

The current use of wearable sensors to enhance safety and performance in breath-hold diving: A systematic review

Giovanni Vinetti^{1,2}, Nicola F Lopomo², Anna Taboni³, Nazzareno Fagoni¹, Guido Ferretti^{1,3}

¹ Department of Molecular and Translational Medicine, University of Brescia, Brescia, Italy

² Department of Information Engineering, University of Brescia, Brescia, Italy

³ Department of Anesthesiology, Pharmacology, Intensive Care and Emergencies, University of Geneva, Geneva, Switzerland

Corresponding author: Dr Giovanni Vinetti, Department of Molecular and Translational Medicine, University of Brescia, Viale Europa 11–25123, Brescia, Italy
g.vinetti001@unibs.it

Key words

Physiology; Patient monitoring; Telemetry; Computers; Equipment; Training

Abstract

(Vinetti G, Lopomo NF, Taboni A, Fagoni N, Ferretti G. The current use of wearable sensors to enhance safety and performance in breath-hold diving: A systematic review. *Diving and Hyperbaric Medicine*. 2020 March 31;50(1):54–65. doi: [10.28920/dhm50.1.54-65](https://doi.org/10.28920/dhm50.1.54-65). PMID: [32187619](https://pubmed.ncbi.nlm.nih.gov/32187619/).)

Introduction: Measuring physiological parameters at depth is an emergent challenge for athletic training, diver's safety and biomedical research. Recent advances in wearable sensor technology made this challenge affordable; however, its impact on breath-hold diving has never been comprehensively discussed.

Methods: We performed a systematic review of the literature in order to assess what types of sensors are available or suitable for human breath-hold diving, within the two-fold perspective of safety and athletic performance.

Results: In the 52 studies identified, sensed physiological variables were: electrocardiogram, body temperature, blood pressure, peripheral oxygen saturation, interstitial glucose concentration, impedance cardiography, heart rate, body segment inertia and orientation.

Conclusions: Limits and potential of each technology are separately reviewed. Inertial sensor technology and transmission pulse oximetry could produce the greatest impact on breath-hold diving performances in the future.

Introduction

Underwater activities are commonly performed for recreational, occupational or competitive purposes.^{1,2} The most common approaches include either a self-contained underwater breathing apparatus (SCUBA) or breath-holding. These activities carry an intrinsic health risk due to the physiological stresses related to hypoxaemia, hyper- or hypocapnia, hydrostatic pressure and cold water,² potentially resulting in loss of consciousness and drowning. Given that the majority of reported adverse events are related to a delay in recognizing a life-threatening problem,¹ the risk can be minimized through primary and secondary prevention strategies. In these contexts, field measurement of relevant physiological parameters is an emergent challenge, as the improvement of divers' safety requires a better understanding of diving physiology. This challenge is being met thanks to technological advances in wearable sensors (i.e., water and pressure proofing, miniaturization and underwater communication).^{3,4} In breath-hold (BH) diving, remarkable increases in the number of active competitors and dramatic improvement in diving performance have occurred in the last 20 years.⁵ As BH divers rely only on their own physiological capabilities, sensor technology provides potential for training feedback and enhancement of human performance and safety.

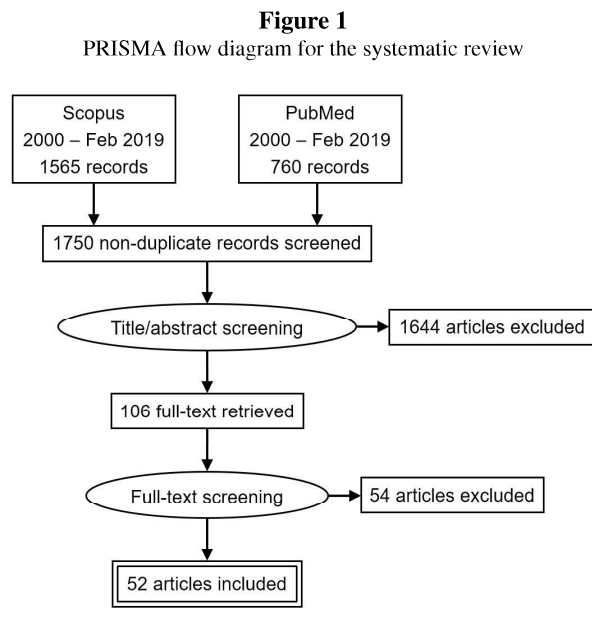
This work aimed to systematically review wearable sensor technologies usable during BH diving, with the twofold perspective of inferring its potential applications to safety and performance. Specifically, this review aimed at addressing the following questions:

- What type of wearable sensors can be used in human BH diving?
- What wearable sensors used for SCUBA diving are potentially applicable also to BH diving?
- What water- and pressure-proofing strategies have been adopted to adapt monitoring technology to the underwater environment?
- At which depth have the various approaches been reported to work?

