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Sensor Integrated Pilot Mask for On-Board, Real-Time, Monitoring of Pilot Breathing Gas

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A pilot's job is unique in the demands it places on the human body, and many conditions can seriously affect pilot performance, threatening mission completion and pilot safety. The gas in a flight mask contains key indicators of the pilot's physiological state, including oxygen inhaled and carbon dioxide exhaled, which can signal hypoxia, hyperoxia, hypocapnia, and hypercapnia. A fiber optic-based sensor system, integrated into the pilot mask, has been developed to monitor in real time, during flight, the pilot breathing gas levels. Monitoring the partial pressure of oxygen and carbon dioxide in the pilot mask supports real-time closed loop control of the on-board oxygen generation system, based on a direct reading of what the pilot is actually breathing. The pilot Mask Sensor (MASES) system incorporates luminescence sensors for pO_2, pCO_2, relative humidity, pressure, and temperature in a compact probe in the pilot mask; it is based on sensor technology developed for gas monitoring in space suit systems, in work supported by NASA under the Small Business Innovation Research program. Relevant requirements for the MASES system include sensor operation while wet, operation at reduced pressure, ability to withstand rapid decompression, operation in a pure oxygen atmosphere, low power consumption, a compact readout unit, and flexible miniature sensors; many of these requirementsw are shared with gas monitors in space suits. Data are presented from tests conducted with human subjects in an altitude chamber and in a centrifuge.

Nomenclature

AFE = aircrew flight equipment
AFRL = Air Force Research Laboratory
BMP = breaths per minute
GOR = Gradual Onset Rate
ICES = International Conference on Environmental Systems

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LMCO = Lockheed Martin Aeronautics Company
MASES system = Mask Sensor system
NASA = National Aeronautics and Space Administration
OD = outer diameter
PBG = pressure breathing for G
RH = relative humidity
ROR = Rapid Onset Rate
t90 = time to reach 90% of sensor signal variation after receiving a stimulus
UPE = unexplained physiological effect

I. Introduction

A military pilot's job is unique in the demands it places on the human body; pilots are exposed to extreme environmental conditions, including reduced pressure and high acceleration, which may cause hypoxia, hyperoxia, hypocapnia, or hypercapnia. Historically, rates of unexplained physiological effects (UPEs) are low, but heightened awareness has increased aircrew reporting of in-flight hypoxia-like physiologic symptoms. In the past few years, concerns for physiological episodes have led the U.S. Air Force and U.S. Navy to temporally limit missions with several military aircraft, including the T-45 Goshawk, F-22 Raptor, and F-35A, and most recently (January 2018) the U.S. Air Force suspended all solo flights in T-6 Texan training aircraft following hypoxia-like events that affected four instructor pilots and one student pilot in four flights, because the investigation experts could find no specific cause for those hypoxia-like events.

Physiologic events are a recognized aviation hazard, so military aircrews are trained to recognize and respond to physiological symptoms and safely recover their aircraft. However, differentiating, for instance, between lack of oxygen and excess of ventilation (hypocapnia) can be difficult; both conditions can cause confusion, abnormal heart rate, and headaches, among other symptoms. The information provided by the pilots and current on-board sensor systems often cannot unambiguously determine the root cause and nature of such physiological events. The gas in the flight mask contains potential key indicators of the pilot's physiological state resulting from oxygen inhaled and carbon dioxide exhaled. This information can be used to determine hypoxia, hyperoxia, hypocapnia, and hypercapnia conditions, which could be keys to understanding UPEs. Giving pilots information about a specific, unfavorable condition in real time could enable them to deal with the situation by taking previously identified counteractions, such as adjusting their breathing rate. Furthermore, real-time monitoring of pressure, oxygen, and carbon dioxide may support closed loop control of on-board oxygen generation systems, based on a direct reading of what the pilot is actually breathing.

Monitoring gas composition in the pilot mask requires a sensor technology that meets some particular specifications, including a compact readout unit, a miniature sensor element (the tiny space inside the mask already accommodates a microphone), operation at low pressure or altitude, survival of rapid decompression, operation while wet, even with vomit, operation in a pure oxygen atmosphere, and under the conditions of flight (acceleration, vibration…). Finally, the sensor inside the mask should not interfere with the gas flow.

Over the past seven years, Intelligent Optical Systems has developed fiber optic sensors for monitoring gases in space suit systems. Working closely with NASA Lyndon B. Johnson Space Center, and in particular with the Space Suits and Crew Survival Systems Branch, we have developed sensors for monitoring partial pressure of oxygen and carbon dioxide, relative humidity, and trace contaminants (ammonia, volatile alcohols…). The requirements for sensors operating in space suits are similar to those for monitoring gases in a pilot mask. The ultimate objective for space suit sensors is to ensure that crew members can perform highly demanding tasks in an environment that prevents physiological events resulting from inappropriate levels of oxygen or carbon dioxide.

In a collaborative effort between Lockheed Martin Aeronautics Company (LMCO) and Intelligent Optical Systems, guided and supported by the U.S. Air Force, we have developed a Mask Sensor (MASES) system that incorporates luminescent sensors for pO_2, pCO_2, relative humidity, pressure, and temperature into a pilot mask. The integrated sensor pilot mask, or MASES system, takes advantage of sensor technology developed in collaboration with NASA for monitoring gases in space suits.

The sensor technology for O_2, CO_2, and relative humidity, and its performance under relevant environmental conditions for space suit monitoring have previously been described at ICES under the titles "Miniature Sensor Probe for O_2, CO_2, and H_2O Monitoring in Portable Life Support Systems"[1] and "Compact Multi-gas Monitor for Life

Support Systems Control in Space: Evaluation Under Realistic Environmental Conditions."[2] In this paper we described how we have adapated those sensors and integrated them into the pilot mask, our evaluation of the Mask Sensor system in the laboratory, and validation of it through studies with human subjects.

II. Pilot Mask Sensor System

In order to integrate the five desired sensors into the pilot mask (oxygen, carbon dioxide, humidity, temperature, and pressure), we designed a cylindrical sensor probe 9.8 mm in diameter and equipped the mask with a standard 9.5 mm OD insertion port, located right in front of the pilot's mouth, below the microphone, and between the two ports for breathing gas input and output (Figure 1). The sensor elements for pO_2, pCO_2, and relative humidity are thin luminescent polymeric films, which are directly exposed to the inhaled and exhaled gas without interfering with the gas flow. Thin film sensors had previously been used inside a space suit helmet prototype, taking advantage of the minimal volume, demonstrating suitability to monitoring gas levels without interfering with gas dynamics.[3,4] A novel luminescent sensor for pressure, which operates on the same principle as the gas sensors (indirect measurements of luminescence emission lifetime by phase-resolved luminescence detection) was incorporated inside the probe cylinders, together with a standard PT-100 temperature probe.

