Technical articles

Oxygen sensor signal validation for the safety of the rebreather diver

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Key words

Rebreathers/closed circuit, oxygen, monitoring device, equipment

Abstract

(Sieber A, L'Abbate A, Bedini R. Oxygen sensor signal validation for the safety of the rebreather diver. *Diving and Hyperbaric Medicine*. 2008;38:38-45.)

In electronically controlled, closed-circuit rebreather diving systems, the partial pressure of oxygen inside the breathing loop is controlled with three oxygen sensors, a microcontroller and a solenoid valve – critical components that may fail. State-of-the-art detection of sensor failure, based on a voting algorithm, may fail under circumstances where two or more sensors show the same but incorrect values. The present paper details a novel rebreather controller that offers true sensor-signal validation, thus allowing efficient and reliable detection of sensor failure. The core components of this validation system are two additional solenoids, which allow an injection of oxygen or diluent gas directly across the sensor membrane.

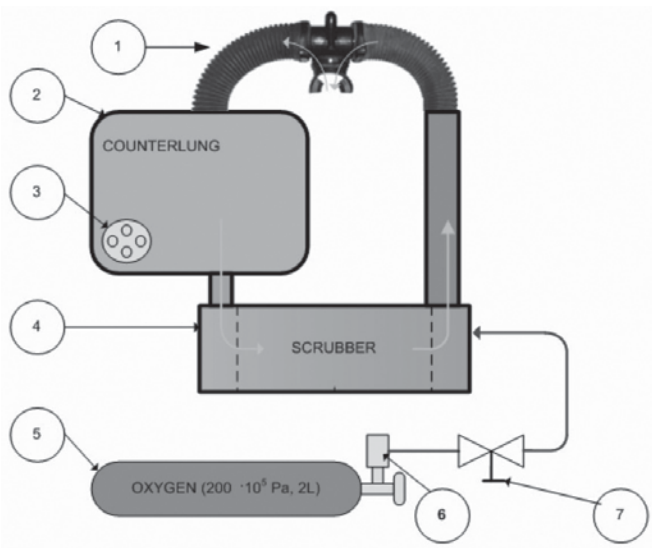
Introduction

REBREATHER SYSTEMS

Closed-circuit rebreather (CCR) diving with its many advantages in comparison to open-circuit diving is becoming increasingly popular.[1] In an oxygen (O_2) rebreather (Figure 1) the diver exhales into a bag – the so called 'counter-lung'.[2] A scrubber removes carbon dioxide (CO_2) and fresh gas is added to replace metabolized oxygen (O_2). This recycled gas is then inhaled by the diver again. In the case of a pure O_2 rebreather, the circuit contains mainly O_2. Thus the partial pressure of O_2 (ppO_2) inside the circuit is dependent on the ambient pressure (Dalton's Law). Such a rebreather has the advantages of maximizing the efficiency of gas usage, and provides bubble-free, silent diving and warm, humid breathing gas. The presently recommended ppO_2 limits for life-sustaining breathing gas range from 0.1 bar (10.1 kPa) to 1.6 bar (162 kPa).* A ppO_2 above this upper limit may lead to acute oxygen toxicity, manifested as an epileptiform convulsion, which is likely to be fatal underwater. A ppO_2 below 0.1 bar (10.1 kPa) will lead to unconsciousness.[3,4] The maximum ppO_2 limit recommended varies from 1.4–1.6 bar, and sets the depth limit for pure O_2 and mixed-gas rebreathers. Rebreathers are classified into either semi-closed-circuit rebreathers (SCR) or manually or electronically controlled closed-circuit rebreathers (mCCR or eCCR).[5,6] In an SCR, O_2-enriched gas enters the breathing loop via a constant flow injector (commonly an orifice, typically 6–12 bar L.min^{-1}) to substitute the metabolized O_2 (Figure 1). Excess gas in the circuit is then vented through an overpressure valve. The maximum depth for an SCR is mainly limited by the percentage of O_2 in the supply gas.

In a CCR, the ppO_2 is usually kept at a constant level, only the metabolized O_2 is substituted. In mixed-gas diving, the breathing gas in a CCR contains nitrogen (N_2) or helium (He) or, for deeper dives, a He-N_2 mixture. To maintain the ppO_2 at a constant level, a control loop is needed.[7,8] Therefore, electrochemical oxygen sensors, whose output signals are proportional to the ppO_2, are used as sensing elements. In a mCCR, the diver reads the ppO_2 from a display, then, as necessary, adjusts the O_2 injection needle valve and/or adds O_2 manually. In an eCCR this control task is usually performed by a microcontroller and a solenoid valve.

