

Original articles

Performance of mainstream capnography under hyperbaric (243 kPa) oxygen conditions

Darren L Wolfers and Michael H Bennett

Key words

Capnography, carbon dioxide, equipment, ventilators, patient monitoring, hyperbaric oxygen

Abstract

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We evaluated the performance of the SpaceLabs Medical 90369G and 90516 capnography modules (mainstream infra-red spectroscopic capnographs) under clinical hyperbaric oxygen conditions (2.4 atmospheres absolute (243.12 kPa), FiO_2 1.0). Each module was ventilated alternately with known concentrations of carbon dioxide (CO_2) in oxygen and 100% oxygen. The input concentrations of CO_2 were varied to assess accuracy, reproducibility and stability over time. The 90516 module could not be studied as it was incapable of functioning under our conditions. The 90369G module consistently over-read but was highly predictable so that true end-tidal CO_2 (mmHg) = 0.619 x capnograph end-tidal CO_2 + 2.60 ($r^2 = 1.00$, $P < 0.0001$). The module had highly reproducible and stable results that showed no hysteresis. We conclude the 90369G capnography module is suitable for use in monitoring ventilated patients in hyperbaric practice. The correction factors are applicable only to our module, under the specific conditions of oxygen and pressure we used. We offer possible causes for the module's inaccuracy, and some putative solutions.

Introduction

There are a number of approved indications for hyperbaric oxygen therapy that involve compression of mechanically ventilated patients.¹ Capnography allows the early detection of inadvertent extubation or patient-ventilator disconnection and of hypercapnoea that may result from the change in function of mechanical ventilators known to occur with therapeutic hyperbaric pressures.^{2,3} Hypercapnoea is believed to increase the risk of central nervous system (CNS) oxygen (O_2) toxicity in humans.³ In Australia, capnography is mandatory during general anaesthesia.⁴ It is also our routine practice to monitor end-tidal CO_2 in ventilated patients in our hyperbaric chamber.

Infra-red spectrography is the cheapest, most compact and most widely used of the techniques available for quantitative detection of end-tidal carbon dioxide (CO_2).⁵ Side-stream (as opposed to mainstream) sampling methods are problematic under both normobaric and hyperbaric conditions.⁵⁻⁸ Several authors have speculated that infra-red spectrographic capnographs may be inaccurate at therapeutic hyperbaric pressures; the only published evaluation of such a mainstream capnograph under clinical hyperbaric oxygen conditions found the capnograph gave falsely elevated readings.⁹⁻¹¹

The aim of our study was to evaluate the performance of the SpaceLabs Medical capnography options 90369G and 90516 when used under clinical hyperbaric oxygen conditions. The 90369G 'add-on' module (SpaceLabs Medical, Redmond,

WA, USA) is a mainstream infra-red spectrographic capnograph that may be used with both the capnograph and associated monitor placed in the chamber with the patient. In-chamber use of this module has been certified as safe by our clinical engineering department. The pressures used clinically, however, are well outside the 90369G module's operating specifications (69.7–101.3 kPa).¹² The newer 90516 module, also a mainstream infra-red spectrographic capnograph, was assessed as it is being adopted elsewhere within our institution. It has the advantage of user (not factory) recalibration.¹³ Specifically, we wanted to establish the accuracy, reproducibility and stability over time of readings under clinical hyperbaric oxygen conditions, using these two modules.

The 90369G is also marketed as, and identical to, the 90367G and 90309Q add-on options and the 90515 removable module. The 90516 removable module is also marketed as, and identical to, the 90367H and 90369H add-on options (information provided by manufacturer, SpaceLabs Medical, Redmond, WA, USA).

Methods

We used customised reference beta-mix gases of various concentrations of CO_2 in O_2 with a certified analysis tolerance of $\pm 2\%$ relative (Linde Gas, Yennora, NSW, Australia), to allow simulation of inspired and expired gas across a range of CO_2 concentrations. Concentrations of 1.10%, 1.66%, 2.25%, 2.75%, 3.31% and 4.29% CO_2 in O_2 were provided, delivering a pCO_2 of 20.1, 30.3, 41.0,

50.2, 60.4 and 78.3 mmHg CO₂ (1 mmHg = 0.133 kPa) respectively at our experimental conditions of 243 kPa (2.4 ATA). The reference gases were delivered to the module's mainstream sensor alternately with 100% O₂ via a custom pneumatic timer driving a flow interrupter in order to simulate a human respiratory pattern.