Figure 1. Multi-sensor probe prototype integrated in the pilot mask sensor port. (left) Sensor head inside the mask, showing the oxygen, relative humidity, and carbon dioxide sensors (temperature and pressure sensor are not visible). (right) External interface, showing connections for the optical cable.

A flexible optical bundle was fabricated to connect the sensor elements with the readout unit and transmit the excitation light and emission signal to and from the sensor elements. The readout unit was a compact four channel fiber optic phase-resolved luminescence detector designed to provide excitation in the blue region of the spectrum and collect emission in the red region. Because all four luminescent sensors incorporate indicator dyes from the same chemical family and have similar photochemical properties (excitation and emission wavelengths and emission lifetime), a single unit can read the four sensors, making the hardware very compact. In fact, the only things different between the four sensor channels are the sensor films in the sensor probes.

A. Evaluation in a breathing simulator system

We conducted a full system evaluation and analytical characterization, incorporating the sensor probe into a flow-through cell inside a temperature chamber, following a protocol similar to the one for the space suit gas monitor.[2] After characterizing and calibrating the system, we evaluated it in a breathing simulator setup. The testing setup incorporates a programmable artificial lung, which connects to gas cylinders in order to control CO_2 levels, and to a humidifier. The output tubing of the artificial lung incorporates inline off-the-shelf sensors for monitoring humidity, oxygen, and CO_2 concentration, and it is connected to the back of a manikin head that wears the pilot mask. A computer-based LabVIEW interface is used to collect the data for the off-the-shelf reference sensors. Figure 2 illustrates the testing setup.

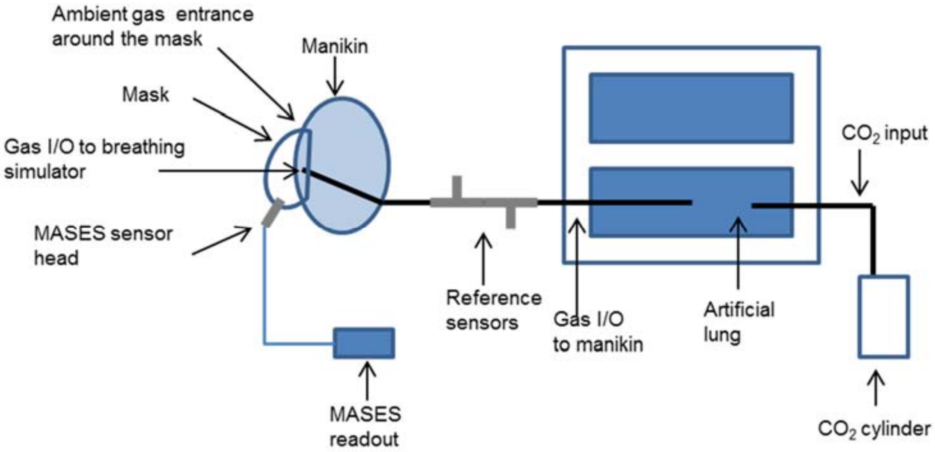
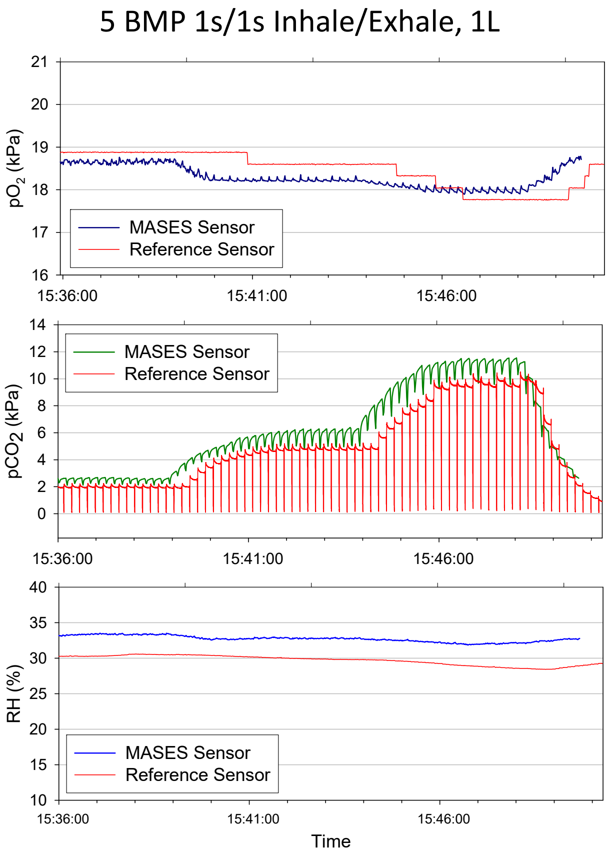


Figure 2. Breathing simulator setup for initial system evaluation in the laboratory.

We conducted a first battery of tests, operating the breathing simulator system under conditions that included varying respiration frequency, "lung volume," and exhaled CO$_2$ concentration. The correlation between the readings from the MASES system and those from the reference sensors was linear, but in some of the tests the pCO$_2$ values recorded by the optical sensors were below those calculated from the data from the reference sensor. Gas cylinders with a certified concentration of CO$_2$ were used to establish the correlation between the optical sensor and reference sensor, and during those tests we always observed comparable pCO$_2$ values. Adjusting the attachment of the mask to the manikin head and relocating the optical and reference sensors affected the correlation between the optical and reference CO$_2$ sensors. We concluded that the difference in position of the two sensors in the setup (one in the mask and the other close to the artificial lung), together with the differences in the response time of the sensors (kinetics), were responsible for those effects. The reference sensor t90 response time is <1 s, while that of the optical sensor is ~10 s.

