiac work. This information can be used to understand blood shifts and may help to establish if divers with preexisting conditions can safely dive.

Technologies in SV and CO measurements predict the amount of fluid in the heart (Tab. I). The use of Fick's principle measuring the thermodilution of cold injective is the clinical standard to determine cardiac output [121], [122], but it is invasive and impractical for diving.

The thoracic electric bioimpedance (TEB) method was introduced by Kubicek to determine SV and CO non-invasively [123] – [127]. Kubicek proposed that pulsatile changes in resistance occur during ventricular systole and diastole. Four electrodes are applied on the neck and thorax and drive a current of known amplitude and frequency across the thorax. The pulsation is measured in voltage changes where the amplitudes of the output signal is compared to the input signal. The trans-thoracic impedance (Z_0) can be calculated and changes proportionally to the amount of fluid in the thorax. The stroke volume is proportional to the impedance change dZ/dt over the left ventricular ejection time, T_{LVE}. Early studies showed a poor agreement between TEB and thermodilution [128] and agreement was even worse with an increase of blood in the thorax (as is expected during scuba diving) [129]. TEB is also inaccurate in settings with electrical background noises, physical activity and environmental factors, while being sensitive to the electrodes placement [130], [131]. TEB seems of limited use for scuba diving.

Another method is bioreactance, a phase shift in voltage across the thorax [125] – [127], [132]. The human thorax was described as an electrical circuit containing a resistor R and a capacitor C, creating the thoracic impedance Z_0. The values of R and C determine two components of the impedance; the amplitude and magnitude of the impedance measured in ohms; and the phase orientation measured in degrees. Pulsatile blood flow modifies R and C, leading to instant changes in amplitude and phase. The phase shift depends directly on the flow and constitutes the parameter of interest. The system operates on four dual electrodes. One electrode pair is driving an electric current across the thorax and the other pair measures voltage. The CO is determined by the relative phase shift, , between the input and output signals. The peak rate of the phase shift, ($\Delta\Phi$), is proportional to the peak aortic flow. The SV is calculated using the phase shift peak rate and the ventricle ejection time T_{VET}. Unlike the TBE, the bioreactance method does not use a static impedance. Studies show a high correlation between bioreactance and thermodilution [133] – [135]. The good agreement, strong resistance against motion artifacts and low sensitivity to environmental and physical factors all suggest bioreactance may be usefully applied in scuba diving.

An optical approach to measure peripheral volume changes is photoplethysmography (PPG) [136]. This method illuminates the skin and measures the amount of transmitted or reflected light to a photodiode. The amount of light detected at the photodiode is proportional to changes in the skin blood volume, however, these devices do not produce a quantitative measurement [137]. PPG can, however, be used to measure oxygen saturation and heart rate, and has been used in immersed conditions [138].

The challenges for scuba diving application are to ensure accuracy and safety underwater (Tab. I). In particular, the impact of immersion is unknown. Trials and studies are required to determine technical, physical and physiological factors for successful blood shift measurements.

V. OUTLOOK

This review has provided an overview of diving medicine and related monitoring technology. Each identified technological approach is considered to be applicable for advanced, wearable data acquisition underwater and may ultimately contribute to a detailed evaluation of diving physiology and diseases.

The long-term health consequences of compressed gas breathing are poorly defined and require further investigation as relatively few data are available and some are contradictory [139] – [142]. To date, some studies imply that cognitive and neurological impairments are the most serious long-term consequences of diving. While such long-term effects are assessed using questionnaires, coordination and reaction tests and imaging technologies (MRI, SPECT); wearable means to evaluated real-time impairment have also been described. A wearable critical flicker fusion frequency (CFFF) device has been used to determine alteration or arousal of cortical performance [143], [144]. Studies have shown that an increase of fusion frequency is equated with brain activation and a decrease equated in alteration of brain arousal with potential application for real-time evaluation of nitrogen narcosis [145]. An other approach to measure brain activity is the application of a wearable electroencephalogram (EEG) [146]. EEG patterns can be used to investigate the impact of increased pressure [147] and nitrogen narcosis on the cortical performance [148]. Information obtained from a real-time measurement of cognitive functions could be used to prevent dangerous conditions and to investigate long-term impairments.

Sensors for respiration and breathing gas analysis were not considered in this review. Gas analysis requires sensor attachment and modification of the breathing regulator and therefore was not considered in the scope of wearable technology.

This review has concentrated on compressed-air diving and has not considered specific issues relating to the use of different breathing gas mixtures (such as those containing helium) [149]. These issues will need to be considered in relation to deep diving safety.

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