Technical validation of the EMMA capnometer under hyperbaric conditions

Alicia Tucker[1], David Smart[1]

[1] *Department of Diving and Hyperbaric Medicine, Royal Hobart Hospital, Hobart, Tasmania, Australia*

Corresponding author: *Dr Alicia Tucker, Department of Diving and Hyperbaric Medicine, Royal Hobart Hospital, 26 Campbell St, Hobart 7000, Tasmania, Australia*
ORCiD ID: 0000-0003-3578-8320
alicia.tucker@ths.tas.gov.au

Keywords
Carbon dioxide; Capnography; Hyperbaric oxygen treatment; Intensive care medicine; Patient monitoring

Abstract
(Tucker A, Smart D. Technical validation of the EMMA capnometer under hyperbaric conditions. Diving and Hyperbaric Medicine. 2023 June 30;53(2):100–110. doi: 10.28920/dhm53.2.100-110. PMID: 37365127.)
Introduction: End-tidal carbon dioxide ($ETCO_2$) monitoring is essential for monitoring intubated critical care patients, yet its use in hyperbaric environments can be problematic. We postulated that the EMMA mainstream capnometer may function accurately under hyperbaric conditions.
Methods: Stage 1. The EMMA mainstream capnometer was tested at 101 kPa against a reference side-stream capnometer, Philips IntelliVue M3015B microstream, using 10 customised reference gases of various carbon dioxide (CO_2) concentrations (2.47%–8.09%, or 18.5–60.7 mmHg at 101 kPa) in either air or oxygen. Stage 2. The functionality and accuracy of the EMMA capnometer was tested under hyperbaric conditions, 121–281 kPa, using the same test gases.
Results: At 101 kPa, the EMMA capnometer measured CO_2 at levels lower than expected (mean of differences = -2.5 mmHg (95% CI -2.1 to -2.9, $P < 0.001$)). The Philips capnometer measured CO_2 more closely to expected CO_2 (mean of differences = -1.1 mmHg (95% CI -0.69 to -1.4, $P < 0.001$). Both devices demonstrated a significant linear relationship with expected CO_2. The EMMA capnometer functioned up to the maximum test pressure (281 kPa). The device over-read CO_2 measurements at pressures > 141 kPa. Although variance increased at pressures in the therapeutic range for hyperbaric treatments, a significant linear relationship between expected and EMMA measured CO_2 was demonstrated. The EMMA capnometer tolerated pressures to 281 kPa, but its display was limited to CO_2 < 99 mmHg.
Conclusions: This study validated EMMA capnometer function to 281 kPa in the hyperbaric environment. The device over-read CO_2 measurements at pressures >141 kPa, however there was a linear relationship between expected and measured CO_2. The EMMA capnometer may be clinically useful for monitoring expired CO_2 in patients undergoing hyperbaric oxygen treatment.

Introduction

Hyperbaric oxygen treatment (HBOT) has approved indications in Australia.[1,2] Some patients requiring hyperbaric oxygen are critically ill. They require the same standard of care and monitoring when pressurised as occurs at 101.3 kPa (1 atmosphere absolute [atm abs]).[3–5] For ventilated patients, pulse oximetry and end-tidal carbon dioxide ($ETCO_2$) are essential for monitoring patients.[6] End-tidal CO_2 monitoring provides real-time evidence of ventilatory compromise such as hyper- or hypoventilation, and displacement or obstruction of the tracheal tube.[7,8] Central nervous system (CNS) oxygen toxicity during HBOT may be worsened by hypercapnia.[9] Preventing hypercapnia is an important reason for monitoring $ETCO_2$ in ventilated patients receiving HBOT.

Hyperbaric medical devices must meet strict safety guidelines.[10] Hyperbaric facilities with critical care capability must test equipment to ensure devices are safe and can function in hyperbaric conditions.[11] Some devices may not physically withstand pressure, requiring modification. Modifications carry a risk of voiding the device warranty. Electrical equipment also produces heat which increases fire risk during HBOT.[12] This risk can even occur for battery-operated (or backed up) equipment, especially if powered by lithium batteries, or if sparks are generated by brushed motors.[13]

Options to minimise risk from electrical devices include not using the equipment or situating the devices outside the chamber and connecting the equipment to sensors (including sampling lines) or effectors inside the chamber via 'penetrators' which traverse the chamber hull.[4,14] In-chamber devices may also be placed in nitrogen-flushed housings to reduce fire risk. In such cases, this limits accessibility to the equipment which then must be operated remotely.

Mainstream $ETCO_2$ determination, in hyperbaric conditions, is subject to errors due to the 'pressure broadening effect'

produced by the increased density of gas. As a result, falsely high values of the patient's $ETCO_2$ are usually reported, which need to be corrected using mathematical equations for each device.[15,16] One study demonstrated a good correlation between $ETCO_2$, using a mainstream capnometer, and P_aCO_2, taken during hyperbaric conditions at 284 kPa.[17] In hyperbaric facilities, devices to monitor $ETCO_2$ may increase fire risk because they produce heat via infrared transmitters, particularly with traditional mainstream devices, exacerbated by 100% oxygen under pressure.

To monitor patients' ventilation, hyperbaric physicians have also used arterial blood gas (ABG) P_aCO_2 analysis, transcutaneous carbon dioxide tension ($P_{TC}CO_2$), or externally connected side-stream $ETCO_2$ samplers. In some facilities, in-chamber $ETCO_2$ monitoring is not even used due to the lack of a suitable and easily applicable device (Personal correspondence with Austrailian clinical leads 2019).

Side-stream capnometers aspirate gas from the breathing circuit. Even at sea level pressures, the measurements may be affected by water removal, different conditions at the sampling site and sample cell (temperature and humidity), mixing of the sample gas when drawn through the cell and variable pressure drop across the tubing. Some of these effects can be compensated, but not all.[18] Side-stream capnometers have been used successfully during hyperbaric treatments, with the mains-powered analyser remaining outside of the chamber, and sampling gas lines exiting through a penetrator. Practical limitations to these devices include: the requirement for additional penetrators and potential delays in displaying and calculating corrected $ETCO_2$ which delays clinical interventions. Mass spectrometry has been successfully used with side-stream analysis of decompressed gas samples, but this is clinically impractical.[19]

The EMMA mainstream capnometer (Masimo, Daneryd, Sweden) is a small, in-line device that contains a CO_2 sensor and display in the same unit. It can be rapidly deployed and displays an averaged $ETCO_2$ and respiratory rate.[20]

Given its compact, small size and low voltage (two AAA alkaline batteries), our study planned to technically evaluate the EMMA capnometer under hyperbaric conditions. We assessed whether it would accurately monitor $ETCO_2$ under a range of hyperbaric pressures (121–283 kPa) using test gases of known CO_2 concentrations.