Figure 3 shows data collected with the MASES system and with the reference sensors during tests conducted with a sensor installation that exhibited good correlation for pCO$_2$, pO$_2$, and RH during operation with the artificial lung. All these tests were conducted at ambient pressure, at varying exhalation and inhalation volumes and times, and at varying breathing frequencies. The levels of CO$_2$ were also varied from 0 to 75 mmHg.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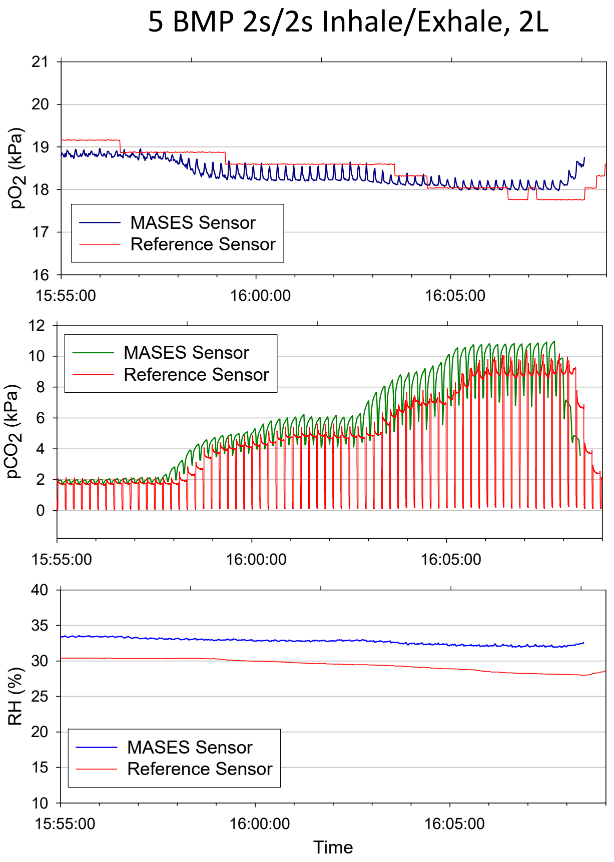
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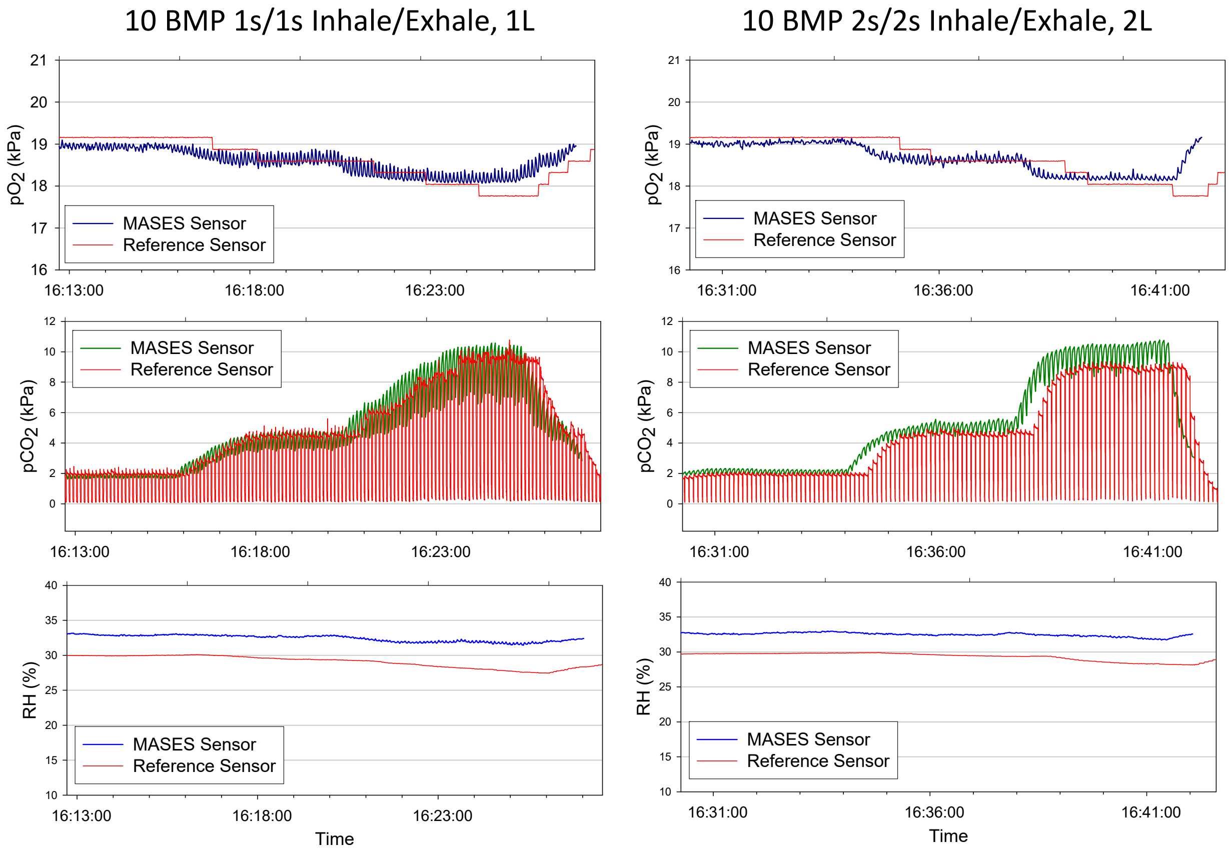


Figure 3. Gas levels recorded by the MASES system and the reference sensors during the study conducted at Lockheed laboratory with the breathing simulator.

Figure 4 shows that although the optical pCO_2 sensor registers each individual inhalation and exhalation, the CO_2 levels do not reach values close to zero as in the reference sensor, most likely due to the response time.