Figure 1
Schematics of an oxygen rebreather
1: mouthpiece, 2: counterlung, 3: overpressure valve, 4: CO_2 scrubber, 5: oxygen cylinder, 6: pressure regulator, 7: manual valve



Footnote: * In this report, pressure is expressed as bar pressure (1 bar = 0.1013 MPa, 101.3 kPa)

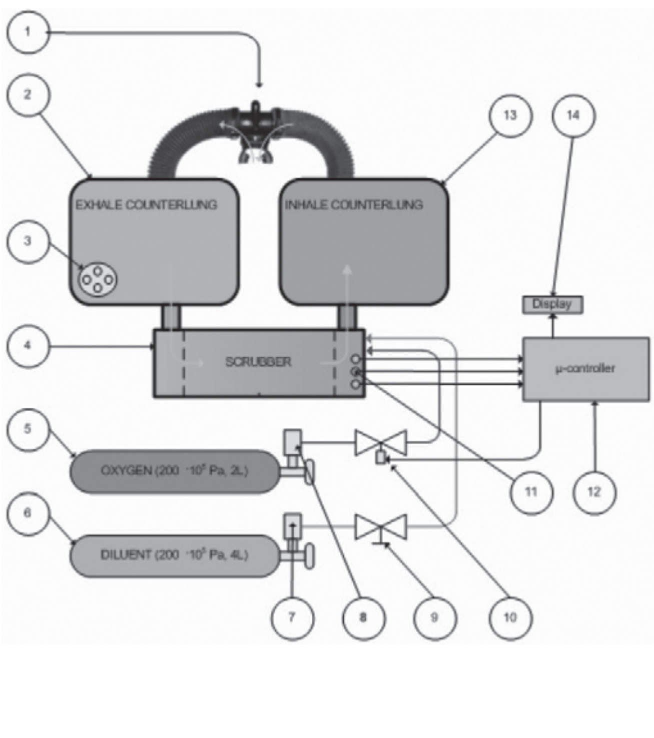
Both types of closed rebreather systems have many advantages:

- Gas efficiency: Open-circuit scuba diving has a low gas utilisation efficiency from less than 5 % on the surface, to below 0.5 % at 100 metres' sea water (msw) depth. In CCRs, because the breathing gas is recycled and, under optimal conditions, only the metabolised O_2 is replaced, gas efficiency may approach 100 %, enabling the design of comparatively small, lightweight systems where gas costs and supply are no longer the limiting factors.
- Silence: CCRs allow bubble-free, silent diving; only during ascent gas is vented from the circuit.
- Warm, humidified breathing gas: Gas from open-circuit scuba is dry and, because of expansion of the gas in the regulator, cold. Cold breathing gas cools the diver and, in very cold water, may lead to regulator malfunction due to freezing. In a rebreather, the breathing gas is usually warm and humid, as the chemical CO_2 absorption produces water and heat as by-products. However, in cold water, scrubber efficiency can also be impaired.

REBREATHER SAFETY

To ensure the safety of the diver, rebreathers sold within the European Union have to be CE-marked (European Normative EN14143:2003),[9] and are classified as Category III Personal Protective Equipment. They must be certified by an independent, certified Notified Body.[10]

Figure 2
Schematics of an electronic closed-circuit rebreather
1: mouthpiece, 2: exhale counterlung, 3: overpressure valve, 4: CO_2 scrubber, 5: oxygen cylinder, 6: diluent cylinder, 7, 8: pressure regulators, 9: manual diluent valve, 10: solenoid, 11: ppO_2 sensors, 12: microprocessor, 13: inhale counterlung, 14: display



Unfortunately there is already a long list of rebreather diving incidents and fatalities.[1,11,12] The most commonly identified systems failures in these deaths are:

- ppO_2 outside of life-sustaining limits
- high CO_2 levels
- water leakage into the breathing circuit.

High CO_2 levels can be avoided by good scrubber design and conservative scrubber management. The latest developments use pre-packed scrubbers, to avoid poor scrubber filling methods that may cause channeling, an important cause of raised CO_2 levels in the breathing circuit. Water leaking into the circuit reacts with the scrubber chemicals, causing the so called 'caustic cocktail'. Some CCRs avoid this by incorporating hydrophobic membranes in the inlet and outlet of the scrubber, that prevent water from entering or leaving.