Methods

Low-risk ethics approval was sought from the Human Research Ethics Committee (HREC) Network (Tasmania) but waived following direct communication from the Chair, due to being an equipment validation study without test subjects (personal communication from Chair of HREC, March 2019).

In stage 1, we tested the reliability of the EMMA mainstream capnometer at 101 kPa against a reference microstream (side-stream) capnometer, Philips IntelliVue M3015B using a range of CO_2-containing test gases 2.47%–8.09% (18.5–60.7 mmHg at 101.3 kPa [1 atm abs]).[22]

In stage 2, the functionality and accuracy of the EMMA capnometer was tested under hyperbaric conditions, 121–281 kPa, using the same calibrated test gases as Stage 1.

A third stage was intended to compare the EMMA capnometer against the same reference microstream capnometer in Stage 1 (Philips IntelliVue M3015B), however, the latter failed to function beyond 110 kPa, the cause of which could not be identified or remediated. This stage was abandoned.

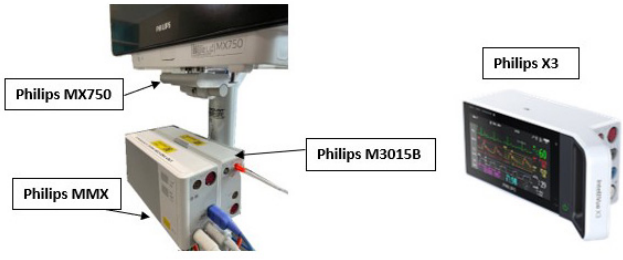
EQUIPMENT

Capnometers

The EMMA mainstream capnometer is a small, alkaline battery-powered, in-line device that contains an infrared CO_2 sensor and display in the same unit (Figure 1). It displays the average maximum measured CO_2 of the last 4 breaths when $ETCO_2$ changes by < 25%, or the last breath when $ETCO_2$

Figure 1
EMMA capnometer

Figure 2
Philips IntelliVue MX750, Philips Microstream capnometer (M3015B), Philips IntelliVue MMX and X3 multi-measurement monitoring modules



changes by > 25%.[20] It also displays a respiratory rate. The EMMA capnometer displays an average of maximum expired CO_2, which in a strict sense, is not the $ETCO_2$. In addition, measurements in this study were conducted on test gases, so we have adopted a convention of describing data values in this study as concentration or partial pressure of CO_2, not $ETCO_2$.

The Philips IntelliVue MX750 (Figure 2) is an integrated critical care monitor. The M3015B (Figure 2) extension module can be attached to either the IntelliVue X3 (Figure 2) or MMX (Figure 2) multi-measurement monitoring modules that integrate with the MX750 monitor. Gas is sampled from a sidestream (microstream M3015B device) which is placed in line with the airway tubing. The infrared CO_2 sensor is located inside the extension module instead of utilising an external sensor.

The MX750 itself was assessed as not suitable for pressurisation, owing to heat production and battery type (lithium ion). Like the MX750, the IntelliVue X3 has an LED touch screen which could be affected with changes in ambient pressure. The screenless MMX monitoring pod and microstream device also contained electronics and motorised pumps. It was assessed by local biomedical technicians as suitable for hyperbaric conditions provided continuous purging with nitrogen occurred.[12] The MX750 power source and output leads traversed the chamber wall via a penetrator. A hyperbaric compatible slave screen inside a nitrogen purged housing allowed viewing of observations within the chamber. Prior to use, both devices were calibrated according to the manufacturer's instructions.[20,21]

Test gases

Ten customised reference gases of various concentrations of CO_2 in either air or oxygen were used. 'Air' and 'oxygen' test gases were chosen to represent a physiological range of expired gas from ventilated patients completing HBOT. This attempted to ensure that the EMMA was validated for the entirety of HBOT, including air breaks. For test cylinders containing 'air', the nitrogen percentage was kept constant, and the oxygen percentage was reduced in substitution of the additional CO_2 (Table 1). 'Oxygen' test cylinders contained a specific CO_2 percentage with the balance of the volumetric composition to 100% made up with oxygen. These were supplied with a certified standard analysis accuracy of ± 2% of the test gas concentration (BOC, Hobart, Australia). Final test gas mixes are summarised in Table 1.

Conversion calculations

Test gases were presented as a percentage of CO_2. Because the capnometers display measured CO_2 in mmHg, all test gas percentages were used to calculate an expected CO_2 (mmHg) measurement for each gas (Table 1). Conversion of test gas percent to mmHg was derived as follows:

Expected PCO_2 (mmHg) = (test gas CO_2%/100) x 760 mmHg
For example, PCO_2 for test gas A1 = (2.58/100) x 760 = 19.6 mmHg

The study was conducted in the Royal Hobart Hospital Department of Diving and Hyperbaric Medicine multi-place hyperbaric chamber (Fink Engineering Triple Lock Chamber S/N:229AH93, 10/2017 - Warana, Queensland, Australia).

Table 1
Test gas mixtures, including calculated expected CO_2 at 101 kPa

Test gas	CO_2 (%)	Expected CO_2 (mmHg @ 101 kPa)	O_2 (%)	N_2 (%)
'Oxygen' test gases				
A1	2.58	19.6	97.4	0
B1	4.06	30.9	95.9	0
C1	5.04	38.3	95.0	0
D1	6.56	49.9	93.4	0
E1	8.09	61.5	91.9	0
'Air' test gases				
A2	2.47	18.8	18.3	79.2
B2	4.05	30.8	17.1	78.8
C2	4.92	37.4	15.7	79.4
D2	6.45	49.0	14.6	78.9
E2	8.00	60.8	12.9	79.1

Chamber pressure was measured in kPa using a Trafag digital transducer gauge (accuracy ± 0.25%, model 8253.77.2417, Trafag, Bubikon, Switzerland). The department is located on the third floor, approximately 10 m above sea level. Local barometric pressure can range from 99 to 104 kPa. During the study period, the pressure ranged between 100 and 101 kPa. For calculations a pressure of 101 kPa (760 mmHg) was assumed. It was accepted that a 0.9% error would occur in the expected CO_2 calculation for test gas mixes. EMMA and Philips capnometer measurements were in whole numbers of mmHg, hence, for a CO_2 measurement in the physiological range, this could lead to greater errors, up to 2.5% (1 mmHg/40 mmHg).