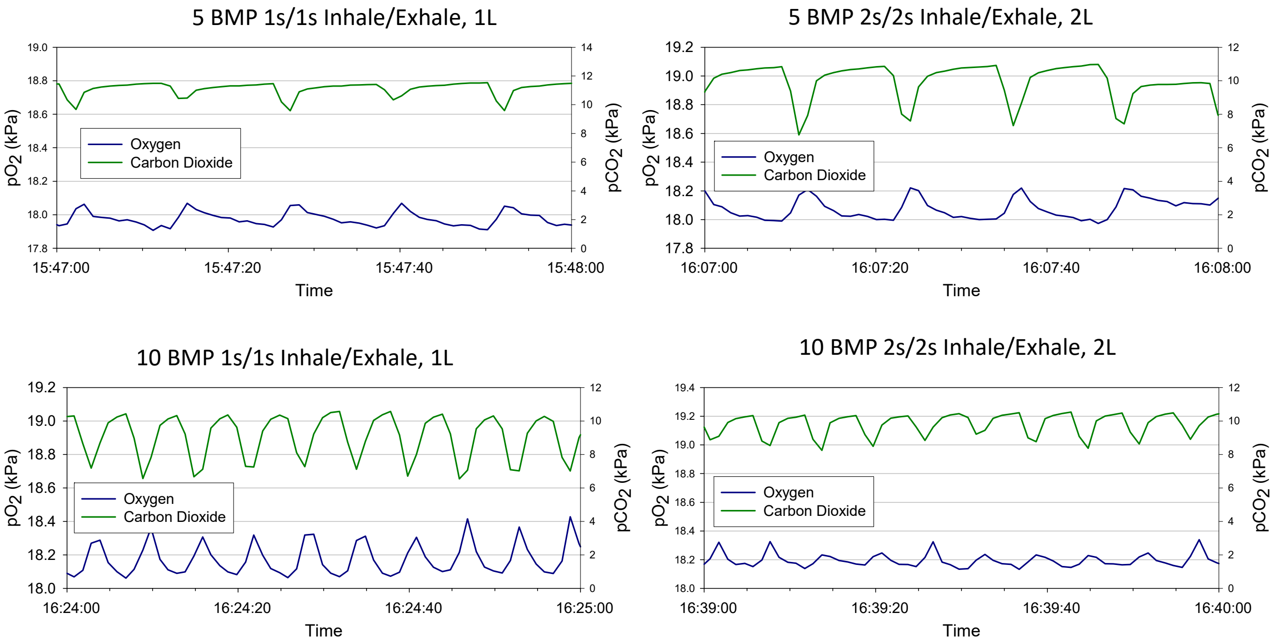


Figure 4. Oxygen and carbon dioxide levels recorded by the MASES system during tests conducted at variable breath per minute (BMP) and inhale/exhale volumes with the breathing simulator.

B. Evaluation with subjects in an altitude chamber

In order to evaluate the performance of the MASES system under relevant altitude conditions, we first conducted a study with the instrumentation in a small altitude chamber at AFRL Wright-Patterson Air Force Base, where the operation of the sensor system at high altitude and during rapid decompression was validated. Then we conducted studies with human subjects in an altitude chamber at KBRwyle, Brooks City-Base in San Antonio, Texas, USA.

The altitude chamber at KBRwyle is designed and equipped for flight-readiness training, including hypoxia training, and for human performance assessment, including physiological measurements (EKG, oxygen saturation, inspiratory demand) and assessment of psychological responses, and for equipment performance assessment.

A total of ten tests with subjects were included in this study. Each subject was asked to complete one or two altitude test sessions following a predefined flight profile. The flight profile included a sinus and ear check to 5,000 ft. of altitude (1,524 m), followed by an ascent to 17,500 ft. (5,334 m). Because of the relatively low altitude, no pre-breathe was required. Upon reaching 17,500 ft. (5,334 m), 100% oxygen was provided through the mask for two minutes to collect a baseline. After two minutes the mask breathing gas was switched to 21% oxygen (normal ambient air). The subjects were asked to simply sit and breathe in order to evaluate the MASES system performance. The session was ended after 30 minutes or if the arterial blood oxygen saturation fell to 75%, whichever came first, at which time 100% oxygen was again provided to the mask, and the chamber altitude was returned to ground level.

The aircrew flight equipment (AFE) worn by the subjects included an HGU-55/P Helmet with a Nonin Ear Cup Mounted Pulse Oximeter, a sensor-integrated MBU-20/P Mask (the MASES System, Figure 5), a Nonin Ear Plug-style Pulse Oximeter, and a CRU-60/P Regulated Terminal Block. Sampling tubes were incorporated in the mask and connected to a mass spectrometer gas analyzer for real-time monitoring of oxygen and carbon dioxide.

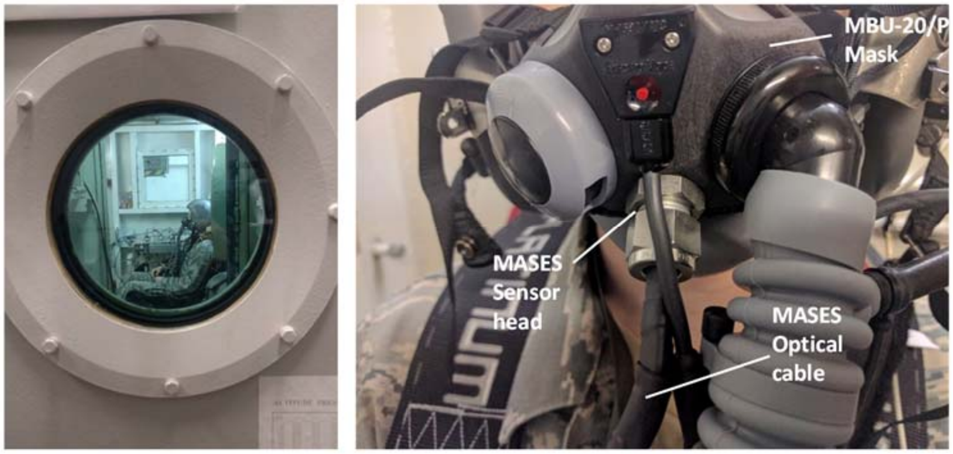


Figure 5. Subject wearing sensor integrated pilot mask during the test in the altitude chamber.

Figure 6 shows the partial pressure of oxygen monitored by the MASES system and by the reference gas analyzer during one of the test sessions. The gas analyzer measures oxygen concentration, and partial pressure was calculated from the nominal pressure in the chamber. Similar to what is observed in Figure 6, excellent correlation between the optical sensor and the mass spectrometer was observed for all ten test sessions with subjects.

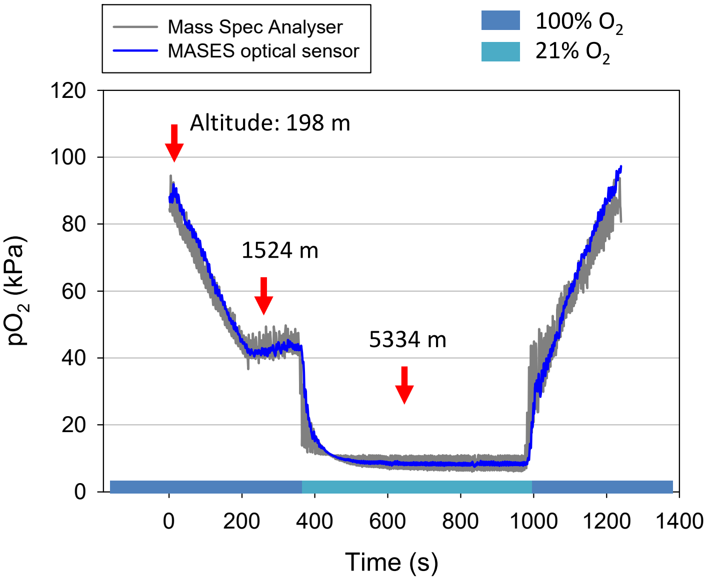


Figure 6. Partial pressure of oxygen measured by the MASES system and by the gas analyzer, during one of the tests conducted in the altitude chamber.

