Technical report

Quantifying discrepancy between indicated and actual oxygen flow rates delivered by Comweld Ezi-flow low and standard flowmeters under hyperbaric conditions: a technical report

Yoav Aufgang[1,2], Bridget Devaney[1,3,4], Jason Chan[1,2], Ian Millar[1,4], Theo Tsouras[1]

[1] *Department of Intensive Care and Hyperbaric Medicine, Alfred Health, Melbourne, Australia*
[2] *School of Translational Medicine, Faculty of Medicine Nursing and Health Sciences, Monash University, Melbourne, Australia*
[3] *Emergency and Trauma Centre, Alfred Health, Melbourne, Australia*
[4] *School of Public Health and Preventive Medicine, Faculty of Medicine Nursing and Health Sciences, Monash University, Melbourne, Australia*

Corresponding author: *Dr Bridget Devaney, Department of Intensive Care and Hyperbaric Medicine, Alfred Health, 55 Commercial Road, Melbourne, VIC 3004, Australia*
ORCiD: *0000-0001-6521-418X*
b.devaney@alfred.org.au

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Abstract
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Introduction: During clinical use of extracorporeal membrane oxygenation (ECMO) in hyperbaric conditions at our centre, upward titration of indicated sweep gas flow rates is required to maintain adequate CO_2 clearance. This project measured the impact of hyperbaric pressure on oxygen flow rates delivered by the Comweld Ezi-Flow flowmeters used in our centre.
Methods: Oxygen flow rates through Comweld Ezi-flow standard and low oxygen gas flowmeters were set at 101.3 kPa (1 atmosphere absolute [atm abs]) and then measured at intervals up to 284 kPa (2.8 atm abs) using a calibrated gas flow analyser, with cross verification against a small Douglas bag test type apparatus. During testing, the chamber was compressed and decompressed at a rate of 10 kPa·min^{-1}. Flow rates during chamber compression and decompression were compared.
Results: The indicated rate of oxygen gas flow through the unadjusted flowmeters changed minimally – typically rising by a maximum of half of the diameter of the indicator ball. The actual (volumetric) flow, tested across indicated flow rates from 3 to 12 L·min^{-1}, was consistently reduced by approximately 50% as the chamber pressure increased from 101.3 to 284 kPa (1 to 2.8 atm abs). A slightly smaller reduction was observed when assessing the low flowmeter across the same pressure range; reductions of 40.0 and 43.3% were demonstrated at 0.3 to 0.6 L·min^{-1} respectively. Differences in flow rates between compression and decompression were minor except at the very lowest flows.
Conclusions: At 284 kPa (2.8 atm abs), actual volumetric flow of oxygen through Comweld Ezi-Flow flowmeters is dramatically reduced and this needs appropriate compensation to ensure therapeutic aims are achieved.

Introduction

Patients receiving hyperbaric oxygen treatment (HBOT) vary from low acuity ambulant patients to critically unwell intensive care patients dependent on life support systems. Hyperbaric clinical and technical staff should have a clear understanding of the effects of raised pressure upon the function of healthcare technology used within the hyperbaric chamber and this includes equipment controlling and measuring gas flow.

The hyperbaric service at our centre has a rigorous process in place for the assessment and validation of equipment for use in hyperbaric conditions and has previously validated a number of medical devices for use in hyperbaric conditions. These include the HeartMate III left ventricular assist device, a pleural vacuum relief device for use with underwater seal drains, several syringe drivers, and more recently, a modified Maquet (Getinge) original series Rotaflow and Quadrox i-adult HMO 70000 (Quadrox) oxygenator.[1–6]

Although we have demonstrated successful delivery of HBOT to patients supported by both VA (veno-arterial) and VV (veno-venous) extracorporeal membrane oxygenation (ECMO) at our centre, much work remains to be done to assess, test and calibrate the function of various components

of multiple models of ECMO equipment. This paper reports upon the flowmeters used to provide 'sweep gas' to the ECMO oxygenator used to treat our first two hyperbaric ECMO (HECMO) patients.[5] Oxygen was the sweep gas used in both cases and was delivered by standard flow Comweld Ezi-flow flowmeter in one (adult) case, and low flow Comweld Ezi-flow flowmeter in the other (paediatric) case. Indicated flow was pragmatically titrated to carbon dioxide levels and acid base status, with an increase in indicated flow required during each HBOT session.