The expected CO_2 for each test gas was calculated at each hyperbaric test pressure (Table 2).
For example, PCO_2 for test gas A1 @ 121 kPa = (2.58/100) x (121/101) x 760 = 23.5 mmHg

Gas delivery and 'airway' apparatus

An oxygen clean flow meter was attached to the test gas cylinder. The test gas was delivered through a test circuit (Figure 3) using standard tubing and connectors. One-way valves were incorporated to prevent backflow.

Both capnometers were placed in series in the circuit. Initial testing demonstrated no difference in output readings if the devices were placed singularly or in a series configuration with either device in the primary position. The exhaust gas was released at least 1.5 m away from the test devices. During chamber testing, flushing occurred at regular intervals to keep the chamber atmosphere at acceptable standards in accordance with AS/NZS4774.2(2019).[22] Chamber temperature and humidity were also kept within the operating ranges of each test device.

Initial testing was performed at 101 kPa to determine the best flow rate and time to reach steady readings for each test device. The Philips device would not show an $ETCO_2$ reading until respiratory effort had been initiated (by detecting changes in flow). To remedy this, a disposable, paediatric resuscitator bag (Laerdal Medical Corporation, Norway), with a ventilation bag volume of 500ml, simulated a respiratory rate of 12·min^{-1}. The paediatric resuscitator bag was used to create variability in the gas flow to simulate ventilation to trigger the Philips capnometer and to allow flushing of the circuit. It achieved both the latter and former with as low volumes as possible so as not to exhaust the test gas supply.

The ventilation bag was compressed by hand to achieve 50–100% of volume delivery. Measured CO_2 readings at 101 kPa were consistent, using this technique. A final flow rate of 3 L·min^{-1} was chosen which produced steady readings for both devices in < 30 seconds.

Repetitions

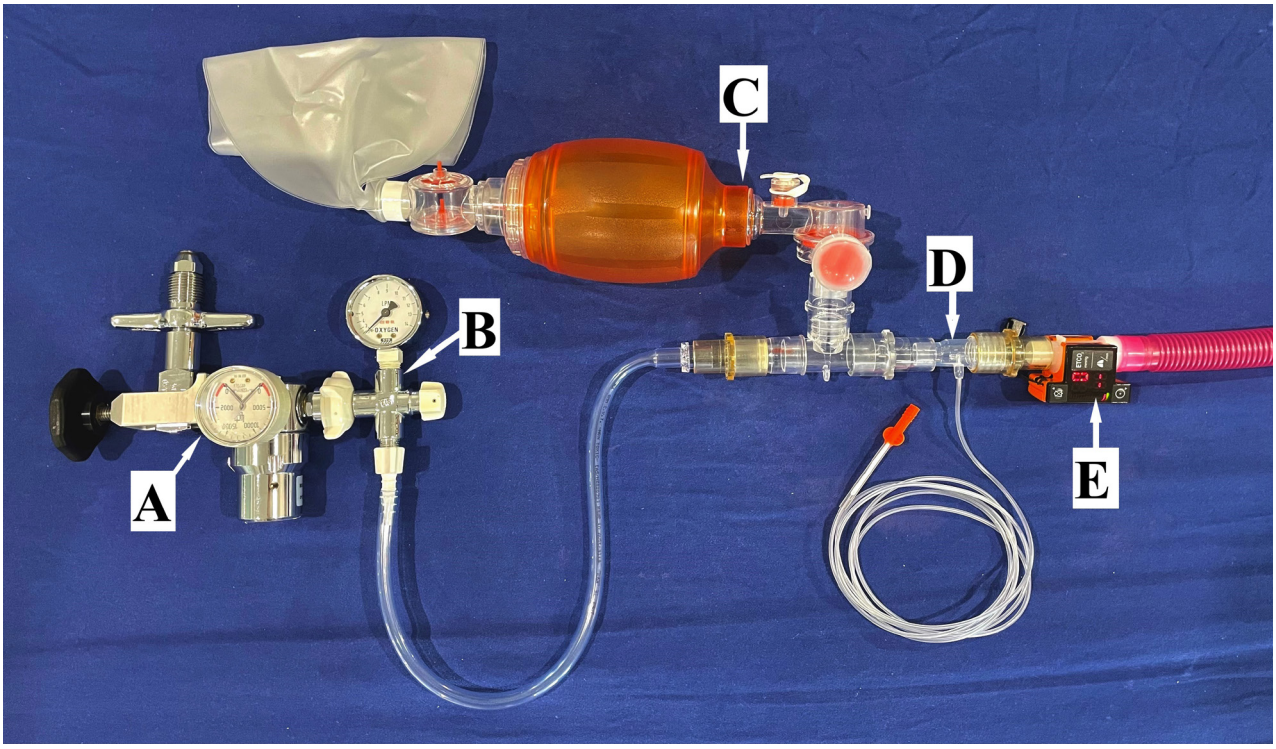
During stage 1, EMMA and Philips capnometer readings were compared at 101 kPa. Ten readings were completed for each test gas at 101 kPa.

In stage 2, measurements of test gases in an ascending pressure profile (20 kPa increments 121–281 kPa) were conducted using the EMMA capnometer. Chamber pressure profiles were within DCIEM dive table no-decompression limits; supervised by trained hyperbaric technicians and

Table 2
Calculated expected CO_2 at various test pressures

Test gas	CO_2 (%)	Expected CO_2 (mmHg)								
		101 kPa	121 kPa	141 kPa	161 kPa	181 kPa	201 kPa	221 kPa	241 kPa	281 kPa
'Oxygen' test gases										
A1	2.58	19.6	23.5	27.4	31.3	35.1	39.0	42.9	46.8	54.9
B1	4.06	30.9	37.0	43.1	49.2	55.3	61.4	67.5	73.6	86.5
C1	5.04	38.3	45.9	53.5	61.1	68.6	76.2	83.8	91.4	107.3
D1	6.56	49.4	59.2	69.0	78.7	88.5	99.2	109.1	119.0	138.7
E1	8.09	61.5	73.7	85.8	98.0	110.2	122.4	134.5	146.7	171.1
'Air' test gases										
A2	2.47	18.8	22.5	26.2	29.9	33.6	37.4	41.1	44.8	52.6
B2	4.05	30.8	36.9	43.0	49.1	55.2	61.3	67.4	73.5	86.2
C2	4.92	37.4	44.8	52.2	59.6	67.0	74.4	81.8	89.2	104.8
D2	6.45	49.0	58.7	68.4	78.1	87.8	97.6	107.3	117.0	136.4
E2	8.00	60.8	72.8	84.9	96.9	109.0	121.1	133.0	145.1	169.2

Figure 3
Test circuit connected to the EMMA and Philips capnometers; A – regulator; B – oxygen clean flow meter; C – paediatric Laerdal bag; D – Philips capnometer; E – EMMA capnometer



clinicians. Ten measurements of CO_2 were made for each test gas at each test pressure.