The 90516 capnography module could not be studied as it was incapable of functioning under our experimental conditions. The 90369G capnography module was displayed on an Ultraview 1050 (90369) Portable Bedside Monitor (SpaceLabs Medical, Redmond, WA, USA), our routine monitor. The module is capable of reporting concentration of CO₂ in both partial pressure of CO₂ (mmHg) and volume percentage of CO₂ (% CO₂); both methods of reporting were investigated throughout the experiment. The module reports both minimum inspired or baseline CO₂ – when the flow interrupter switches to 100% O₂ to simulate inspiration – and maximum or end-tidal CO₂ – when the flow interrupter delivers reference gas containing CO₂ to simulate expiration. The optional O₂ measurement cell was not used with the capnography module. The capnograph underwent calibration verification at 1.0 ATA (101.3 kPa) prior to each experimental run, as per the manufacturer's instructions.¹² The manual O₂ compensation was activated as we were using greater than 60% O₂ at all times.

All readings were taken at 2.4 ATA, with reference gases, timer/flow interrupter, capnography mainstream sensor, module and monitor in-chamber, in a compartment of our multiplace hyperbaric chamber (EBSRAY Pumps Pty Ltd, Brookvale, NSW, Australia). To ensure accurate delivery of chamber pressure of 2.4 ATA, ambient barometric pressure and temperature were recorded from a properly calibrated electronic digital barometer and thermometer, placed outside the chamber. Chamber pressure was measured on an analogue gauge (Budenberg, Sydney, Australia) with accuracy of +/- < 0.1 msw (< 1.00 kPa). Chamber temperature and relative humidity were monitored to ensure they stayed within the capnography module's operating environmental requirements.¹²

Preliminary work established the best simulated clinical measurement conditions and these were used for the experiment: respiratory rate 15 breaths per minute with an inspiratory to expiratory ratio of 1 to 3, O₂ flow of 3 l.min⁻¹, and CO₂ in O₂ flow of 1 l.min⁻¹. Ninety seconds after the introduction of a new reference gas, end-tidal CO₂ was measured in mmHg and then measured in % CO₂ a further 30 seconds later. Reference gases were all dry gases delivered at chamber temperature and readings were reported in ATPD.

Following pressurisation of the chamber to 2.4 ATA, alternating 100% O₂ and 1.10% CO₂ in O₂ were delivered to establish the accuracy of the baseline and end-tidal CO₂. These were manually recorded from the capnograph display in mmHg. Then the module was switched to report % CO₂

and the end-tidal CO₂ and chamber pressure as detected by the capnography module were recorded. This experiment was then repeated with 1.66%, 2.25%, 2.75%, 3.31% and 4.29% CO₂ in O₂ respectively.

To assess reproducibility, this procedure was repeated four times, twice with increasing reference gas CO₂ concentration and twice with decreasing CO₂ concentration. This not only gave four assessments of each input CO₂ to assess reproducibility of results but also two entire ascending then descending CO₂ runs to examine hysteresis.

To assess for stability of readings over time, an alternating CO₂ of 0 mmHg and 41.0 mmHg (at 2.4 ATA, in maximal oxygen) was delivered to the capnograph to simulate normal human respiration. This experiment was run for 90 minutes, with the baseline and end-tidal CO₂ recorded every five minutes in both mmHg and % CO₂ as well as the chamber pressure detected by the capnography module. All readings were again manually recorded from the relevant monitors.

Statistical analysis was performed using StatsDirect Statistical Software Version 1.9.8 (Iain Buchan, 2001). Accuracy data were subjected to simple linear regression and correlation analysis where appropriate. Simple descriptive statistics were used to report stability and reproducibility data. ANOVA with Tukey correction for multiple comparisons was used to detect any hysteresis in the reproducibility data. Statistical significance was accepted when P < 0.05.

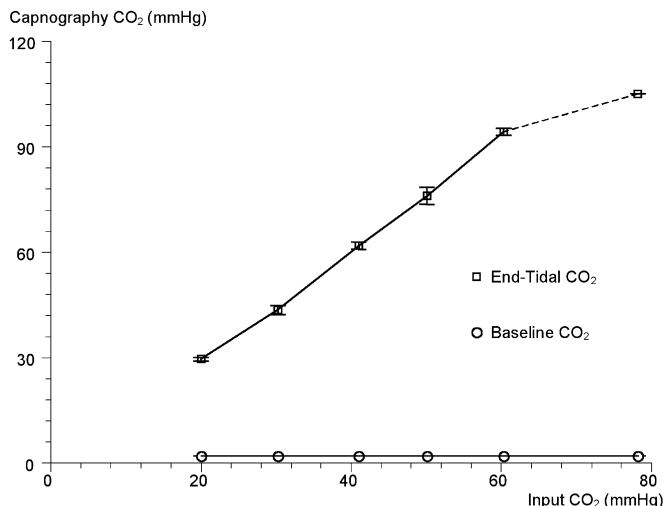
Results

The 90369G capnograph module passed prescribed calibration verification at 1.0 ATA.¹² Chamber environmental conditions were always within the module's requirements with the exception of operating pressure.¹² Chamber and delivered-gas temperatures were 21.6–25.3 °C throughout the experiment. Chamber pressure was within 0.52 kPa or 0.37% relative of 2.4 ATA at all times. Interestingly, the chamber pressure as detected by the 90369G capnography module was always 740 mmHg, despite the true value being 1824 mmHg (243 kPa).