Figure 7 shows the partial pressure of carbon dioxide monitored by the MASES system and by the reference gas analyzer during two tests sessions with different subjects. Very similar results were collected with all ten subjects. As observed in the tests conducted in the laboratory with an artificial breathing system, the reference gas analyzer with its fast response registers values of carbon dioxide near zero at the end of each inhale, while the slower-responding optical sensor did not enable the system to record those low carbon dioxide levels. Still, the optical sensor did track the breathing frequency, as observed in Figure 7 in the two plots at the bottom. Breathing training is critical for the pilots to prevent physiological events during extreme maneuvers, and real-time information about breathing frequency is of great value and could improve pilot performance.

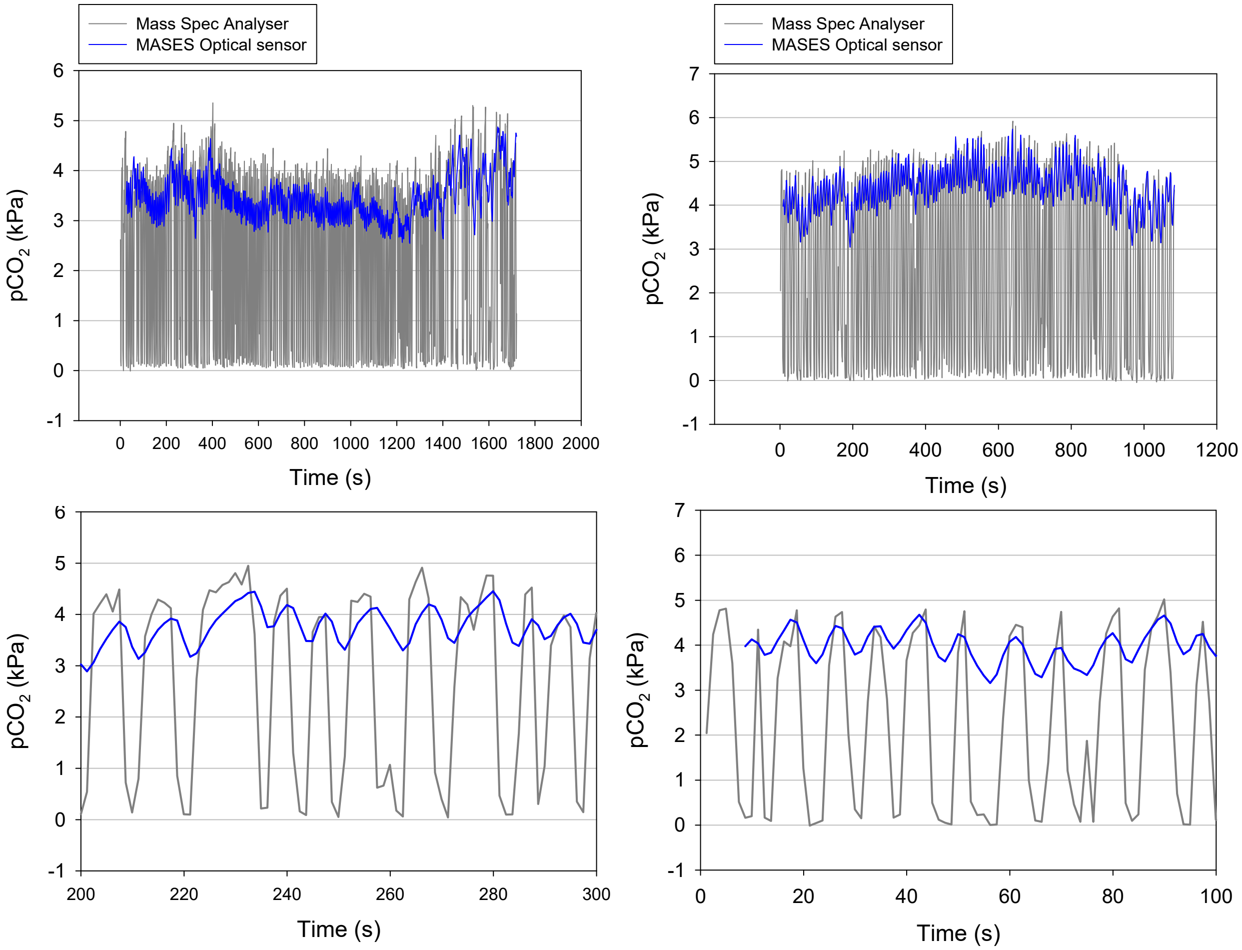


Figure 7. Partial pressure of carbon dioxide measured by the MASES system and by the gas analyzer, during two of the tests conducted in the altitude chamber. (top) Entire test sessions; (bottom) detail of 100 seconds.

Even though the optical sensor does not record the highs and lows of carbon dioxide, we expect the average CO_2 measured to match that recorded by a faster monitoring system. However, due to the asymmetric kinetics of the optical sensor, which exhibits faster response to increasing concentrations of CO_2 than to decreasing ones, the optical sensor might overestimate the average partial pressure of carbon dioxide in the mask. The optical sensor data overlaps throughout the entire study with the high range of carbon dioxide levels (upper 25% segment) measured by the reference analyzer. That excellent overlap, together with the capability of detecting the gas inhale and exhale, will enable us to extrapolate the data collected by the MASES system and generate a set of data very similar to that recorded in the studies with the mass spectrometer.

C. Evaluation with subjects in a human centrifuge

To evaluate the performance of the MASES system under relevant acceleration conditions and evaluate the interface with human subjects, we conducted studies with human subjects in a human centrifuge at KBRwyle. The centrifuge is used to simulate dynamic maneuvering loads, conduct research on human responses, and develop appropriate protective technologies. Additionally, it is used to conduct training in established protective techniques, including those to prevent or mitigate physiological events during exposure to high acceleration. The centrifuge research, development, test, and evaluation capabilities include the ability to conduct man-rating of new aircrew life-support equipment and to assess new aeromedical instrumentation. As such, it is an optimal environment for evaluating the MASES system in a high fidelity scenario. The centrifuge has an acceleration capability from +1 to 30 G, with a payload of 680 kg and peak power of 1.5 MW.

Two studies were conducted, one with eight subjects and the other with seven subjects. At the conclusion of the first study, the MASES system design was revised to improve the robustness of the optical cable and incorporate a fiber optic pressure sensor.

The centrifuge test session for each subject involved performing multiple +Gz acceleration sequences using a Gradual Onset Rate (GOR) at 0.1G/s and Rapid Onset Rate (ROR) at 6G/s (see Table 1).

G-profiles started with a GOR from +1 to +9 Gz relaxed with no G-suit pressure or pressure breathing for G (PBG) until they reached the light loss criteria established in the testing protocol, upon which the subjects were asked to perform an Anti-G Straining Maneuver until they again reached the light loss criteria or +9 Gz.