Figure 2 details the ppO_2 control in an eCCR. A solenoid stuck in either the open or closed positions is a typical failure of the O_2 injection system. A properly trained diver will be able to handle this and other emergency situations. The state of the art for the electronic components is to use redundant design; typically the diver carries two or three independent ppO_2 meters and several displays, the ppO_2 inside the loop depending on the accuracy and reliability of the sensor signals.

O_2 SENSORS

In current rebreathers, galvanic O_2 sensors are used. The core element of a galvanic O_2 sensor is an electrochemical cell ('fuel cell') consisting of two electrodes of dissimilar metals (cathode – a noble metal behind a diffusion barrier, usually of Teflon; anode – lead) in contact with a liquid or semisolid basic electrolyte, usually potassium hydroxide. When the sensor is exposed to the breathing gas, O_2 diffuses through the Teflon membrane and is chemically reduced at the surface of the cathode to hydroxyl ions. The hydroxyl ions then flow toward the lead anode, where an oxidation reaction occurs generating an electrical current proportional to the ppO_2.

In most cases, a resistor is incorporated in the electrical circuit, thus the output from the sensor is measured in mV. Many sensors incorporate temperature compensation in the electronics. Typical specifications for an O_2 sensor for diving purposes are:

- Range: 0–100% O_2, 0–2 bar O_2
- Signal output: 8–13mV @ 0.21 bar O_2 (linear slope: 40–75 mV per bar pressure)
- Response 90%: 6 s

In the reaction with O_2, the anode is consumed, which is the limiting factor determining the lifetime of the sensor, typically 12–24 months.

O_2 SENSOR FAILURES

Typical O_2 sensor failures are:

- non linearity
- current limitation (the output signal of the sensor is limited, thus will remain constant at a certain ppO_2)
- slow signal response
- other sensor failures (mechanical or electrical damage).

The most common failure mode is not achieving the correct electrical output for a given ppO_2. This is due either to exhaustion of the anode or loss of water from the electrolyte solution, resulting in a low reading. The most serious failure is not giving the correct output above a given ppO_2. Exhaustion of the anode surface results in an increase in the response time and then what is called current limitation, voltage limitation, or ceiling fault. Sensors can fail temporarily if the sensor membrane is exposed directly to water. This results in a dramatic increase in the response time and sensor readings that are too low. This problem can be avoided by good design, such as where the sensors are mounted top down, so that water cannot collect on the sensor membrane. Damage of the sensor membrane due to impact shocks may lead to electrolyte leakage, which usually results in an increased current output.

Failure of the electronic components may lead to several problems. Oxygen sensors generate an electrical charge, which is drained via a resistive load; in the case of a failed resistor this charge will build up until current leakage is sufficient to dissipate the charge generated: this can be as high as 100V. With a thermistor failure, the output may vary by up to 2% per degree Celsius. In the case of a shortcut of the resistor, the sensor will produce no output. Other sensor failures that may occur temporarily are current changes caused by fast decompression and He and CO_2 susceptibility.

Non-linearity and current limitation are the most serious failures for a rebreather diver; for example, a current-limited cell may report a ppO_2 of 1.2 bar correctly, but a ppO_2 above this will not be correctly indicated. This is despite calibration with 100% O_2 on the surface showing normal values. This causes injection of more O_2, resulting in a potentially dangerous elevation of ppO_2 inside the circuit outside of life-sustaining limits. For these reasons, multiple, typically three, O_2 sensors are used together with a 'voting algorithm'.[13,14] Here, the sensor signals are continuously compared with each other. If one sensor signal differs from the others, that sensor signal is 'voted out'. In such a case, the two remaining sensors are used for further control of the system and the user is notified with an alarm signal. For example, in the Hammerhead™ CCR electronic (Juergensen Marine, USA) a sensor is voted out if its signal deviates by more than 15% from the average value of the other two sensors. As the voting algorithm is based on a comparison of sensor signals, it will fail when two or more sensors give the same but incorrect signals; this cannot be reliably detected with the voting algorithm. Unfortunately similar concurrent sensor failures do occur, especially when sensors from the same manufacturer and same production lot are used. Rebreather divers have tended to replace all the sensors at the same time with the same type of sensor. This practice is now changing so that sensors from different production lots and/or manufacturers are used and additional checks are performed. Pre-dive preparation currently includes a single-point normobaric calibration with 100% O_2 or air. Since during diving a ppO_2 above 1.0 bar will occur, this is not optimal. Some rebreather divers now pressure test sensors at 1.6 bar to check linearity.