Although some of the physiological changes discussed in this review may apply to all types of diving (see e.g., the blood pressure increase⁶), the conclusions arrived at are specific to BH diving. "Analogous reviews on SCUBA diving were previously published^{3,4} and the interested reader may refer to them.

Methods

Article selection was based on a systematic search of the scientific databases PubMed and Scopus following the



PRISMA guidelines.⁷ To avoid outdated technology, only items published after January 2000 were included in the search. The keyword string was: (*sensor* OR *ECG* OR *electrocardiogram* OR “*heart rate*” OR “*blood pressure*” OR *hemodynamics* OR “*oxygen saturation*” OR *EEG* OR *IMU* OR “*inertial measurement unit*” OR *accelerometer* OR *gyroscope* OR “*body temperature*” OR “*blood glucose*”) AND (*diver* OR *diving*).

The title and abstract of each result were reviewed and evaluated based on the relevance to the aims of this study. When appropriate, full-text was obtained for a more detailed analysis. Article references were examined for further pertinent publications.

Inclusion criteria were that the publication: appeared in a peer-reviewed academic source; was related to the utilization or the development of wearable sensors explicitly or potentially applicable to human BH diving; included experiments carried out completely below the water level, at a depth (either real or simulated with a hyperbaric chamber) of more than 2 m. Exclusion criteria were: studies performed in shallow water (less than 2 m deep); sensors applicable only to SCUBA diving; invasive or non-portable sensors.

The following information was extracted from articles meeting the inclusion criteria: sensed physiological variable, sensor technology, sensor sealing precautions, studied diving mode, test environment, maximal tested depth.

Results and discussion

The initial search yielded 1,565 titles on Scopus and 760 on PubMed updated to 28 February 2019. Duplicates were removed, 248 abstracts were further analysed and

subsequently 106 full-text papers were downloaded. After full-text assessment, we finally selected 52 publications for inclusion in this review (Figure 1). The parameters extracted from each publication are specifically reported in Tables 1–6, which will be discussed in detail below.

Thirteen studies involved BH diving, 38 SCUBA diving and one saturation diving. Tested depths ranged from 2 to 160 metres’ sea or fresh water. Sensed physiological variables were: electrocardiogram (ECG, 19 studies), body temperature (six studies), arterial blood pressure (ABP, five studies), peripheral oxygen saturation (SpO₂, five studies), interstitial glucose concentration (five studies), impedance cardiography (four studies), heart rate (13 studies), body segments inertia and orientation (three studies), electroencephalogram (one study). Six studies involved simultaneous measurements of multiple parameters, such as ECG and impedance cardiography (one study), ECG and SpO₂ (one study), ECG, ABP and SpO₂ (two studies), heart rate and core and skin temperature (one study), ECG and body temperature (one study). In all studies, an appropriate casing was used for the water- and pressure-proofing of electronic components.

ELECTROCARDIOGRAM AND HEART RATE

The ECG has previously been applied to BH diving and unsurprisingly was the most common physiological variable recorded.⁸ As reported in Table 1, depth ranged between 2–70 m. In ECG monitoring there are two different elements that must be waterproofed: the electrodes and the electronics. Performing differential measurements between devices, such as ECG the front-end electronics typically require amplifiers which present high input impedance, high level of gain and a large common-mode rejection ratio (CMRR). These must provide a large amount of gain for very low-level signals, often in the presence of high noise levels. Immersion in salt water introduces a parallel resistance between electrodes, increasing the load and decreasing the signal by an amount that depends on water conductivity (i.e., salinity) and electrode properties. Therefore, the optimal and most widespread solution was to place electrodes under a dry suit.^{9–13} Alternatively, electrode insulation was achieved via direct coverage with biocompatible adhesive patches^{14–19} or with hydrophobic dental impression material.^{20–23} All the reported solutions avoided modifying the original manufactured skin-electrode interface while maintaining the correct inter-electrode insulation. Finally, a novel solution based on intrinsically waterproof electrodes has been recently developed.²⁴

The ECG signal analysis can be restricted to heart rate only, as in commercial cardiometers and diving computers, which were studied at 3–65 m depth^{25–37} or in shallow water during static apnoea competitions.^{38,39} Cardiac arrhythmias are common during BH diving^{40,41} and real-time ECG analysis can be used to trigger alert signals based on pre-

Table 1

Studies reporting measurement of the electrocardiogram and heart rate. BH = breath hold. HVP = hydrophilic vinyl polysiloxane. NS = not specified. PC = personal computer. S = SCUBA. trans = transmission. WHC = wet hyperbaric chamber. * = probably not monitored in real-time due to Bluetooth constraints underwater