After a two minute rest period the subjects were asked to perform four ROR profiles: +5 Gz for 15 seconds, +7Gz for 15 seconds, +9Gz for 10 seconds, and a 4 set maximum Simulated Aerial Combat Maneuver profile, with each set consisting of +5 Gz for 10 seconds followed by +9 Gz for 10 seconds. The subjects were given a two minute rest between successive ROR profiles. G-suit inflation and PBG was provided for all ROR profiles through the sensor integrated mask (model MBU-20/P), according to the standard aircraft schedule of 12 mmHg per G beginning at +4 Gz with a maximum pressure of 60 mmHg at +9Gz. A CRU-93 regulator provided PBG for all conditions.

Table 1. Summary of profiles included in each test session.

Profile	Onset*	G-Load	G-Suit	PBG	Duration
1	Gradual	9 Gz	0 psi	None	Until determined
2	Rapid	+5 Gz	5 psi	+12 mmHg	30 seconds
3	Rapid	+7 Gz	8 psi	+36 mmHg	15 seconds
4	Rapid	+9 Gz	11 psi	+60 mmHg	15 seconds
5	Rapid Rapid	4 sets of +5 Gz 4 sets of +9 Gz	5/11 psi	+12/60 mmHg	10 seconds 10 seconds

* Gradual = 0.1 G/second; Rapid = 6 G/second

The aircrew flight equipment (AFE) worn by the subjects included an HGU-55/P Helmet with a Nonin Ear Cup Mounted Pulse Oximeter, a sensor-integrated MBU-20/P Mask (the MASES system, Figure 8), a Nonin Ear Plug-style Pulse Oximeter, a CRU-60/P Regulated Terminal Block, and a G-suit.

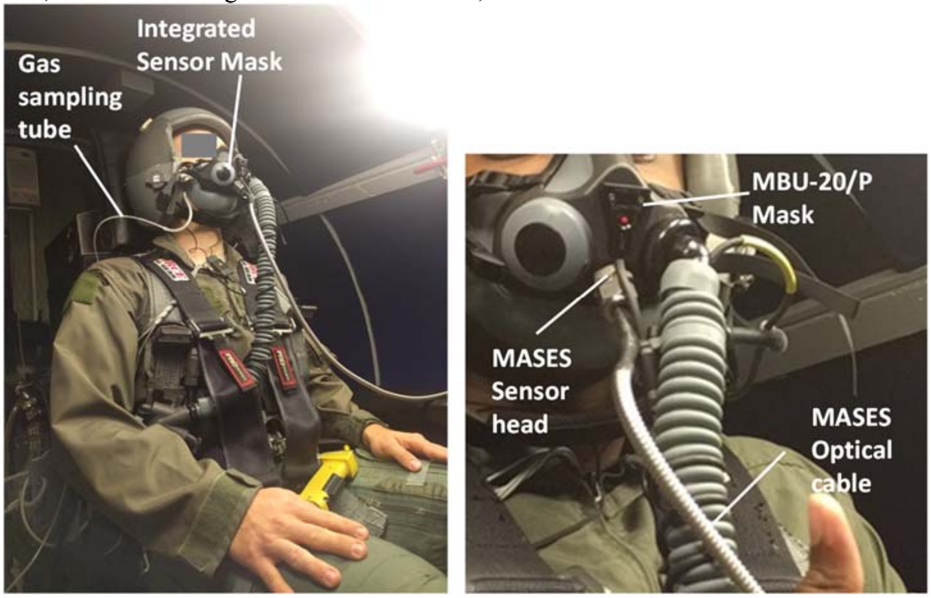


Figure 8. Subject prepared to start a test session in the human centrifuge wearing the MASES system.

The subject could elect to stop any centrifuge run at any time, for any reason, by releasing a hand brake or verbally requesting that the run be stopped. The medical team, trained to recognize the effects of G forces or acceleration on the body, continually monitored the subjects' condition throughout the entire centrifuge run, and stopped the run when they had any concern about the medical state of a subject during the test session. Most of the subjects completed the five mission profiles, although some tests were ended before completing the five profiles on recommendation of the medical team or request by the subject.

The subjects were instructed to wear the mask during profiles 1 to 5, and were allowed to remove the mask in the resting periods between profiles. During the first study no reference gas monitor was used, and data was only collected with the MASES system. During the second study, a sampling tube was placed inside the mask to conduct gas from the mask to a pre-calibrated reference gas analyzer. The gas analyzer monitored oxygen percentages in real time, which were later converted to partial pressure. Carbon dioxide and humidity measurements were only taken with the MASES system. The MASES system used in the second study included a prototype fiber optic pressure sensor, the operation of which is not discussed in this article.

Figure 9 shows the profiles of oxygen, carbon dioxide, humidity, and temperature, recorded by the MASES system during the five mission profiles described above, performed by one of the subjects. Very similar profiles were recorded for the 15 test sessions included in the two studies. Increasing partial pressure of oxygen is observed during the acceleration period, which corresponds with the operation of the gas delivery system that supplies positive pressure of oxygen to the mask, proportional to the acceleration. Simultaneously with the increase in oxygen, we observed a decrease in the partial pressure of carbon dioxide and humidity.