The present work details an alternative to the voting algorithm, in which a novel sensor signal validation concept allows reliable detection of sensor failure and automatic sensor calibration without any interaction by the user.

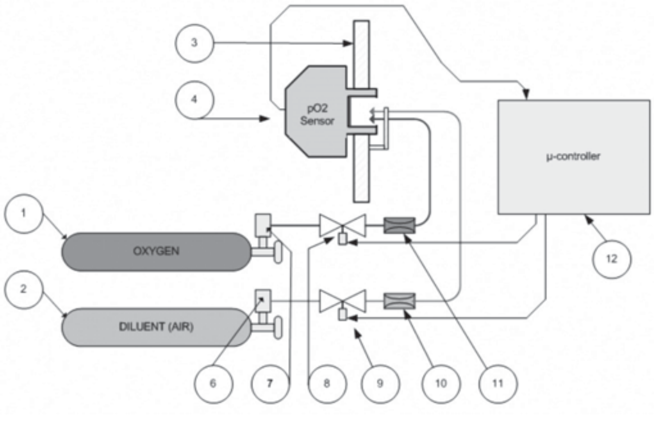
Methods

OXYGEN SENSOR SIGNAL VALIDATION

The principle of the sensor signal validation technique is based on injection of a gas with a known O_2 fraction across the O_2 sensor membrane. As the actual depth is known from the readings of the pressure sensor, the ppO_2 of the injected gas can be calculated. The injected gas flushes the sensor membrane, so that the ppO_2 of the injected gas is read, not that of the breathing gas in the circuit. The sensor readings can then be compared to the theoretically calculated values, confirming whether or not the sensor is working correctly. Any O_2 sensor suitable for diving applications may be used with this sensor validation method.

Figure 3 shows the practical setup of the sensor signal validation apparatus to allow flushing the sensor membrane with O_2 or with diluent. Two solenoids are incorporated for

Figure 3
The principle schematics of the ppO_2 sensor signal validation system
1: oxygen cylinder, 2: diluent cylinder, 3: sensor support, 4: ppO_2 sensor, 5: support for O_2 and diluent injection, 6, 7: pressure regulators, 8, 9: solenoids, 10, 11: flow restriction orifices, 12: microprocessor



the flow control. In some previous CCR units, a similar device to flush the sensor membrane manually with diluent could be found, but frequent cell failures have been reported with this technique. This is likely to be a result of the injection of gas at intermediate pressure (8–10 bar above ambient) directly onto the sensor membrane, possibly shooting moisture drops on the orifice at the sensor at high velocity. To avoid this problem in the new system, orifices with an internal diameter of 140 µm are mounted on the exit of the solenoids reducing the gas velocity at the output and limiting the gas flow to approximately 2 bar $L.min^{-1}$.

Sensor signal validation with diluent is carried out every 120 s (default setting, range 60–255 s). In addition to that, in a depth range of 0–10 msw the same procedure can be carried out with O_2. This allows detection of non-linearity and/or current limitation of the sensor when combined with periodic checks with diluent allowing calibration of the sensor at a ppO_2 greater than 1 bar. By analysis of the signal response the t_{90} response time can be calculated, which also allows recognition of slow response times. The typical duration of flushing the sensor membrane is 6 s, which results in 0.2 bar L of injected gas. Considering a total circuit volume of about 6 L, the signal validation procedure with air causes a decrease of ppO_2 inside the circuit of approximately 0.01 bar; with 100 % O_2, it will lead to an increase of the ppO_2 of 0.016 bar.

The ppO_2 control in the first prototype was designed to keep the oxygen fraction (FO_2) in the circuit constant at 0.50 to a maximum depth of 14 msw. Below that depth, the ppO_2 has a set point of 1.2 bar. If a failure is detected, the diver is notified via an alarm. The diver should then change to an independent bailout system and abort the dive. Theoretically safe operation can be achieved with just one sensor with this sensor signal validation system. However, for redundancy purposes, the first prototypes included two O_2 sensors along with the electronics and the solenoids housed inside the scrubber (Figure 4). In the case of one sensor failure, the dive can be continued. In the case of a failure of both sensors, the diver has to switch to bail out.