Sensor	Ref.	Diving mode	Setting	Tested depth (m)	Manufacturer	Real-time display	Data storage or display	Data trans	Water-and pressure-proofing of the wearable sensor	Max. depth (m)
Electrodes	40	BH	WHC	55	NS	Yes	EKG recorder	Not specified	Not specified	–
Electrodes + ECG transmitter	13	S	WHC	27	Fukuda-Denshi	Yes	EKG recorder (Dynascope DS-1040)	Wireless	All inside diver's dry suit	–
	12	S	Pool	2	Prototype	Yes	Data logger	Wireless (acoustic)	Electrodes: under diver's dry suit; ECG transmitter: inside cylindrical housing attached to an aqualung	–
	46	S	Sea	20	Nihon-Kohden	No	EKG transmitter	Cable	Electrodes: not specified; ECG transmitter: water- and pressure-proof case.	–
Electrodes + ECG recorder	17	BH	Sea	70	Sorin Group	Yes	EKG recorder (storage); PC (display)	Cable	Electrodes: covered with transparent adhesive (Tegaderm, 3M, St. Paul, Minn., USA); ECG Holter: plastic tube (Comex SA, Marseille, France)	190
	14	S	Pool	4	Reynolds Medical	No	EKG recorder	Cable	Electrodes: waterproof tape; ECG recorder: professional diving pouch (TMT, ewa-marine)	–
	47	S	Lake	8	PicoMed	No	EKG recorder	Cable	Electrodes: special clips; ECG recorder: not specified	–
Electrodes + ECG recorder	15	S	Sea	25	Mortara	No	EKG recorder	Cable	Electrodes: first layer (Visulin, Hartmann) + second layer (Steri-Drapes, 3M); ECG Holter recorder: pressure-proof anticorrosional aluminium housing, with a plexiglass cover (Metralab s.r.l.)	50
	9,10	S	Sea	30 ⁹ 61 ⁹	Rozinn-Electronics ⁹ , NS ¹⁰	No	EKG recorder	Cable	All inside diver's dry suit	–

Table 1 continued.

Electrode patches embedded in an ECG recorder	16	BH	WHC	20	NS	No	ECG recorder	Embedded	Electrodes: special adhesive patch; ECG recorder: water- and pressure-proof case	-
Electrodes + data logger	20-23	BH	Pool	20,21 10,5 ^{22,23}	Prototype	Yes	Data logger	Cable	Electrodes: HVP dental impression material (Elite H-D+, Zhermack); Data logger: lexan tube	200
	19	S	Pool	4.6	UFI	Yes	Data logger	Cable	Electrodes: benzoin + waterproof tape + moleskin; Data logger: not shown	-
Electrodes + ECG sensor + smartphone	11	S	Pool	2.7	Shimmer-Research Ltd	Only vibratory alerts	Smartphone	Wireless (Bluetooth)	All inside diver's dry suit; Smartphone: professional diving pouch	-
Electrodes + Monitoring Board	18	S	Sea	30	Prototype	Yes	PC	Cable to a Bluetooth buoy	Electrodes: hot glue + self-adhesive waterproof film (Tegaderm, 3M); ECG Monitor: Case (DryCase 2000, OtterBox)	-
Electrodes chest strap + ECG transmitter	24	S	Pool	4.5	Prototype	Yes	PC	Wireless (Bluetooth)*	Electrodes: intrinsically waterproof (hydrophobic, Carbon Black/ Polydimethylsiloxane electrodes, meshed with embedded copper mesh); ECG transmitter: not specified	-
Electrodes chest strap + wrist monitor	26-30-36-37	BH ³⁷ S ^{26,30,36}	Sea	3 ³⁶ 5 ³⁰ 20 ^{26,37}	Polar	Yes	Wrist monitor	Wireless	Electrodes: built-in water insulation (textile electrodes); Monitor: built-int waterproof case	50
	25	S	Pool	4.5	Timex	Yes	Wrist monitor	Wireless	Not specified	-
	27-29-31-35	S	Sea	18 ^{27,28,33-35} 20 ²⁹ , 54 ³² 65 ³¹	Scubapro-Uwatec	Yes	Wrist monitor	Wireless	Electrodes: built-in water insulation; Monitor: built-int waterproof case	120

determined criteria.¹¹ Moreover, heart rate response to exercise is only partially suppressed by the diving reflex and still remains influenced by the metabolic rate:^{17,42-45} it could be therefore monitored by an experienced diver as a real-time surrogate of the energy cost of underwater swimming.

ARTERIAL BLOOD PRESSURE

Underwater ABP measurement was successfully carried out at depths between 2–10.5 m (Table 2). In designing the pressure transducer, electrical component waterproofing without preventing (or excessively delaying) barometric equalization in the reference chamber is critical to allow correct measurement in the aquatic environment, especially in dynamic conditions (ascent and descent).⁴⁸ We found only two different approaches to achieving this. The first solution was putting a commercial ABP device inside a downwardly-open plexiglass housing,⁶ whose resulting water-air interface was set at the level of the middle of the blood pressure cuff. Subsequent studies improved the portability of the sensor, with the ABP device encapsulated into a Lexan tube directly located over the cuff, inflated with the gas coming from a SCUBA tank.^{20,21,48,49} BH was reported to increase ABP either modestly⁴⁸ or dramatically.⁵⁰ Therefore, it would be useful to monitor individual ABP responses to BH diving both for research and screening purposes.