STATISTICS

Expected CO_2 was paired with the EMMA capnometer and Philips capnometer measured CO_2 at 101 kPa for correlation. Sampling under hyperbaric pressures compared expected CO_2 to the measured CO_2 samples from the EMMA capnometer at each pressure. Data were entered into Excel Spreadsheets (Microsoft® Corporation, Redmond Washington USA) and analysed using GraphPad Prism version 9.1.0.03 for Windows (GraphPad Software, San Diego, California, USA, 2021). Simple descriptive statistics were used to report reproducibility data.

Basic analyses included means, means of differences, standard deviations, and linear regression. Measurement data were subjected to simple linear regression and correlation analysis comparing EMMA Capnometer CO_2 measurements with expected CO_2 for test gases.

Bland-Altman plots were generated to assess agreement between the EMMA measured CO_2 and the expected CO_2 across the range of CO_2 concentrations and hyperbaric pressures. Graphs were produced comparing the EMMA CO_2 measurements at various chamber pressures, compared to expected CO_2 values from the test gas to determine if a predictable relationship would allow a correction equation to be calculated. Statistical significance was accepted when $P < 0.05$.

Results

Data were collected from June 2020 to July 2021.

STAGE 1: DEVICE AGREEMENT AT 101.3 kPa

Measurements across the test gas concentrations using the Philips capnometer at 101 kPa were highly reproducible with standard deviations ranging from 0.0 to 0.7 mmHg (0–1% of the means). Measurements using the EMMA capnometer at 101.3 kPa were also highly reproducible with standard deviations ranging from 0.4 to 0.7 mmHg (0–2% of the means).

Figure 4 shows a graph of the expected CO_2 versus measured EMMA and Philips CO_2 readings at 101 kPa. The grey line indicates the line of exact agreement between the devices and expected CO_2. The EMMA capnometer consistently measured CO_2 at lower levels than expected (mean of differences -2.5 mmHg (95% CI -2.1 to -2.9, $P < 0.001$). The Philips capnometer measured CO_2 more closely to the expected CO_2 (mean of differences -1.1 mmHg (95% CI -0.69 to -1.4, $P < 0.001$). There was a narrow variance in measured CO_2 for both devices. These results were consistent with the manufacturers' stated sensitivities for both devices.[20,21]

Figure 4
Expected CO_2 vs measured CO_2 with EMMA and Philips capnometers at 101 kPa

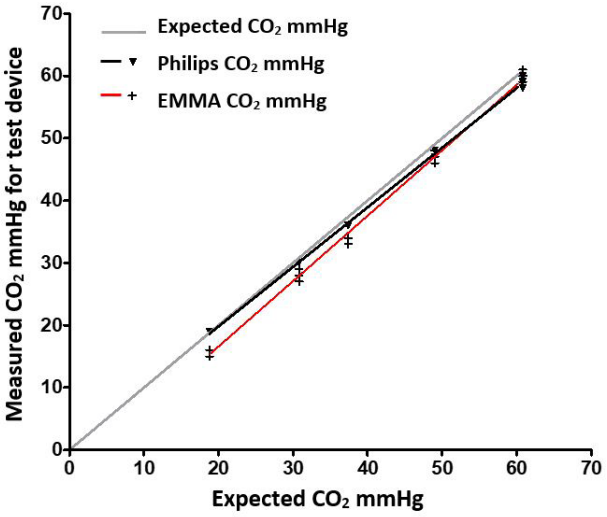


Figure 5
Measured EMMA CO_2 compared to expected CO_2 for oxygen/CO_2 test gases in hyperbaric conditions

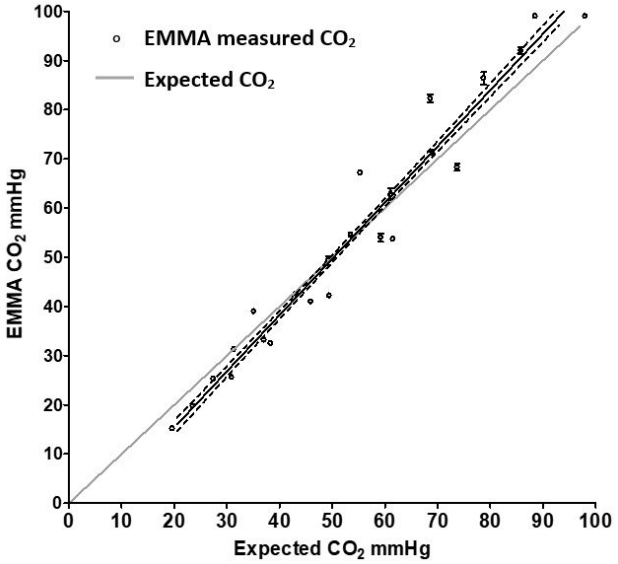


Figure 6
Measured EMMA CO_2 compared to expected CO_2 for air/CO_2 test gases in hyperbaric conditions

