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

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Abstract

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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 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:

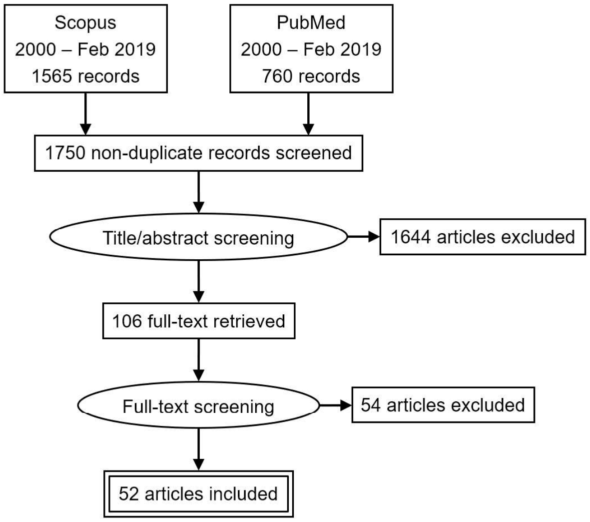
- What type of wearable sensors can be used in human BH diving?
- What wearable sensors used for SCUBA diving are potentially applicable also to BH diving?
- What water- and pressure-proofing strategies have been adopted to adapt monitoring technology to the underwater environment?
- At which depth have 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 increase[6]), 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

Figure 1
PRISMA flow diagram for the systematic review



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 (SpO_2, 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 SpO_2 (one study), ECG, ABP and SpO_2 (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 electrodes 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 cardiotachometers 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 = hypdrophilic 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	ECG recorder	Not specified	Not specified	–
Electrodes + ECG transmitter	13	S	WHC	27	Fukuda-Denshi	Yes	ECG 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	ECG transmitter	Cable	Electrodes: not specified; ECG transmitter: water- and pressure-proof case.	–
Electrodes + ECG recorder	17	BH	Sea	70	Sorin Group	Yes	ECG 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	ECG recorder	Cable	Electrodes: waterproof tape; ECG recorder: professional diving pouch (TMT, ewa-marine)	–
	47	S	Lake	8	PicoMed	No	ECG recorder	Cable	Electrodes: special clips; ECG recorder: not specified	–
	15	S	Sea	25	Mortara	No	ECG recorder	Cable	Electrodes: first layer (Visulin, Hartmann) + second layer (Steri-Drapes, 3M); ECG Holter recorder: pressure-proof anticorodal 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	ECG 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	2[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 modestly[48] 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 chamber[40] 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 O_2 in the arterial blood. It can be measured non-invasively in the peripheral circulation (SpO_2), 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 SpO_2 at 100%. Only during a prolonged period at depth and/or during the ascent (when there is reversal of the above process) would O_2 depletion manifest as a decrease in SpO_2. As a consequence of circulation time between lungs and forehead, the nadir of SpO_2 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' biomechanics[56] 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 diving[66] 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 underwater[77] by protecting the electrodes under a full-face latex mask, further covered by a bathing cab. 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
Skin 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
	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.

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