IMPEDANCE CARDIOGRAPHY

Impedance cardiography allows for non-invasive monitoring of the electrical impedance changes in the thorax thus providing estimation of the cardiac stroke volume and, together with the ECG measurement, of several derived cardiovascular parameters. These systems usually rely on the use of a set of electrodes (at least four) placed on the thorax. An alternating high frequency small amplitude current is applied through two electrodes, whereas the electrical potential difference is measured using the other pair. Secured in a pressure chamber⁴⁰ or into an underwater torch case in open sea,⁵¹⁻⁵³ the device allows measurements up to 55 m depth (Table 3). While it represents an index of myocardial performance, it adds limited benefits for BH diving safety and performance compared to ECG alone.

PERIPHERAL OXYGEN SATURATION

Arterial haemoglobin saturation is a key performance parameter for BH and reflects the partial pressure of O₂ in the arterial blood. It can be measured non-invasively in the peripheral circulation (SpO₂), although motion artefacts and reflex peripheral vasoconstriction prevents the utilization of classical transmission pulse oximeters at fingertip or earlobe. Accordingly, only reflectance pulse oximeters at the forehead were used underwater,^{20-22,54} at a depth of 2–10 m (Table 4). In the design of the device, waterproofing was specifically obtained by soaking it in a highly sealing and electrically insulating polymeric material. Battery change was facilitated by introducing a separate waterproof compartment.

The descent phase of a BH dive cannot be guided by pulse oximetry, because the depletion of oxygen stores is counterbalanced by transmission of the surrounding hydrostatic pressure to the alveolar gas, thus increasing arterial partial pressure of oxygen and resulting in a fairly stable SpO₂ at 100%. Only during a prolonged period at depth and/or during the ascent (when there is reversal of the above process) would O₂ depletion manifest as a decrease in SpO₂. As a consequence of circulation time between lungs and forehead, the nadir of SpO₂ at forehead occurs 4–8 s after surfacing,⁵⁵ or even later if cardiac output is reduced by a marked diving response.⁵³

BODY SEGMENT INERTIA AND ORIENTATION

Classical movement analysis systems (optical motion capture, force and pressure measurement sensors, global positioning systems) are not suitable for the deep underwater environment. Inertia measurement units (IMU) incorporate accelerometers, gyroscopes and magnetometers in a small space and can be easily waterproofed. For these reasons, IMU arose as a powerful tool for the investigation of competitive swimmers' biomechanics⁵⁶ and the energetics of air-breathing diving animals.^{57,58} IMUs have been used in experimental studies on human divers in only three studies (Table 5), two conducted at a depth of 2 m^{59,60} and one at 10 m.⁶¹ Electrical insulation was achieved by means of either external cases^{59,60} which can be easily acquired and applied, or by embedding the electronics in a polymeric potting compound.⁶¹

The main outcomes of Kuch et al.⁶⁰ and Goodfellow et al.⁶¹ were, respectively, the reconstruction of diver's posture (to detect anomalous behaviours) and path (to build an inertial based underwater navigation system). However, potential applications of IMU to BH diving extend to investigating the energy cost of underwater swimming, a major determinant of BH distance or depth.⁶² Feedback on swimming economy would be crucial for improving performances of both dynamic and deep apnoeas, especially if provided in real-time. Groh et al.⁵⁹ moved in that direction, trying to establish a biomechanical model to describe leg and upper body orientation during fin kicking. Their proposed algorithm has the potential to be implemented into a wider training system for competitive or recreational divers. However, additional parameters still need to be measured in order to obtain a complete biomechanical model.

BODY TEMPERATURE

Superficial, rectal and ingestible temperature sensors were easily adapted to hyperbaric environments to investigate heat exchange in SCUBA^{18,36,63-65} and saturation diving⁶⁶ at 3–160 m depth (Table 6). Built-in cases are the most common solutions to properly insulate superficial sensors, while rectal and ingestible sensors are designed to be resistant to gastrointestinal fluids thus are already waterproof. However no specifications were found concerning maximum ambient

Table 2
Studies reporting measurement of arterial blood pressure. BH = breath hold. S = SCUBA, trans = transmission

Sensor	Ref.	Diving mode	Setting	Tested depth (m)	Manufacturer	Real-time display	Data storage or display	Data trans	Water- and pressure-proofing of the wearable sensor	Max. depth (m)
Cuff + differential pressure sensor + microcontroller (based on Korotkoff sounds)	6	S	Pool	3	Bosch & Sohn (BoSo)	Yes	On screen via a video-camera	Cable	Plexiglass housing for inflator/display (downwardly open for hydrostatic pressure equalisation); silicone sheath for cuff microphones	-
Cuff + differential pressure sensor + microcontroller (based on the oscillometric method)	20 21 48 49	BH ^{20,21,48} S ⁴⁹	Pool	10.5	Prototype	Yes	Microcontroller	Cable	Lexan tube, inflation air coming from a SCUBA tank	200