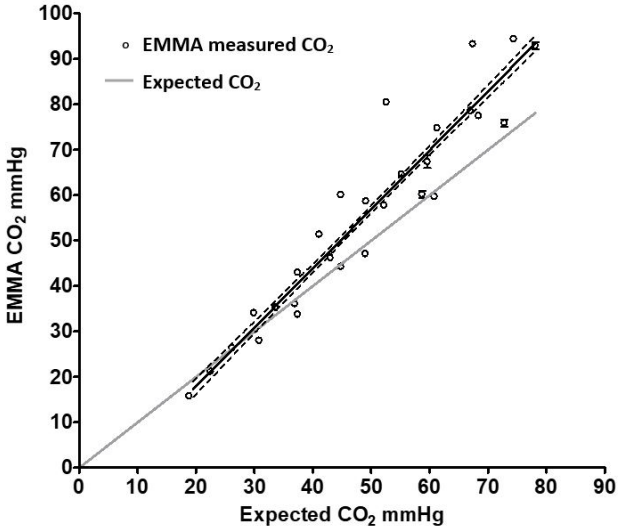
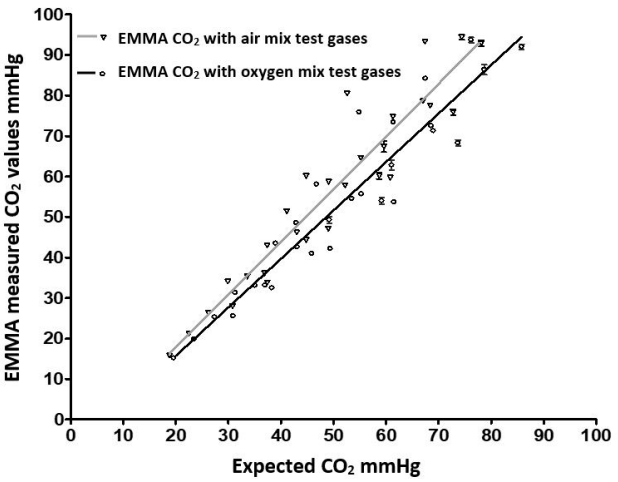


Figure 7
Linear regression graph showing EMMA CO_2 measurements comparing readings during exposure to oxygen and air test gases in hyperbaric conditions



At 101 kPa, both devices demonstrated a linear correlation with expected CO_2 and regression equations could be calculated for each device.

EMMA: Expected CO_2 = EMMA measured CO_2/1.05 + 4.4 (R^2 = 1.0, P < 0.0001).
Philips: Expected CO_2 = Philips measured CO_2/0.96 – 0.7 (R^2 = 1.0, P < 0.0001).

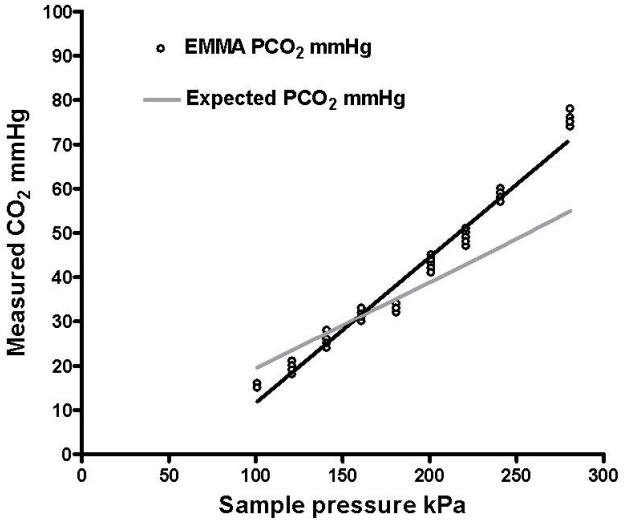
Between devices, the EMMA capnometer under-read compared to the Philips capnometer by a mean of -1.4 mmHg (95% CI -1.8 to -1.0, P < 0.001).

STAGE 2: EMMA CAPNOMETER CO_2 MEASUREMENT UNDER HYPERBARIC CONDITIONS

Figures 5 and 6 show measured EMMA CO_2 versus expected CO_2 for the oxygen/CO_2 and air/CO_2 test gases respectively.

EMMA Device for oxygen/CO_2 Test Gases (Figure 5): Expected CO_2 = EMMA Measured CO_2/1.2 + 6.9 (R^2 = 0.89, P < 0.0001).

Figure 8
Measured EMMA CO_2 versus expected CO_2 for test gas 2.58% CO_2 in 97.42% oxygen at nine different pressures



EMMA Device for air/CO_2 Test Gases (Figure 6):
Expected CO_2 = EMMA Measured CO_2/1.25 + 6.2 ($R^2 = 0.90$, $P < 0.0001$).

The EMMA device demonstrated a statistically significant linear relationship between measured CO_2 and expected CO_2 for both the oxygen/CO_2 test gas mixes and the air/CO_2 test gas mixes in the hyperbaric environment. The linear regression line gradients were significantly different for oxygen versus air CO_2 measurements ($P = 0.004$) (Figure 7).

The EMMA device consistently under-read the test gas CO_2 pressure for the lower values of expected CO_2. Conversely, as the expected CO_2 increased, the EMMA device consistently over-read the CO_2 values (Figures 5 and 6). This effect was observed for all gas mixes, as pressure increased. An example is shown in Figure 8.

There was a statistically significant greater variance in EMMA CO_2 measurement at higher pressures (> 141 kPa) (Tables 3 and 4).

Bland Altman plots were generated for all samples to assess agreement between the EMMA CO_2 measurements with the expected CO_2 values (Figures 9 and 10). Figure 9 shows the bias of the EMMA capnometer Ratio = 1.01 (SD 0.15) (red line) using 'oxygen' test gases. The 95% limits of agreement for the data = 0.72 to 1.3, represented by the grey lines. Figure 10 shows the bias of the EMMA capnometer Ratio = 1.11 (SD 0.16) (red line), using 'air' test gases. The 95% limits of agreement for the data = 0.80 to 1.42, represented by the grey lines. Both demonstrated a more positive trend of differences with increasing CO_2. This was greater for the 'air' gas samples, for which the bias was also higher. However, the differences were

Table 3
Mean of differences and variance between the EMMA CO_2 readings versus expected for test gases containing air mix; *P*-value for all differences < 0.0001; CI – confidence interval

Pressure (kPa)	Mean of differences (mmHg)	95% CI (mmHg)
101	-2.5	-2.8 to -2.2 (0.6)
121	0.4	-0.26 to 1.1 (1.36)
141	5.2	3.9 to 6.5 (2.6)
161	9.1	7.6 to 11.0 (3.4)
181	17.0	15.0 to 19.0 (4)
201	13.0	10.7 to 15.3 (4.6)
221	18.1	14.3 to 21.9 (7.6)
241	15.3	14.5 to 16.1 (1.6)
281	27.9	27.0 to 28.8 (1.8)

Table 4
Mean of differences and variance between the EMMA CO_2 readings versus expected for test gases containing oxygen mix; *P*-value for differences < 0.0001 except 141 kPa ($P < 0.003$) and 161 kPa ($P < 0.001$); CI – confidence interval