ELECTRONICS

Hardware

The core component of the electronics is an 8-bit RISC microcontroller (ATmega 32™, 32kByte flash ROM, 2 Kbyte RAM, Atmel™). A 4x20 characters display (EA DIP 204-4™, Electronic Assembly™, Germany) is connected via a serial peripheral interface (SPI) bus. To enable a detailed post-dive analysis a slot for SD memory cards was incorporated. Three N-FET transistors (NDS355) serve as solenoid drivers.

The microprocessors' internal 10-bit AD-converters are used for sensor signal readout. The programmable gain of 10 and 2000 is sufficient to allow a direct connection of the two sensors (electrochemical pO_2 sensors used in rebreathers typically have a linear output with a slope of approximately 8–13 mV @ 0.21 bar ppO_2). To measure the ambient pressure/depth, two digital pressure sensors (MS5541™, Intersema™, Switzerland) are incorporated. The MS5541 is factory-calibrated for a pressure range of 0–14 bar and has a 15-bit resolution. The maximum working pressure is 33 bar (not specified), and continuous temperature compensation is built in. The sensor is read out via the SPI bus. A rechargeable battery pack (6V, 900mAh, NiMH) is used as power supply for the solenoids. For the electronic components, two low-drop voltage regulators (Texas Instruments) are used for the generation of 3.3 V and 5 V levels.

A second display is used for redundancy purposes.[15] This display has analog inputs and can be connected to the O_2 sensors in parallel with the primary electronics. The core component is again an 8-bit RISC microprocessor (ATmega644p™, 64 Kbyte flash ROM, 4 Kbyte RAM, Atmel). A digital interface line is included, which allows receiving data from the primary electronics (the controller) via a serial interface (either USART or I2C). A graphics display with 128x64 characters is placed behind a concave lens (f = 60 mm, designed for a virtual image distance of 1 m), which allows the display to be mounted directly on the mouthpiece of the rebreather. The two displays show the sensor signal ppO_2 values, depth, central nervous system (CNS) oxygen toxicity percentage, oxygen tolerance units (OTU), diving time and decompression information.

Software

As programming platform, the Atmel AVR Studio 4™, together with the GNU C compiler WinAVR http://winavr.sourceforge.net, was used under Windows XP®. All sensor data are stored on the SD card in spreadsheet format. FAT 16

Figure 4
The two O_2 sensors combined with the electronics and solenoids mounted inside the scrubber in the prototype eCCR; the tubing through which diluent or 100% oxygen can be flushed to perform calibration can be seen