Gases delivered were within the module's output range except with input of 4.29% CO₂ in O₂ when the capnograph detected end-tidal concentrations of CO₂ of 105 mmHg and 14.2%. As these values exceed the maximum reportable by the instrument this result is graphed but not included in further statistical analysis of the relationship between the actual and detected values.¹²

Baseline readings were stable at 1 mmHg regardless of the alternating concentration of CO₂ (Figure 1). The relationship between input CO₂ and end-tidal CO₂ when reported in mmHg is linear (Figure 1), with the capnograph over-reading. The correlation is highly significant (r² = 1.00, P < 0.0001) and linear regression shows that the true end-tidal

Figure 1
90369G capnograph accuracy (mmHg)
 (error bars represent +/- 1 standard deviation of the mean); dashed line – outside module’s specified operating range



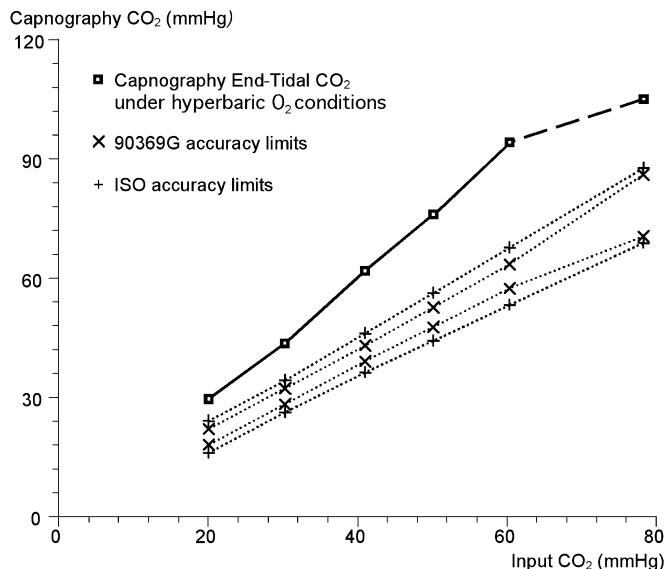
CO_2 or input $CO_2 = 0.619 \times$ capnograph end-tidal $CO_2 + 2.60$. There was a similar linear relationship when analysing CO_2 reported as a volume %, with the capnograph again over-reading. The correlation was highly significant ($r^2 = 1.00$, $P < 0.0001$) and linear regression shows that input % $CO_2 = 0.252 \times$ capnograph end-tidal % $CO_2 + 0.146$.

Results were highly reproducible on repeat testing. The baseline data showed perfect reproducibility with zero variation. The end-tidal data in mmHg showed high reproducibility with the greatest standard deviation 2.45 mmHg or 3.22% of the mean. When reporting in % CO_2 the greatest standard deviation was 0.265% absolute or 2.58% relative of the mean. ANOVA with Tukey correction for multiple comparisons indicated no hysteresis. (Maximum difference between mean ascending and descending values for each input CO_2 was 1.5 mmHg, $P > 0.99$ for each comparison.)

Figure 2 shows the result of the end-tidal CO_2 accuracy data in mmHg plotted against the manufacturer’s limits and the ISO standard’s limits for accuracy.^{12,14}

The 90369G capnograph readings remained very stable when assessed over 90 minutes with 100% O_2 alternating with a single concentration of reference gas, whether reporting in mmHg or % CO_2 . The baseline showed 0 mmHg absolute and 0% relative maximal drift over time. End-tidal CO_2 showed 2 mmHg CO_2 absolute maximal drift and 3.33% relative maximal drift. When end-tidal CO_2 was reported in % CO_2 , absolute maximal drift was 0.6% and relative maximal drift was 7.59% over a 90-minute period.