Pressure (kPa)	Mean of differences (mmHg)	95% CI (mmHg)
101	-6.1	-6.5 to -5.7 (0.8)
121	-4.6	-5.1 to -4.1 (1.00)
141	1.4	0.5 to 2.3 (1.8)
161	2.3	0.98 to 3.6 (2.62)
181	9.9	8.3 to 11.0 (2.7)
201	11.33	9.2 to 13.5 (4.3)
221	11.2	8.5 to 13.9 (5.4)
241	11.3	10.6 to 12.0 (1.4)
281	21.0	19.9 to 22.1 (2.2)

Figure 9
Bland Altman plot of EMMA CO_2 vs expected CO_2 ratio using oxygen test gases

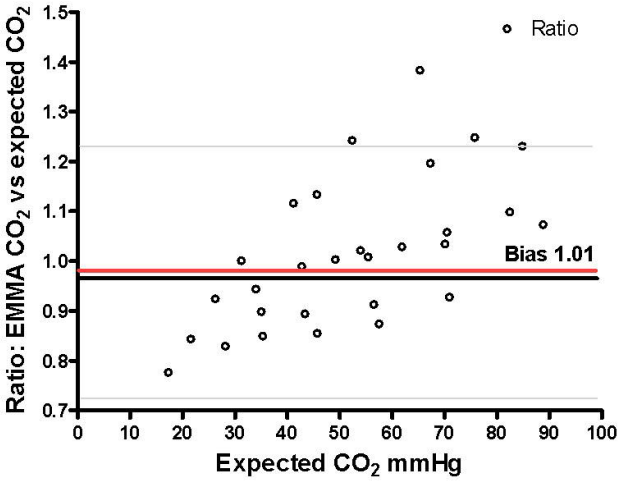
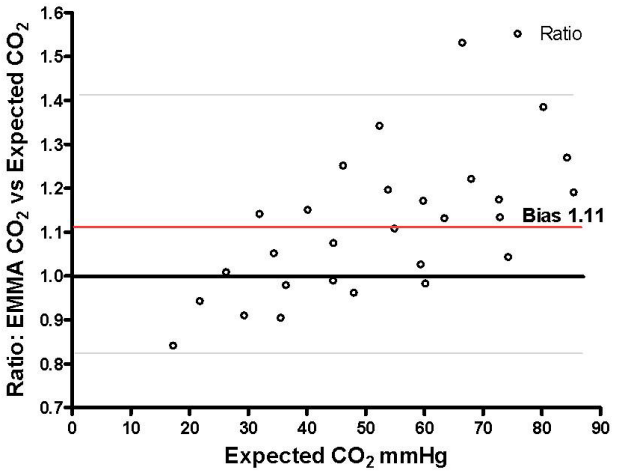


Figure 10
Bland Altman plot of EMMA CO_2 vs expected CO_2 ratio using air test gases



more constant for values within the physiological range of CO_2 (30–60 mmHg) for both types of test gases.

Of note, data collection was limited by the EMMA device having a maximum displayed value of 99 mmHg CO_2. The maximum reading of 99 mmHg was surpassed for a number of the test gases with increased chamber pressures. As a result, measurable data could only be obtained to 141 kPa or 161 kPa for some test gases. Only test gases A1 and A2 were able to be tested to our maximum test pressure of 281 kPa.

Discussion

Our study was designed to technically validate the function of the EMMA capnometer under hyperbaric conditions.

BETWEEN DEVICE AGREEMENT AT 101.3 kPa

At 101 kPa, both the EMMA and Philips capnometers had a linear relationship with the expected CO_2. The EMMA capnometer consistently under-read, by a mean of 2.5 mmHg, compared to the expected CO_2. Similarly, the Philips IntelliVue microstream capnometer also under-read by a mean of 1.1 mmHg.

The two test devices were limited to whole number displays of CO_2, which could produce an error of ± 0.5 mmHg (1.25% at physiological $ETCO_2$ of 40 mmHg). The consistent CO_2 measurements demonstrated that both devices are sufficiently accurate for their intended clinical purpose of monitoring expired CO_2 at 101 kPa. Correction equations for expired CO_2 could be used, but the significant linear correlation means both devices reflect accurate trends in expired CO_2 without the need to apply correction calculations during clinical practice. These results were consistent with the manufacturers' stated sensitivities for both devices.[20,21]

The EMMA capnometer under-read compared to the Philips capnometer by a mean of -1.4 mmHg (95% CI -1.8 to -1.0, $P < 0.001$). Two previous studies have evaluated the EMMA capnometer against integrated $ETCO_2$ monitors under normobaric conditions. In patients undergoing a planned general anaesthetic, one study demonstrated a consistent between-device bias of -2.2 mmHg (limits of agreement -6.0 to +1.6) compared with a reference side-stream capnometer.[23] Another group compared nine EMMA capnometers with an integrated anaesthetic machine side-stream capnograph, using one participant. This study showed good agreement between the devices (median bias -0.3 mmHg), despite study limitations.[24] Both of the above studies assumed that the anaesthesia $ETCO_2$ equipment was the gold standard. Our study showed similar results using test gases. The EMMA capnometer would be an acceptable alternative to the Philips capnometer to monitor trends in CO_2 under normobaric conditions, especially in circumstances where mains power was not available.

VALIDATION OF THE EMMA CAPNOMETER UNDER HYPERBARIC CONDITIONS

Our literature search identified no published studies evaluating the functionality of the EMMA capnometer under increased ambient pressures. Given its size, portability and battery power, the device has potential for monitoring critical care patients in hyperbaric facilities.

Our study demonstrated a linear increase of the EMMA CO_2 measurements with increasing pressures. However, the EMMA capnometer measurements were lower than expected at low pressures and conversely higher than

expected at higher pressures (> 141 kPa). The slope of the EMMA CO_2 line was greater than the expected CO_2 slope. Additionally, there was greater variance in the measured CO_2 data collected where expected CO_2 was above the physiological range for $ETCO_2$ (Figures 5–10). This may be due to both pressure and collision broadening. Despite this, the EMMA device demonstrated a statistically significant linear relationship between measured CO_2 and expected CO_2 for the oxygen/CO_2 test gas mixes and the air/CO_2 test gas mixes in the hyperbaric environment. The EMMA device potentially could be used to monitor trends in the hyperbaric environment.

We chose to use test gases, as opposed to test subjects, to remove the additional variables of inter-person variability in CO_2 production and elimination, and the challenges created by sample dilution and gas bypass in non-intubated patients. Our study cannot be considered an accurate representation of what would occur in a human subject.