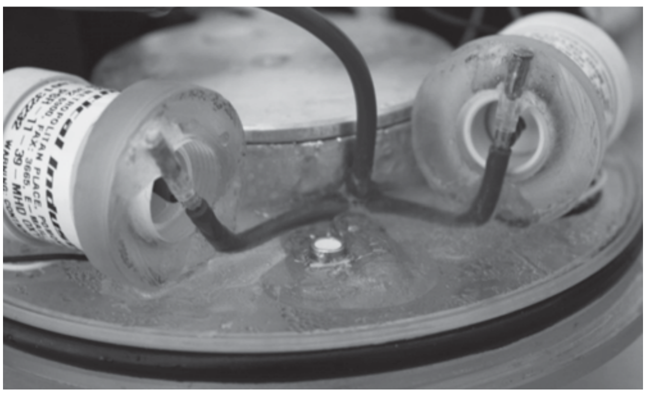
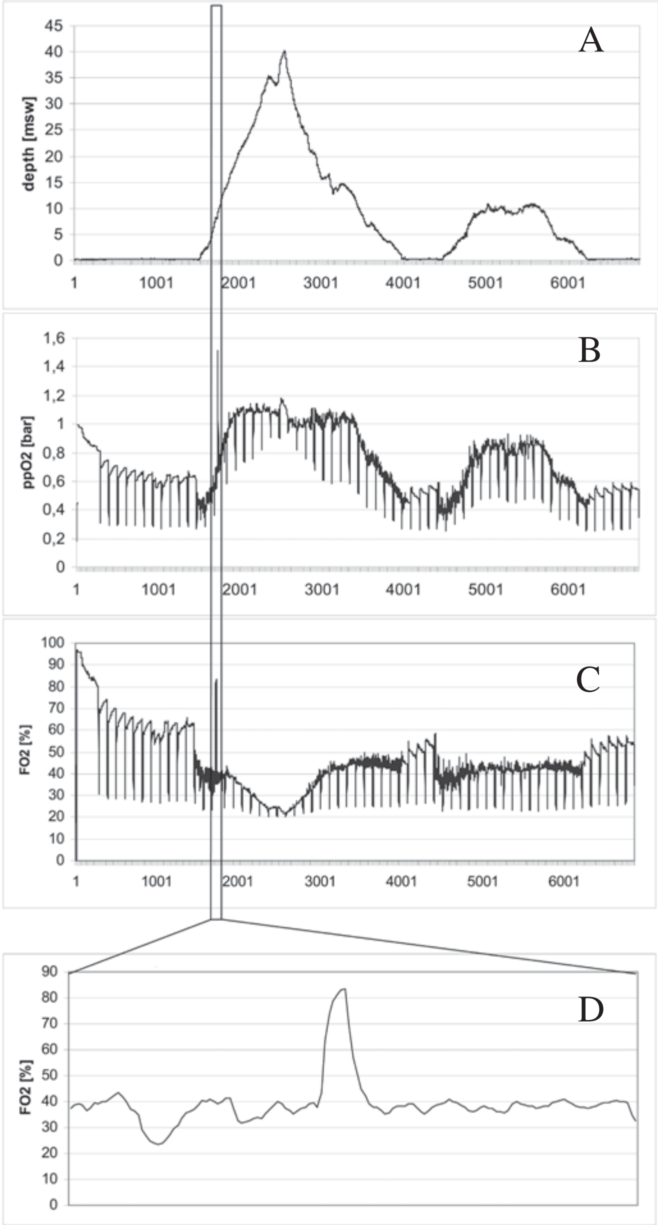


Figure 5
Data from a 100-min open-water test dive to a maximum depth of 40 msw; A: depth profile; B: ppO_2 sensor signals from two sensors; C: calculated FO_2; D: one validation cycle with 100% oxygen at 10 msw



or FAT 32 formatted SD memory cards can be used. For each dive a new file is created. Additional data, such as battery voltage, oxygen injection, oxygen consumption and error messages, are stored. These data can then be displayed with suitable programmes, such as MS Excel® (Figure 5).

Every 120 s, the sensor signal validation procedure, with diluent as the validation gas, is carried out, which results in the spikes in the readings of the ppO_2 sensors (Figure 5B-D shows the signal of one sensor). During the validation cycle the calculated FO_2 must drop to a value less than 0.25; if not, an alarm signal is generated. At a depth between 6 and 10 msw once during a dive, the sensors are checked with 100% O_2 (Figure 5D). Additional validations at depths less than 10 msw may be carried out. Error messages are created if a ppO_2 sensor signal is outside the limits set (see earlier), if the sensor signals differ by more than 0.01 bar from each other, if the battery voltage is below 6.0V and if the calculated O_2 consumption of the diver is less than 0.3 or more than 3 bar $L.min^{-1}$.

As the validation procedure is carried out with two different gases, it is possible to detect incorrect calibration, non linearity and slow sensor response. Because the response time of O_2 sensors is typically about 6 s (t_{90}), at the end of the validation cycle, the sensors will read, at 10 msw depth, a ppO_2 in the range of 1.6–1.9 bar rather than 2.0 bar. During the 6 s, the sensor signal output is measured every second. As the signal response has a single exponential character (the signal response time is mainly limited by diffusion of O_2 through the Teflon membrane), it is possible to forward calculate the final value. To pass the test at 10 msw, the sensors have to read a minimum 1.6 bar ppO_2 at the end of the O_2 injection and the forward calculated signal has to correspond to an O_2 fraction of greater than 90%. If the test is failed, an alarm is created and the dive should be aborted. If, despite the alarm, the dive is continued on closed circuit, for safety reasons the maximum ppO_2 set point is automatically changed to 1.0 bar. The forward calculation is applied only during the checks with 100% O_2, not for calibration or measurement purposes.