Figure 2
90369G capnograph accuracy compared with accuracy standards (dotted lines); dashed line – outside module’s specified operating range



Discussion

Both the 90369G and the 90516 modules were to be tested for suitability for use under clinical hyperbaric oxygen conditions. The 90516 module proved incapable of operating under these conditions; a reading error of the barometric pressure is the only plausible explanation.¹³

The comparison of observed values plotted against the manufacturer’s limits and the ISO standard’s limits for accuracy shows the 90369G module to be inaccurate under clinical hyperbaric oxygen conditions. However, our highly significant correlations between input and measured CO_2 show that corrections can be applied allowing true end-tidal CO_2 to be calculated under the conditions of this experiment (2.4 ATA, with an FiO_2 of 1.0 and the manual oxygen compensation activated). Our experiment further shows that the 90369G capnography module produces highly reproducible results with no hysteresis and very stable readings over time. Thus the SpaceLabs Medical 90369G modular mainstream infra-red spectrographic capnograph is suitable for use in the clinical hyperbaric oxygen environment.

The difference in the slope of our two end-tidal CO_2 correction equations is likely due to an error introduced through inaccurate barometric reading within the module (detecting 740 mmHg instead of 1824 mmHg) during calculation of the percentage CO_2 . When this error is accounted for, the gradients of the end-tidal CO_2 equations are almost identical (input % CO_2 slope of 0.252×760 mmHg per 1 ATA / 740 mmHg $\times 2.4$ ATA = 0.620 compared with input CO_2 mmHg slope of 0.619).

There are several possible explanations for the inaccuracy of the 90369G module under these conditions: problems with calibration, collision broadening due to O₂ and pressure broadening. Problems with calibration under varied atmospheric pressure are known to affect the accuracy of some infra-red spectrographic capnographs.^{15,16} Whilst the capnograph passed calibration verification at 1.0 ATA, its method of calibration is unknown to us; we can only speculate that the accuracy of this calibration technique may be affected by our experimental conditions.

Collision broadening due to the presence of oxygen is known to affect the accuracy of infra-red spectrographic capnographs.⁵ Molecules of O₂ and CO₂ collide causing a transfer of energy that results in a broadening of the absorption peak for CO₂ (the wavelengths where absorption of infra-red light is greatest). This causes significant under-reading of CO₂, the opposite of our experimental finding.⁵ We speculate the module's manual oxygen compensation function was unable to fully compensate for the high oxygen levels in our experiment.

Pressure broadening is the broadening of the spectral absorption peaks of a gas such as CO₂ owing to an increase in the absolute pressure of the gas sample.¹⁵ This causes a significant over-reading of CO₂.¹⁵ Whilst the 90369G module is said to have automatic barometric pressure correction, the internal barometer was not functional under our experimental conditions.¹² Therefore, pressure broadening is highly likely to have contributed to the 90369G module's false elevation of results at 2.4 ATA. Given the likely effects of collision broadening due to oxygen and pressure broadening on the accuracy of our module, our reported correction factors should not be applied to other conditions of oxygen and pressure.

The accuracy of the 90369G module under clinical hyperbaric oxygen conditions may be improved by addressing the likely factors above. Infra-red spectrographic capnographs determine the concentration of CO₂ by comparison with a known standard, making accurate calibration essential.⁵ It has been suggested that calibration should occur at each measurement pressure with a known pCO₂ and the ambient pressure manually entered into the module.⁵ This will not only overcome many of the problems of calibration under varied ambient pressure, but potentially also the error due to pressure broadening. Error from collision broadening due to oxygen could also be minimised if calibration was done using oxygen as the carrier gas.^{15,17} Currently the 90369G module cannot be manually calibrated so significant modifications would be required.

As an alternative, further work could be done to calculate correction equations such as ours for a large range of ambient pressures and carrier gas oxygen concentrations. Improved module barometric-pressure and oxygen sensors, accurate over the range of pressure and pO₂ found in clinical hyperbaric oxygen practice, could be incorporated. Internal

module software would then complete this full-range automatic barometric pressure and oxygen compensation.

We strongly caution against applying our results directly to other capnography systems. The performance of different capnographs varies even at 1.0 ATA, whilst the relative effect of pressure/collision broadening has been shown to vary with the capnograph used.^{15,18} We believe there is a case for further investigation of both our capnographs under other common hyperbaric conditions, and other available capnographs.

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- Darren L Wolfers, MBBS(Hons), FANZCA, DipDHM, and Associate Professor Michael Bennett, MD, FANZCA, MM(Clin Epi), are senior staff specialists in the Department of Diving and Hyperbaric Medicine, Prince Of Wales Hospital, Sydney.*

Address for correspondence:

Darren L Wolfers,
Department of Diving and Hyperbaric Medicine,
Prince of Wales Hospital,
Randwick, NSW 2031,
AUSTRALIA

Phone: +61-(0)2-9382-2222

Fax: +61-(0)2-9382-3882

E-mail: <Darren.Wolfers@SESIHHS.HEALTH.NSW.GOV.AU>

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