The test gases were supplied as a specific concentration of CO_2, so it is expected with increased pressure, the percentage of CO_2 would stay the same, but the measured CO_2 partial pressure would increase (Dalton's Law). The use of test gases is not the same as for a human subject exhaling CO_2. A stable patient should produce CO_2 at a constant rate, and a consistent partial pressure of $ETCO_2$ at 101 kPa. At higher chamber pressures, metabolic CO_2 would be diluted in the alveoli by the extra molecules of oxygen (+/- nitrogen). Theoretically, this would reduce alveolar CO_2 but maintain a measured $ETCO_2$ within physiological ranges. Additionally, the test gases used during the study were dry. In humans, exhaled gas is normally saturated in water vapour, at body temperature. Its presence would likely further reduce measured $ETCO_2$ when used clinically.[18] Therefore, $ETCO_2$ at all pressures should remain in a range that could be measured by the EMMA capnometer (< 99 mmHg). EMMA measurements in the physiological range had less deviation from expected CO_2, so the EMMA device may be useful clinically, particularly to monitor trends.

One group tested the SpaceLabs Medical 90369G mainstream capnometer using a range of test gases with known CO_2 concentrations (in oxygen only) under hyperbaric conditions.[25] This study tested the device at only one experimental pressure of 243 kPa (2.4 atm abs), a typical hyperbaric oxygen treatment pressure. Five test gas concentrations were selected to reflect an expected range of PCO_2 from 20.1–78.3 mmHg at this experimental pressure. Our findings with the EMMA capnometer, were similar to theirs. Their device also read erroneously high under hyperbaric conditions, which they presumed related to calibration issues, pressure broadening and collision broadening from oxygen. They identified a correction equation applicable to their device, but only under specific conditions of oxygen and pressure.

We used test gases of known CO_2 concentration in either an 'air' or 'oxygen' mix. Patients undergoing HBOT are treated with 100% oxygen periods with intermittent air breaks, to reduce the risk of oxygen toxicity.[26] Our test gases were chosen to represent typical $ETCO_2$ in HBOT patients throughout their treatment period. We chose a range of CO_2 percentages to represent a range of $ETCO_2$ of 20–60 mmHg at 101 kPa. These values represent normal physiological $ETCO_2$ extended to include levels expected with possible hyper- or hypoventilation. Our study was limited by the inability to assess all test gases to our maximum experimental pressure of 281 kPa as some test gas expected CO_2 pressures were higher than the display capability (99 mmHg) of the EMMA device.

It is possible that a collision broadening effect may influence capnometer-measured CO_2 readings. This phenomenon affects the sensitivity of infrared analysers which leads to erroneous CO_2 readings.[27] It results in the broadening of spectral absorption peaks of a gas (e.g., CO_2) due to the collision or proximity of molecules of another gas, e.g., N_2O, oxygen. Typically, the addition of molecules such as He, N_2O and H_2O to a gas tends to cause erroneously higher CO_2 readings because the energy absorbed by a carbon dioxide molecule is transferred to the larger (additional) molecule when the two collide, permitting the carbon dioxide molecule to absorb more infrared energy, resulting in less infrared reaching the capnometer detector and a higher CO_2 reading.[28] This effect is less pronounced with homonuclear diatomic gases such as oxygen and nitrogen.[28] Capnometers are usually calibrated with known concentrations of CO_2 in nitrogen and oxygen at 101 kPa.[28] The practical consequences of collision broadening influencing the EMMA CO_2 readings for either our 'air' or 'oxygen' test mixes should be low, but data are limited from devices used at higher ambient pressures. In our study, both air and oxygen test gas mixes demonstrated a linear relationship between measured and expected CO_2 under normobaric and hyperbaric conditions with conversion equations able to be derived for both. However, there was a statistically significant difference between the air versus the oxygen test gas mixes under hyperbaric conditions, with more consistent readings (compared with expected) and a shallower slope with the oxygen test gases (Figures 7, 9–10). This could be due to the collision broadening effect of oxygen versus nitrogen. Even though this is statistically significant, the difference is so small, it would be unlikely to be clinically significant, and for practical purposes, the EMMA device can be used to monitor trends both during oxygen treatment periods and air breaks.

One group demonstrated that $ETCO_2$ readings were erroneously high in hyperbaric conditions, which was attributed to the pressure broadening effect of increased gas density.[15,16] This is a similar concept to collision broadening described above, however, it is the density of the molecules that increases collisions and ergo energy absorption and

alters the infrared detection causing erroneously high measured CO_2 at higher pressures. Pressure broadening could be the main influence from nitrogen and oxygen on $ETCO_2$ measurements when measured at pressures > 101 kPa. Again, despite this phenomenon, a linear relationship could be derived for both groups of test gases.

Data collection was limited by the EMMA device having a maximum displayed value of 99 mmHg CO_2. With increased pressures, there was an expected increase in CO_2 of the test gases. As per Table 2, we predicted that the expected CO_2 would surpass 99 mmHg for test gases C1 and C2 at 281 kPa, D1 and D2 by 201 kPa and for E1 and E2 by 181kPa. However, during our study, we observed that as the pressure increased, the EMMA device consistently overread at pressures higher than 141 kPa as well as having greater variance (Tables 3 and 4). The maximum reading of 99 mmHg was surpassed earlier than expected. As a result, measurable data could only be obtained to 141 kPa or 161 kPa for some test gases. Only test gases A1 and A2 were able to be tested to our maximum test pressure of 281 kPa. A possible solution for the maximum display value would be increasing the display capabilities of the EMMA device from two to three digits. However, as per previous reasoning, the EMMA capnometer display range should be adequate for clinical monitoring in the hyperbaric environment.

Conclusion

This study validated the function of the EMMA capnometer in the hyperbaric environment. The device over-read CO_2 measurements at test pressures > 141 kPa, however there was a linear relationship between expected and measured CO_2. These data suggests that the EMMA capnometer may be clinically useful for monitoring $ETCO_2$ trends in patients undergoing hyperbaric oxygen treatment.

References

1 Medical Services Advisory Committee. Review of interim funded service: hyperbaric oxygen therapy (HBOT) for the treatment of chronic non-diabetic wounds and non-neurological soft tissue radiation injuries. MSAC application 1054.1. Canberra: Commonwealth of Australia, 2011. [cited 2022 Jun 22]. Available from: http://www.msac.gov.au/internet/msac/publishing.nsf/ Content/1054.1-public.