Table 3
Studies reporting measurement of impedance cardiography. BH = breath hold. NS = not specified. trans = transmission. WHC = wet hyperbaric chamber

Sensor	Ref.	Diving mode	Setting	Tested depth (m)	Manufacturer	Real-time display	Data storage or display	Data trans	Water- and pressure-proofing of the wearable sensor	Max. depth (m)
Electrodes	40	BH	WHC	55	Bomed	Yes	Recorder	NS	Not specified	-
Electrodes + recorder	51 52 53	BH	Pool ^{52,53} Sea ⁵¹	3 ^{52,53} 30 ⁵¹	2C Technologies Inc	No	Recorder	Cable	Recorder: underwater torch case; Electrodes: surgical 15x10 cm patches (Plastod, Bologna, Italy)	90

Table 4
Studies reporting measurement of peripheral oxygen saturation. BH = breath hold. trans = transmission

Sensor	Ref.	Diving mode	Setting	Tested depth (m)	Manufacturer	Real-time display	Data storage or display	Data trans	Water- and pressure-proofing of the wearable sensor	Max. depth (m)
Reflectance sensor (8000R) + module (OEM III) + data logger	20-22 54	BH	Pool	2 ^{20,21} 10.5 ^{22,54}	Nonin	Yes	Data logger	Cable	Data logger: either (i) inside a lexan tube or (ii) filled with silicone gel (SilGel 612, Wacker Chemie AG) with a water- and pressure-proof compartment for battery.	200

Table 5

Studies reporting measurement of body segment inertia and orientation. IMU = Inertia measurement unit. PC = personal computer. S = SCUBA. trans = transmission. * = personal communication

Sensor	Ref.	Diving mode	Setting	Tested depth (m)	Manufacturer	Real-time display	Data storage or display	Data trans	Water- and pressure-proofing of the wearable sensor
Accelerometer + magnetometer + gyroscope (IMU)	60	S	Pool	2	ST Microelectronics + InvenSense	Yes	PC at surface	Cable	Lexan tube
	61	S	Pool	10	Pololu	Yes	PC at surface	Cable	Spokes: 3D printed housing, filled with polyurethane potting compound; Hub: 5083 grade aluminium alloy housing
	59	S	Pool	2*	Prototype	No	IMU	Cable	Professional diving case or pouch for cameras or mobile phones

pressure in which those sensors may be operated. Electrical insulation of the data loggers was achieved by means of cases or housings designed to allow easy access.

Monitoring body temperature would be useful in repetitive diving, such as spearfishing competitions and professional dives, because it allows timely diagnosis and prevention of hypothermia.⁶⁷ This was reported to be a frequent event in Ama divers,⁶⁸ which could eventually elicit chronic adaptation to cold.⁶⁹ The usefulness of such monitoring is underscored also by the reduction in maximal BH duration in cold water due to an increased resting metabolic rate.⁷⁰ Some commercially available diving computers offer skin temperature measurement from the heart rate chest strap,^{27–29,31–35} but have not been the subject of published scientific studies. In fact, it is noteworthy that the gold standard for a comprehensive characterization of human thermal balance is to measure both skin and core temperature.⁷¹

INTERSTITIAL GLUCOSE CONCENTRATION

Subcutaneous sensors for interstitial glucose concentration have been waterproofed with adhesive films and dental impression material^{72,73} or simply kept under the dry suit^{74,75} or even the wet suit.⁷⁶ In this case, there is no issue related to the direct contact with water, since the sensor (i.e. a thin needle) is placed within the interstitial fluid. Electrical insulation had to be ensured only to avoid issues related to power supply and data transmission. Devices were studied at depths 22–40 m (Table 7). In insulin-dependent diabetic SCUBA divers these devices may diagnose hypoglycaemia during the dive, although the very short immersion times hamper their usefulness for BH diving.

ELECTROENCEPHALOGRAM

One pilot study obtained electroencephalographic (EEG) recordings 4 m underwater⁷⁷ by protecting the electrodes under a full-face latex mask, further covered by a bathing cap. In this case, waterproofing is essential to ensure inter-electrode insulation and prevent surface biopotentials becoming equipotential, as discussed earlier in relation to ECG and impedance cardiography. Signals were transmitted via cable to an amplifier at the surface. Although acute cognitive impairment is an important safety issue in extreme BH diving, real-time applicability of EEG in this field remains unfeasible at this time. Nevertheless, it could be important to develop portable underwater EEG devices, especially to study development of adaptive changes in EEG reported in trained breath-hold divers.⁷⁸

Conclusions

Since the first tests on BH diving populations,^{79,80} the potential for carrying out physiological measurements during actual BH diving has increased dramatically. The wearable sensors implemented so far have contributed significantly

Table 6
 Studies reporting measurement of body temperature. NS = not specified. PC = personal computer. S = SCUBA. Sat = Saturation. trans = transmission