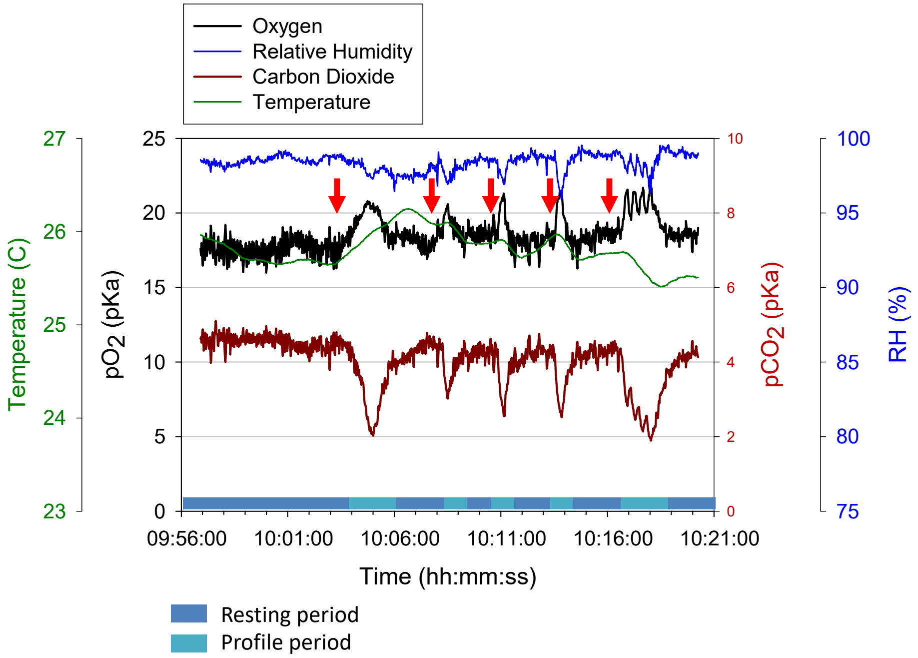
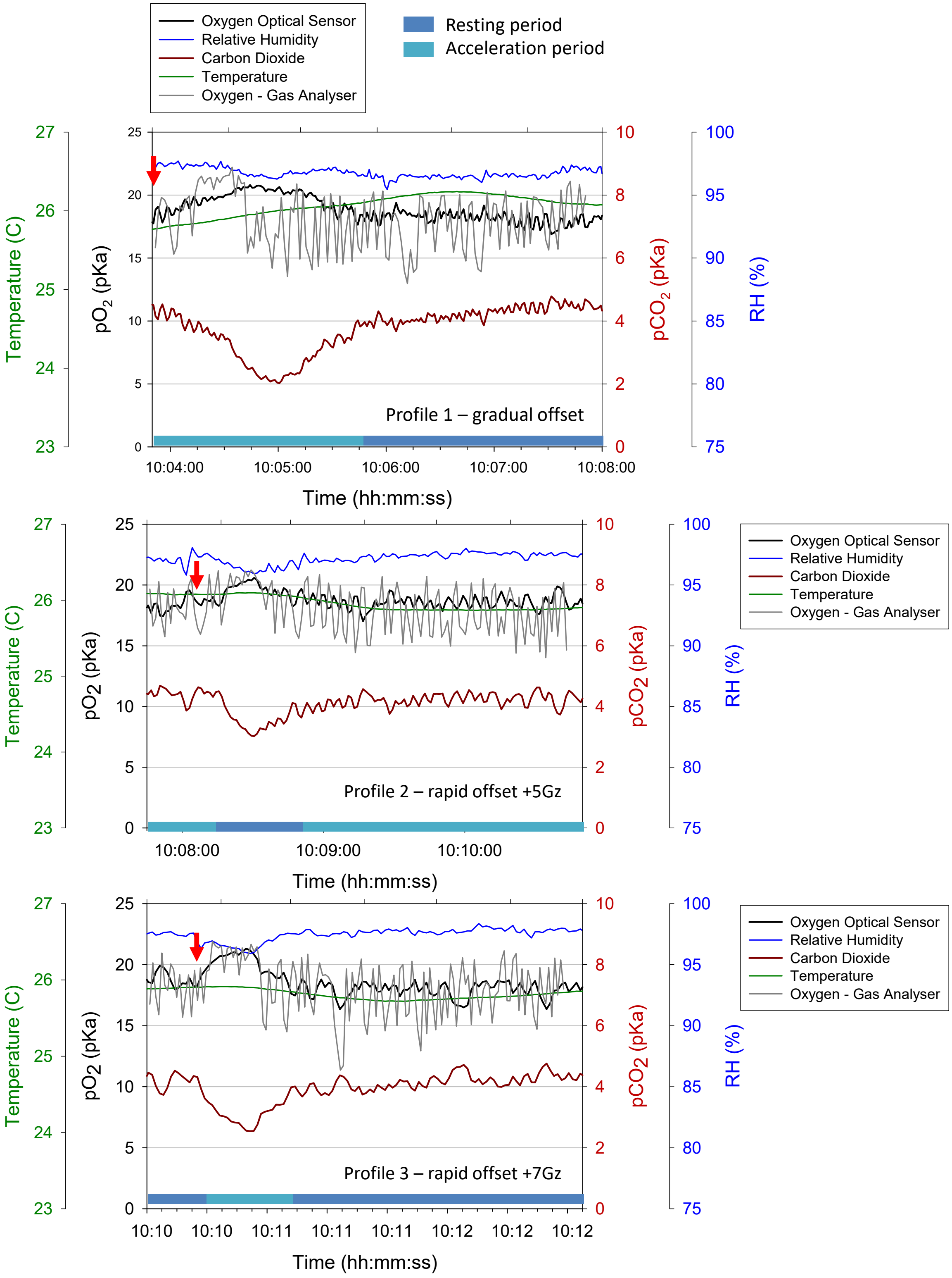


Figure 9. Gas levels recorded for one of the subjects during a test session completed from profile 1 to profile 5 as described in Table 1. Red arrows indicate the start of acceleration periods.

Figure 10 shows the gas profile for each of the five individual acceleration profiles, for the same subject, displaying the correlation between the increasing oxygen levels and decreasing partial pressure of carbon dioxide. In the plots included in Figure 10 we can also observe how the oxygen pressure returns to baseline levels after the acceleration period, once no additional oxygen is supplied to the mask. This effect, and in particular the lower carbon dioxide levels recorded during the acceleration period, is not only associated with the pressure breathing for G supplied to the mask, but also with the subjects' breathing when they are exposed to high acceleration. The pilots are trained to breathe with very short inhale and exhale times during maneuvers that involve high acceleration, holding each breath for a few seconds to maintain the desired breathing frequency.

Figure 10 also shows excellent correlation between the oxygen levels recorded by the MASES system and the mass spectrometer (the reference gas analyzer), and the same correlation was observed for all test sessions with all subjects. The faster response time of the reference analyzer is observed with peaks in the partial pressure of oxygen not fully recorded by the optical sensor. The excellent correlation of the optical oxygen sensor with the reference gas analyzers during the tests in the altitude chamber and in the centrifuge strongly validates not only the oxygen sensor itself but the sensor integrated mask form factor.