Several pre-checks have to be performed before diving with a CCR. To facilitate this, a six-step semi-automated test sequence has been implemented:

1. The user is asked to evacuate the loop of gas.
2. As soon as a pressure drop of −15 mbar is registered, the user is asked to close the mouthpiece.
3. To test for circuit leaks, the negative pressure must not fall to less than −10 mbar within the following 60 s, otherwise the test is failed.
4. After a successful negative pressure test, the loop is inflated with 100% O_2 until an overpressure of 15 mbar is registered. For the inflation, the solenoid valve opens cyclically every second for 200 ms; the cycles are counted. A correctly operating solenoid takes 45 +/− 1 cycles to inflate the counter lungs with a volume of 5 L; 42–48 counted cycles are needed to pass the test.
5. The O_2 sensors are calibrated; readings must be higher than 40 mV to pass the calibration test.
6. In step 4, the loop is inflated to +15 mbar; this pressure must not drop more than 5 mbar in 60 s to pass the test.

After successfully passing all six steps, the unit is ready to dive. If the unit is dived without a correctly passed test an alarm is created and, if the diver is still at a depth less than 6 msw, O_2 sensor calibration is immediately carried out by injection of O_2 for 15–20 s directly onto the sensor membrane. If the diver is already deeper than 6 msw, no calibration will be carried out but the maximum ppO_2

setpoint is automatically limited to 1 bar.

TESTING OF THE SENSOR SIGNAL VALIDATION ALGORITHM

For validation of the algorithm implemented on the microcontroller, a PC-based dive simulator was designed. A sensor signal simulator was developed which could be connected to the PC's printer port. Its core component is a six-channel digital potentiometer (Analog Devices™, AD5206™). Each potentiometer has a nominal value of 10 kΩ and 8-bit resolution. One of the potentiometers is connected in series with a 10 kΩ resistor to a stabilized 5 V direct-current supply for the generation of an output voltage of 0–2.5 V. For simulation of dives, the firmware of the microcontroller was slightly modified. Instead of processing the signal of the digital pressure sensors, depth information is gained from an analog to digital converter channel, by converting input voltages from 0–2.5 V to 0–100 msw depth equivalents. To simulate O_2 sensor signals in the range of 0–128 mV with a resolution of 0.5 mV, three of the potentiometers were each connected in series with a 390 kΩ resistor to the 5 V supply. The microcontroller's output usually driving the solenoids is connected to digital IO pins of a multifunction input/output board (National Instruments™, NI USB-6008™).

A graphical user interface which allows programming of the output voltages of the potentiometers at discrete time steps was developed under National Instruments LabView 7.1™. Simulation of depth profiles together with O_2 sensor signals is possible with different scenarios, such as defective O_2 sensors, being simulated with ease. Signal responses of the sensors to signal validation were pre-programmed to simulate correct function, slow response, current limitation and non linearity.

Two prototypes CCRs were designed and manufactured with the following specifications (Figure 6):

- outer dimension: 45 x 25 x 18 cm
- scrubber holds 1.8 kg of soda lime
- maximum recommended depth 40 msw (unit for recreational purposes)
- 1 oxygen cylinder: 1.5 L, 200 bar working pressure
- 1 diluent cylinder: 1.5 L, 200 bar working pressure
- total weight including cylinders: 12 kg
- maximum dive time: 180 min
- positive buoyancy: 40 N
- two O_2 sensors: PSR-11-39MD (Analytical Industries)

The implemented algorithm for sensor signal validation returns a binary validation result: either a 'correctly' or 'incorrectly' working sensor. If one of the criteria is failed, an alarm is activated.

- Validation with diluent: at the end of the validation cycle, the sensor has to read a ppO_2 corresponding to a FO_2 of less than 25%.

Figure 6
The prototype eCCR being prepared for a dive

- Validation with O_2: at the end of the validation cycle, the sensor has to read a ppO_2 corresponding to a FO_2 of at least 80%. The forward calculated sensor signal for the FO_2 has to be higher than 90%.

The sensor signal validation system was first tested in simulated dives in the laboratory, for which O_2 sensors were not required. These tests simulated O_2 sensor behaviour during normal operations to detect non-linearity, current limitation, slow response times and incorrect calibration. All the simulated sensor failures were correctly detected, validating the correct implementation of the algorithm.