Sensor	Ref.	Diving mode	Setting	Tested depth (m)	Manufacturer	Real-time display	Data Storage or display	Data trans	Water- and pressure-proofing of the wearable sensor
Ingestible temperature sensor + data logger	65	S	Pool	3	HQ Inc.	No	Data logger	Wireless	Temperature sensor: capsule; data logger: inside diver's dry suit
	36	S	Pool	3	Philips- Respironics	Yes	Data logger	Wireless	Temperature sensor: capsule; data logger: not specified
	18	S	Sea	30	Philips- Respironics	Yes	Data logger + PC on surface	Wireless (to data logger); Cable to bluetooth buoy (to PC)	Temperature sensor: capsule; data logger: case (DryCase 2000, OtterBox)
	66	Sat diving	Sea	160	Biomed d.o.o.	No	Data logger	Wireless	Temperature sensor: capsule; data logger: professional diving pouch
Rectal temperature sensor + data logger	63	S	Sea	10	Grant- Instruments	Yes	Data logger	Cable	Temperature sensor: inside divers' dry suit; data logger: above water surface
	63	S	Sea	10	Grant- Instruments	Yes	Data logger	Cable	Temperature sensor: inside divers' dry suit; data logger: above water surface
Skin temperature sensor + data logger	64	S	Sea	8	Grant- Instruments	Yes	Data logger	Cable	Temperature sensor: surgical tape (Blenderm, 3M); data logger: above water surface
	36	S	Sea	3	Philips- Respironics	Yes	Data logger	Wireless	Temperature sensor: built-in waterproof case; Data logger: not specified
	18	S	Sea	30	Philips- Respironics	Yes	Data logger + PC on surface	Wireless (to data logger); Cable to bluetooth buoy (to PC)	Temperature sensor: built-in waterproof case; data logger: Case (DryCase 2000, OtterBox)
	66	Sat diving	Sea	160	Biomed d.o.o.	No	Data logger	Embedded	Temperature sensor: embedded in the data logger; data logger: professional diving pouch

Table 7
Studies reporting measurement of interstitial glucose concentration. S = SCUBA. trans = transmission

Sensor	Ref.	Diving mode	Setting	Tested depth (m)	Manufacturer	Real-time display	Data storage or display	Data trans	Water- and pressure-proofing of the wearable sensor
Subcutaneous glucometer + monitor	72	S	Sea	21.5	Medtronic	No	Monitor	Cable	Glucose sensor: hydrophilic vinylpolysiloxane material (Elite H-D, Zhermack) + doubled plastic adhesive dressing + an elastic collodion film between the two dressings; monitor: pressurized aluminium container
	73	S	Sea	20	Medtronic	No	Monitor	Cable	Glucose sensor: taped with an Opsite film; monitor: water- and pressure-proof case
	74 75	S	Sea	22 ⁷⁵ 24 ⁷⁴	Medtronic	No	Monitor	Cable	All inside diver's dry suit
	76	S	Sea	40	Dexcom	Yes	Monitor	Wireless	Glucose sensor: under diver's wet suit; monitor: waterproof case with glass screen

to our understanding of BH diving physiology and to the safety of dives. Adequate waterproof characteristics seem to be achievable for systems originally designed for terrestrial use, provided that the issues of both sensor-body interface and electrical insulation are taken into account. However, the intrinsic depth limits of the adopted technology was not reported in several studies.

Another recent improvement involves the transmission and real-time processing of physiological measurements. On-line medical and physiological information transmission during diving could allow a prompt recognition of an increased risk or a clinical adverse event, leading to timely termination of the dive (for example, significant cardiac arrhythmias or an excessive rise in ABP). Further advances could be obtained by integrating different sensors into a unique “*smart*” suit. In addition to safety, the analysis of multiple data collected in the field would positively impact training and competition strategies, as happens in several other sporting disciplines. Among the sensors that we discussed, transmission pulse oximetry and inertial sensor technology seem to have the greatest potential for further technical improvement and innovative uses. The former could give feedback on available oxygen stores (with the limitations outlined above), and the latter on factors influencing oxygen consumption rate, possibly identifying the most economical swimming technique. Therefore, we expect them to produce the greatest impact in the future.