Oxygen Optical Sensor
Relative Humidity
Carbon Dioxide
Temperature
Oxygen - Gas Analyser
Resting period
Acceleration period
Temperature (C)
pO2 (pKa)
pCO2 (pKa)
RH (%)
Profile 1 – gradual offset
10:04:00
10:05:00
10:06:00
10:07:00
10:08:00
Time (hh:mm:ss)
Profile 2 – rapid offset +5Gz
10:08:00
10:09:00
10:10:00
Time (hh:mm:ss)
Profile 3 – rapid offset +7Gz
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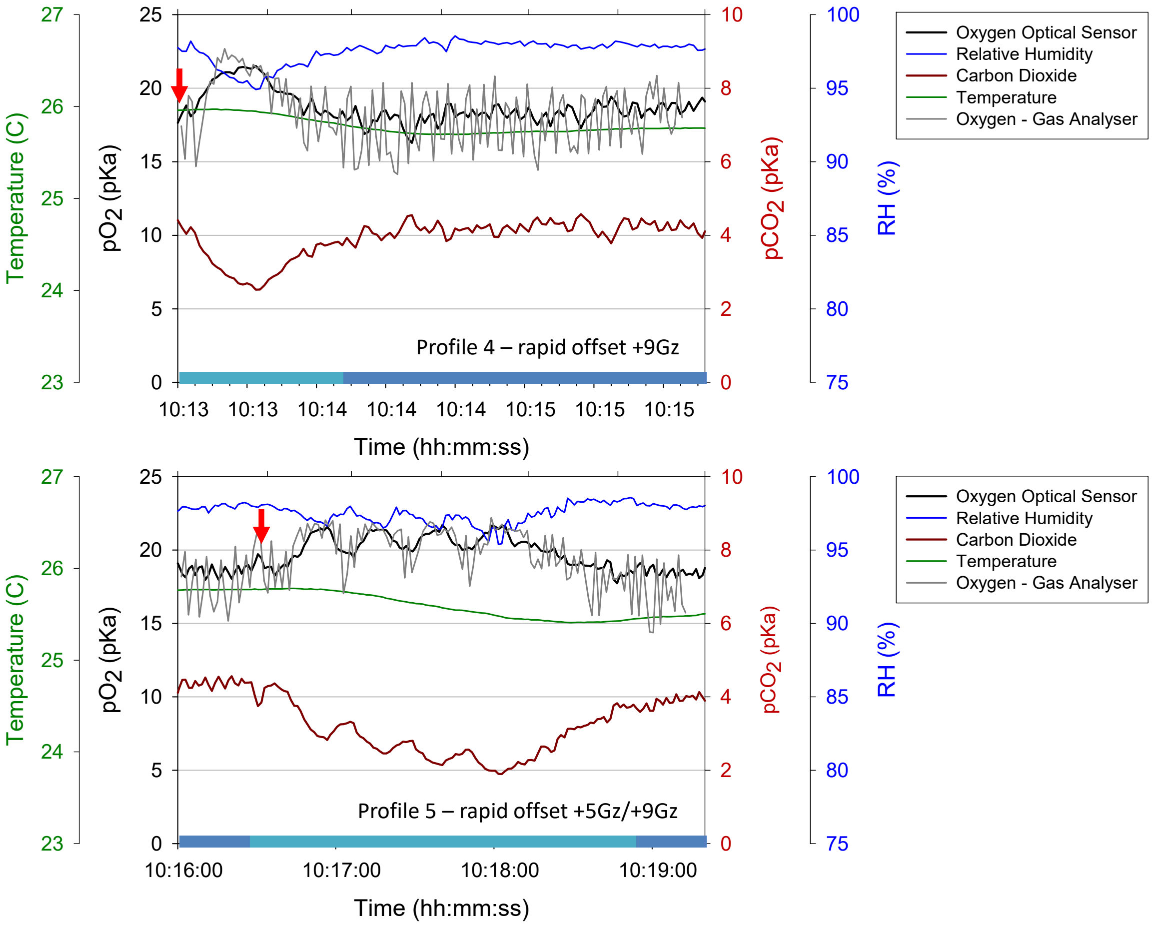

Figure 10. **Gas levels recorded for one of the subjects during a test session completed from profile 1 to profile 5 as described in Table 1. Partial pressure of oxygen calculated from the data recorded with a mass spectrometer is included. Red arrows indicate the start of acceleration periods.**

An important feature of the optical sensor, demonstrated during these studies with human subjects, is its capability of operating while wet. In all tests the humidity reached saturation, and water was found after the tests on the top of the sensor head (Figure 11). Any sensor incorporated in the pilot mask must be capable of operating in the presence of liquid, since saliva spittle and water condensation are very common.

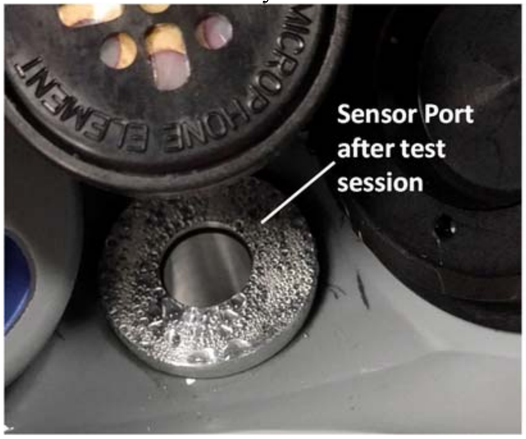

Figure 11. **A wet sensor port inside the mask after a test session in the centrifuge. The sensor head had already been removed.**

III. Conclusion

Monitoring breathing gas composition on-board and in real time in a military pilot mask may help prevent undesired physiological events and enhance pilot performance. Requirements for sensor technologies to be integrated in a pilot mask overlap significantly with requirements for gas monitoring in space suits. Luminescence-based fiber optic sensors developed for NASA programs and gas monitoring during space suit development have been adapted to produce a sensor integrated pilot mask (MASES system), which has been validated in the laboratory and in high fidelity scenarios with human subjects.

The MASES system incorporates inside the pilot masks sensors for partial pressure of oxygen and carbon dioxide, relative humidity, pressure, and temperature, all of them interrogated by a compact phase-resolved luminescence unit.

The gas sensors were first characterized in the laboratory with certified gas cylinders, and then in a breathing simulator system in comparison with off-the-shelf-sensors. Good correlation was found between the optical sensors for oxygen and humidity and the reference sensors. Also, a direct correlation was observed between the optical carbon dioxide sensor and the reference sensor, though that correlation seemed to be affected by the mask positioning, and by the locations of the sensors in the setup. The significant difference between the response time of the reference sensor and those of the optical sensors, together with the fast changes in CO_2 levels when the gas is inhaled and exhaled, might account for the variability observed.

The MASES system was tested in an altitude chamber for resistance to high altitude and rapid decompression, validating the system operation under those conditions. Then the system was evaluated in an altitude chamber with human subjects. Excellent correlation was observed between the oxygen sensor and gas analyzer connected to the mask. Good correlation was also observed for the carbon dioxide sensor with the gas analyzer, though the slow response of the optical sensors (on the order of 10 s) for increasing carbon dioxide levels and the slow recovery to low carbon dioxide levels may result in overestimating the average partial pressure of CO_2 in the mask. An algorithim may be necessary to compensate that effect.

Finally, the integrated sensor pilot mask was validated in a human centrifuge with human subjects, demonstrating the capability of operating under high acceleration conditions, and while the sensors are wet. Excellent correlation was observed between the optical oxygen sensor and a reference gas analyzer, while a reference carbon dioxide analyzer was not used for those tests. Very good consistency was observed between the data collected during 15 test sessions with human subjects.

The MASES system and the fiber optic gas sensor technology developed has shown significant potential as a critical tool to investigate otherwise unexplained physiological events in military flights and to enhance human performance.

Acknowledgments

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