2 Medical Services Advisory Committee. Hyperbaric oxygen therapy (HBOT). MSAC applications 1018-1020. Canberra: Commonwealth of Australia, 2001. [cited 2022 Jun22]. Available from: http://www.msac.gov.au/ internet/msac/publishing.nsf/Content/1018-1020-public.

3 Weaver L. Hyperbaric oxygen in the critically ill. Crit Care Med 2011;39:1784–91. doi: 10.1097/CCM.0b013e31821858d1. PMID: 21460713.

4 Poulton TJ. Monitoring critically ill patients in the hyperbaric environment. Med Instrum. 1981;15:81–4. PMID: 7231244.

5 Rogatsky GG, Shifrin EG, Mayevsky A. Physiologic and biochemical monitoring during hyperbaric oxygenation: a review. Undersea Hyperb Med. 1999;26:111–22. PMID: 10372431.

6 Australian and New Zealand College of Anaesthetists. PS18: Recommendations on monitoring during anaesthesia. Melbourne, Australia: Australian and New Zealand College of Anaesthetists (ANZCA); 2017.

7 Grmec Š. Comparison of three different methods to confirm tracheal tube placement in emergency intubation. Intensive Care Med. 2002;28:701–4. doi: 10.1007/s00134-002-1290-x. PMID: 12107674.

8 Nagler J, Krauss B. Capnography: a valuable tool for airway management. Emerg Med Clin. 2008;26:881–97. doi: 10.1016/j.emc.2008.08.005. PMID: 19059088.

9 Weaver L. Management of critically ill patients in the monoplace hyperbaric chamber. In: Kindwall EP, Whelan HT, editors. Hyperbaric medicine practice. Flagstaff (AZ): Best Publishing; 1999. p. 245–322.

10 American Society of Mechanical Engineers (ASME). Pressure vessels for human occupancy – PVHO-1-2016, Section 5 – medical hyperbaric systems. New York: American Society of Mechanical Engineers; 2016.

11 Al Balushi A, Smart D. Safety and performance of intravenous pumps and syringe drivers in hyperbaric environments. Diving Hyperb Med. 2023;53:42–50. doi: 10.28920/dhm53.1.42-50. PMID: 36966521.

12 National Fire Protection Association. NFPA-99-Healthcare Facilities Code 2018 – Chapter 14 – Hyperbaric Facilities. Massachusetts: National Fire Protection Association; 2018

13 Summer SM. Flammability assessment of lithium-ion and lithium-ion polymer battery cells designed for aircraft power usage. FAA Report: DOT/FAA/AR-09/55, Washington (DC): US Department of Transportation Federal Aviation Administration; 2010.

14 Wang C, Xue L, Yu Q, Liu Y, Ren Z, Liu Y. Evaluation of a new hyperbaric oxygen ventilator during volume-controlled ventilation. Diving Hyperb Med. 2023;53:129–37. doi: 10.28920/dhm53.2.129-137. PMID: 37365130.

15 Swaby G, Brown S, Sutton T, Love T, Fife CE. Calibration of an end-tidal CO_2 monitor under hyperbaric conditions. Undersea Hyperb Med. 1996:23(Supp):79.

16 Handell S, Ansjon R, Casto R, Lind F. Respiratory CO_2 monitoring of the critically ill patient in the multiplace chamber. Basel, Switzerland: EUBS; 1992. p. 59–61.

17 Bjerregård A, Jansen E. Monitoring carbon dioxide in mechanically ventilated patients during hyperbaric treatment. Diving Hyperb Med. 2012;42:134–6. PMID: 22987459.

18 Jaffe MB. Mainstream or sidestream capnography? Respironics Novametrix, 2002. [cited 2022 Dec 1]. Available from: https://www.meddevicedepot.com/PDFs/mainvsside.pdf.

19 Richard RB, Loomis JL. Breath-by-breath monitoring of respiratory gas concentrations during compression and decompression. Undersea Biomed Res. 1991;18:117–26. PMID: 2042263.

20 EMMA™ emergency capnometer user's manual. Article 0000-3804, ed.04. Daneryd, Sweden: Masimo; 2007. [cited 2021 Jun 1]. Available from: https://www.cevimed.com/masimo-emma-mainstream-capnometer.

21 IntelliVue M750 monitor, X3 transport monitor, MMX module, M3015B. Koninklijke: Philips; 2019. [cited 2021 Jun 1]. Available from: https://www.philips.com.au/healthcare/product/HC866471/intellivue-mx750-bedside-patient-monitor.

22 Standards Australia & Standards New Zealand. Australia/New Zealand Standard™ 4774.2.2019: Work in compressed air and

hyperbaric facilities – Part 2: hyperbaric oxygen facilities. Sydney: Standards Australia; 2019.
23 Kim KW, Choi HR, Bang SR, Lee J-W. Comparison of end-tidal CO_2 measured by transportable capnometer (EMMA capnograph) and arterial pCO_2 in general anesthesia. J Clin Monit Comput. 2016;30:737–41. doi: 10.1007/s10877-015-9748-x. PMID: 26264607.
24 Hildebrandt T, Espelund M, Olsen KS. Evaluation of a transportable capnometer for monitoring end-tidal carbon dioxide. Anaesthesia. 2010;65:1017–21. doi: 0.1111/j.1365-2044.2010.06499.x. PMID: 21198468.
25 Wolfers DL, Bennett MH. Performance of mainstream capnography under hyperbaric (243 kPa) oxygen conditions. Diving Hyperb Med. 2006;36:174–78. [cited 2022 Jun 22]. Available from: https://www.dhmjournal.com/images/IndividArticles/36Dec/Wolfers_dhm.36.4.174-178.pdf.
26 Clark JM. Oxygen toxicity. In: Neuman TS, Thom SR, editors. Physiology and medicine of hyperbaric oxygen therapy. Philadelphia (PA): Saunders Elsevier; 2008. p. 527–64.
27 Ammann EC, Galvin RD. Problems associated with the determination of carbon dioxide by infrared absorption. J Appl Physiol. 1968;25:333–5. doi: 10.1152/jappl.1968.25.3.333. PMID: 5669886.
28 Ball J, Grounds R. Calibration of three capnographs for use with helium and oxygen gas mixtures. Anaesthesia. 2003;58:156–60. doi: 10.1046/j.1365-2044.2003.02963.x. PMID: 12562412.

Conflicts of interest and funding: nil

Submitted: 22 June 2022
Accepted after revision: 18 February 2023