References

- Buzzacott P, editor. DAN Annual diving report 2017 edition: A report on 2015 diving fatalities, injuries, and incidents. Durham (NC): Divers Alert Network; 2017. doi: [10.1002/cphy.c160008](https://doi.org/10.1002/cphy.c160008). PMID: 29553634.
- Fitz-Clarke JR. Breath-hold diving. Compr Physiol. 2018;8:585–630. doi: [10.1002/cphy.c160008](https://doi.org/10.1002/cphy.c160008). PMID: 29687909.
- Cibis T, McEwan A, Sieber A, Eskofier B, Lippmann J, Friedl K, et al. Diving into research of biomedical engineering in scuba diving. IEEE Rev Biomed Eng. 2017;10:323–33. doi: [10.1109/RBME.2017.2713300](https://doi.org/10.1109/RBME.2017.2713300). PMID: 28600260.
- Sieber A, L'Abbate A, Kuch B, Wagner M, Benassi A, Passera M, et al. Advanced instrumentation for research in diving and hyperbaric medicine. Undersea Hyperb Med. 2010;37:259–69. PMID: 20929183.
- International Association for the Development of Apnea (AIDA). Athlete Rankings. Available from: <https://www.aidainternational.org/Ranking/Rankings>. [cited 2019 Feb 21].
- Almeling M, Wulf K, Schega L, Witten F, Niklas A. Blood pressure measurement in sport divers - Method and first results [Blutdruckmessung bei sporttauchern - Methode und erste ergebnisse]. J fur Hypertonie. 2005;9(2):7–13. German.
- Moher D, Liberati A, Tetzlaff J, Altman DG, PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. BMJ. 2009;339:b2535. doi: [10.1136/BMJ.B2535](https://doi.org/10.1136/BMJ.B2535). PMID: 19622551. PMCID: PMC2714657.
- Wyss V. ECG of apneic subjects during immersion in water at various depths [Elettrocardiogramma di soggetti in apnea durante immersione in acqua a profondità diverse]. Boll Soc