TESTING THE eCCR PROTOTYPES

After laboratory testing, the function of the prototypes was tested in a hyperbaric chamber at a maximum pressure of 405 kPa and a dive duration of 40 min. The main aim of this test was the validation of the principal correct operation of the ppO_2 control and the sensor signal validation method. The second aim was to ensure that the flow rate was high enough to substitute all the gas in front of the sensor membrane with either O_2 or diluent to achieve a defined FO_2. A flow rate of 2 bar $L.min^{-1}$ turned out to be optimal in the current design. No system failures occurred.

Six test dives were also performed in a 10.5 metres' fresh water (mfw) research pool (Divesystem, Massa Marittima, Italy). Tests were carried out with three old sensors known to be current-limited. The faulty sensors calibrated correctly at surface, showed a correct response to the validation with diluent, but failed the validation at 10 mfw depth where their output signal reached just 1.4 bar (threshold was 1.6 bar). The failures were correctly detected.

Fifty-two open-water dives with the two prototype eCCRs were then carried out by three test divers (average depth 28 msw, range 11–52 msw). During all these dives, sensors with an age of less than one year were used. The ppO_2 control worked flawlessly; no dive had to be bailed out on open circuit. During one dive, the handset cracked and the display inside was flooded and failed. The handset cable leading to the main controller is hermetically sealed, thus no water could reach the main electronics. The dive was successfully continued with the dive data still displayed on the head-up display. In one dive, the sensor connector became loose, resulting in a floating sensor reading. The validation with diluent successfully detected this failure and the dive was continued. An example 100-min dive to a maximum depth of 40 msw is shown in Figure 5; no sensor failures occurred and sensor signal validation cycles with O_2 and diluent (air) were successfully carried out. The present concept of ppO_2 sensor signal validation has now been incorporated into a new eCCR, the Poseidon Discovery™ MK6 rebreather.

Discussion

Like the state-of-the-art voting algorithm, the sensor signal validation method described allows reliable detection of single sensor failures. In addition to this, and unlike the voting algorithm, failures where more than one sensor shows incorrect readings can be reliably recognized. The thresholds for passing the validation procedures were found empirically. The detection of all simulated sensor signal failures proved the correct implementation of the algorithm.

As the method is based on flushing a sensor membrane with a gas with a known O_2 fraction, an interesting case is when the FO_2 in the loop is close to the FO_2 in the diluent. During validation with diluent, no sensor signal changes should occur. Safe operation of a CCR requires a diluent with a FO_2 lower than the FO_2 in the loop, thus such a case should not occur during normal operation. In the first prototype, this scenario was not investigated.

O_2 sensors have to be replaced every 1–1.5 years. By using just one or two sensors instead of three, the yearly maintenance costs are reduced without compromising safety. However, this is offset by the need for additional hardware (two solenoids plus electronics), resulting in higher production costs.

Current limitation does not appear suddenly; it is a result of the aging of the sensor. Depending on the thresholds in the O_2 validation procedure, such a sensor will, sooner or later, be recognized as faulty. Further investigation is needed with a larger batch of O_2 sensors in order to validate and adjust the thresholds for such detection to find a good compromise between conservativeness and cost effectiveness.

Conclusions

The present paper describes a novel system for sensor signal validation and reliable sensor failure detection based on flushing the sensor membranes with a gas with a known fraction/ppO_2. Injection of 100% O_2 directly onto the sensor on the surface is used for initial calibration. Then in water up to 10 msw depth, 100% O_2 is used again to expose the sensors to a ppO_2 of up to 2.0 bar. Both current limitation and non-linearity are detected with this two-point calibration; these sensor failures do not occur temporarily, thus a single check early in the dive is sufficient. Recording the response signal of the sensor to O_2 injection also allows estimation of the sensor signal response time.

In principle, this concept allows safe operation of an eCCR with a single O_2 sensor, where, in the case of a failure, the diver must bail out of the dive. This is acceptable for a recreational unit intended for use for non-decompression dives. For more advanced diving, a second O_2 sensor should be used.

CCR diving requires continuous training and technical understanding of the equipment so that the diver is able to detect and safely handle malfunctions of the system The validation system described in this paper facilitates rebreather handling, as the system itself is able to carry out pre-dive O_2 sensor calibration and sensor signal checks semi-automatically. Reliable automation of safety checks in an eCCR is an important step to enabling recreational divers to dive more safely using these breathing systems.

Acknowledgements

We would like to thank Divesystem (Massa Marittima, Italy) and Poseidon (Göteborg, Sweden) for their support.

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Submitted: 24 July 2008
Accepted: 25 November 2008

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