- Ital Biol Sper. 1956;32(6):503–6. PMID: 13374145. Italian.
- 9 Noh Y, Posada-Quintero HF, Bai Y, White J, Florian JP, Brink PR, et al. Effect of shallow and deep SCUBA dives on heart rate variability. *Front Physiol.* 2018;9:110. doi: 10.3389/fphys.2018.00110. PMID: 29535634. PMCID: PMC5835073.
 - 10 Ołędzki S, Wojtarowicz A, Płońska-Gościński E, Lewandowski M, Gorący J. Scuba diving, patent foramen ovale and heart rhythm disturbances: The role of underwater Holter monitoring - Case report. *Ann Noninvasive Electrocardiol.* 2017;22:e12450. doi: 10.1111/anec.12450. PMID: 28429454.
 - 11 Cibis T, Groh BH, Gatermann H, Leutheuser H, Eskofier BM. Wearable real-time ECG monitoring with emergency alert system for scuba diving. In: Proceedings of the annual international conference of the IEEE engineering in medicine and biology society, EMBS. Milan, Italy: IEEE; 2015. p. 6074–7. Available from: <https://ieeexplore.ieee.org/document/7319777>. [cited 2019 March 22].
 - 12 Istepanian RSH, Woodward B. The design and evaluation of a programmable underwater acoustic biotelemetry system for diver monitoring. *Acta Acust.* 2003;89:95–104.
 - 13 González Olea A, Trigueros MJL, Martínez IA, González CA, López BCA, Callejón PE. Physiological adaptation to cold water diving. [Adaptación fisiológica al buceo en aguas frías]. *Arch Med Del Deport.* 2001;18:603–11. Spanish.
 - 14 Schipke JD, Pelzer M. Effect of immersion, submersion, and scuba diving on heart rate variability. *Br J Sports Med.* 2001;35:174–80. doi: 10.1136/BJSM.35.3.174. PMID: 11375876. PMCID: PMC1724326.
 - 15 Bosco G, de Marzi E, Michieli P, Omar HR, Camporesi EM, Padulo J, et al. 12-lead Holter monitoring in diving and water sports: A preliminary investigation. *Diving Hyperb Med.* 2014;44:202–7. PMID: 25596833.
 - 16 Ehrmann U, Pittner A, Paulat K, Radermacher P, Muth CM. Heart rate and metabolic effects during apnea diving. [Herzfrequenz und metabolische effekte beim apnoetauchen]. *Dtsch Z Sportmed.* 2004;55:295–8. German.
 - 17 Lemaître F, Lafay V, Taylor M, Costalat G, Gardette B. Electrocardiographic aspects of deep dives in elite breath-hold divers. *Undersea Hyperb Med.* 2013;40:145–54. PMID: 23682546.
 - 18 Schuster A, Castagna O, Schmid B, Cibis T, Sieber A. Underwater monitoring system for body temperature and ECG recordings. *Underw Technol.* 2017;34:135–9.
 - 19 Berry NT, Wideman L, Rhea CK, Labban JD, Chon KH, Shykoff BE, et al. Effects of prolonged and repeated immersions on heart rate variability and complexity in military divers. *Undersea Hyperb Med.* 2017;44:589–600. doi: 10.22462/11.12.2017.10. PMID: 29281196.
 - 20 Breskovic T, Uglesic L, Zubin P, Kuch B, Kraljevic J, Zanchi J, et al. Cardiovascular changes during underwater static and dynamic breath-hold dives in trained divers. *J Appl Physiol* (1985). 2011;111(3):673–8. doi: 10.1152/japplphysiol.00209.2011. PMID: 21719730.
 - 21 Kiviniemi AM, Breskovic T, Uglesic L, Kuch B, Maslov PZ, Sieber A, et al. Heart rate variability during static and dynamic breath-hold dives in elite divers. *Auton Neurosci.* 2012;169:95–101. doi: 10.1016/j.autneu.2012.05.004. PMID: 22682754.
 - 22 Kuch B, Bedini R, L'Abbate A, Wagner M, Buttazzo G, Sieber A. Embedded data logging platform for research in diving physiology. In: Proceedings of the 7th workshop on intelligent solutions in embedded systems, WISES 2009. Ancona, Italy: IEEE; 2009. p. 43–8. Available from: <https://ieeexplore.ieee.org/document/5186411>. [cited 2019 March 22].
 - 23 Sieber A, Bedini R, Yong X, Navarri A, Luche MD, L'Abbate A, et al. High resolution ECG and depth data logger: A novel device to study breath hold diving induced variations of the PQ interval. Proceedings of the 1st international conference on biomedical electronics and devices – Volume 1. Funchal, Madeira, Portugal: SciTePress; 2008. p. 269–75. Available from: <http://www.scitepress.org/PublicationsDetail.aspx?ID=kixxvouoCSk=&t=1>. [cited 2019 March 22].
 - 24 Noh Y, Bales JR, Reyes BA, Mollignano J, Clement AL, Pins GD, et al. Novel conductive carbon black and polydimethylsiloxane ECG electrode: A comparison with commercial electrodes in fresh, chlorinated, and salt water. *Ann Biomed Eng.* 2016;44:2464–79. doi: 10.1007/s10439-015-1528-8. PMID: 26769718.
 - 25 Koehle MS, Hodges ANH, Lynn BM, Rachich MF, McKenzie DC. Diffusing capacity and spirometry following a 60-minute dive to 4.5 meters. *Undersea Hyperb Med.* 2006;33:109–18. PMID: 16716061.
 - 26 Chouchou F, Pichot V, Garet M, Barthélémy J-C, Roche F. Dominance in cardiac parasympathetic activity during real recreational SCUBA diving. *Eur J Appl Physiol.* 2009;106:345–52. doi: 10.1007/s00421-009-1010-0. PMID: 19277697.
 - 27 Madden D, Barak O, Thom SR, Yang M, Bhopale VM, Ljubkovic M, et al. The impact of pre-dive exercise on repetitive SCUBA diving. *Clin Physiol Funct Imaging.* 2016;36:197–205. doi: 10.1111/cpf.12213. PMID: 25371042.
 - 28 Susilovic-Grabovac Z, Obad A, Duplančić D, Banić I, Brusoni D, Agostoni P, et al. 2D speckle tracking echocardiography of the right ventricle free wall in SCUBA divers after single open sea dive. *Clin Exp Pharmacol Physiol.* 2018;45:234–40. doi: 10.1111/1440-1681.12883. PMID: 29214659.
 - 29 Steinberg F, Doppelmayr M. Executive functions of divers are selectively impaired at 20-meter water depth. *Front Psychol.* 2017;8:1000. doi: 10.3389/fpsyg.2017.01000. PMID: 28676772. PMCID: PMC5476772.
 - 30 Flouris AD, Scott JM. Heart rate variability responses to a psychologically challenging scuba dive. *J Sports Med Phys Fitness.* 2009;49:382–6. PMID: 20087297.
 - 31 Ljubkovic M, Gaustad SE, Marinovic J, Obad A, Ivancev V, Bilopavlovic N, et al. Ultrasonic evidence of acute interstitial lung edema after SCUBA diving is resolved within 2–3 h. *Respir Physiol Neurobiol.* 2010;171:165–70. doi: 10.1016/J.RESP.2010.02.008. PMID: 20188217.
 - 32 Møllerløkken A, Breskovic T, Palada I, Valic Z, Dujic Z, Brubakk AO. Observation of increased venous gas emboli after wet dives compared to dry dives. *Diving Hyperb Med.* 2011;41:124–8. PMID: 21948496.
 - 33 Bilopavlovic N, Marinovic J, Ljubkovic M, Obad A, Zanchi J, Pollock NW, et al. Effect of repetitive SCUBA diving on humoral markers of endothelial and central nervous system integrity. *Eur J Appl Physiol.* 2013;113:1737–43. doi: 10.1007/s00421-013-2600-4. PMID: 23400567.
 - 34 Madden D, Thom SR, Yang M, Bhopale VM, Ljubkovic M, Dujic Z. High intensity cycling before SCUBA diving reduces post-decompression microparticle production and neutrophil activation. *Eur J Appl Physiol.* 2014;114:1955–61. doi: 10.1007/s00421-014-2925-7. PMID: 24917356.
 - 35 Zanchi J, Ljubkovic M, Denoble PJ, Dujic Z, Ranapurwala S, Pollock NW. Influence of repeated daily diving on decompression stress. *Int J Sports Med.* 2014;35:465–8. doi: 10.1055/s-0033-1334968. PMID: 23771833.
 - 36 Castagna O, Desruelle AV, Blatteau JE, Schmid B, Dumoulin G, Regnard J. Alterations in body fluid balance during fin