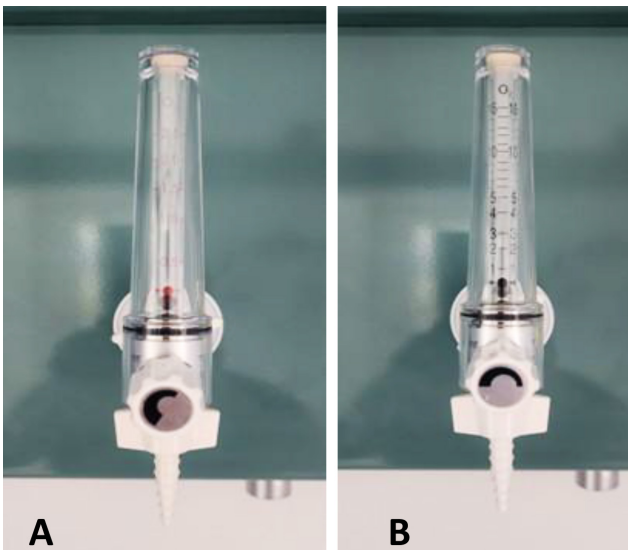
The aim of this project is to quantify the discrepancy between the Actual (or volumetric) gas flow delivered by the candidate flowmeters and the Set (indicated) flow, during hyperbaric versus ambient sea level atmospheric pressure conditions.

There are numerous designs of flowmeters with varying performance and considerably different responses to operation at pressures other than the standard or normal atmospheric conditions upon which calibration is usually based.[7,8] The hyperbaric chambers at our service have multiple modes for delivery of oxygen and these include delivery from Comweld Ezi-flow flowmeters (Figure 1), attached to Australian Standards-compliant medical gas outlets as in standard use around the hospital. These are pressure compensated Thorpe tube type devices with a variable cross section, constant taper flow indicator tube in which a 'ball type' bobbin lifts with increasing flow rate. Ezi-flow flowmeters have an internal and external cylinder and are of a pressure-compensated design with the flow control valve downstream of the flow-indicating cylinder. Such designs are intended to deliver stable gas flow independent of back pressure from the destination of the oxygen flow. Comweld specifies their flowmeters as having an accuracy of ± 5% with the reading to be taken from the centre of the ball.[9]

Comweld calibrate the performance of their Ezi-flow devices when supplied with oxygen at a pressure of 400 kPa. Australian Standards for medical gas pipeline installations call for gas supplies to have a nominal working pressure of 415 kPa at each medical gas outlet,[10] but outlet pressures typically fall slightly when gas is flowing and often vary somewhat between different outlets and depending upon varying total combined flow demands of adjacent outlets. The hyperbaric chambers in our service have specifically regulated medical gas supplies which deliver oxygen and medical air to in-chamber outlets at a nominal 415 kPa above the ambient interior pressure of the chamber.

When medical flowmeters are used at sea-level atmospheric pressure, the Actual flow delivered (volume of gas at ambient pressure per unit of time) should be essentially the same as the Set flow on the flowmeter. In non-standard conditions however, many factors can impact Actual gas flow compared with those measured at the calibration conditions used to determine the 'Indicated flow' of an uncorrected flowmeter. These factors include gas supply pressure, delivery pressure,

Figure 1
Comweld Ezi-flow low (A) and standard (R) flow oxygen flowmeters



water vapour, temperature and, if the wrong flowmeter is used, density differences between gases (e.g., oxygen has a density 1.106 x the density of medical air).[11,12] There are established formulae for calculating the expected Actual flow through control valves and variable area flowmeters at operating pressures, temperatures and gas densities other than those for which the flowmeter was calibrated. The relevant formula depends upon the configuration of the flowmeter – whether the valve is upstream or downstream of the flow indicator tube. In devices such as the Ezi-flow, the principal zone of pressure drop from gas supply pressure to delivery pressure is through the control valve, which is a modified needle valve located downstream of the indicator tube. Such valves perform as 'critical orifices' in which flow velocity emitting from the orifice is constrained to the speed of sound. As a result, a 'choked flow' condition applies where the mass flow through the orifice remains constant despite changes in downstream pressure, provided the upstream pressure remains constant.[13] For Ezi-flow devices, choked flow calculations should provide a reasonable estimate of expected performance under hyperbaric conditions.

In our situation, we would expect that mass flow delivered at hyperbaric pressures would increase in direct proportion to the increase in supply pressure from its starting point at sea level of 515 kPa / 5.08 atmospheres absolute [atm abs].[14] Mass flow is directly proportional to surface equivalent flow at designated standard temperature and pressure conditions such as 'standard temperature and pressure' (101.3 kPa and 0°C) or 'normal' conditions (101.3 kPa and 15°C). As hyperbaric pressurisation increases gas density in direct proportion to chamber pressure, the volumetric, or 'Actual' flow inside the chamber will be calculated by dividing the surface equivalent flow by the chamber pressure, assuming surface pressure conditions are close to 'normal' sea level conditions and in all cases using absolute pressure measures and not differential.

This can be described by the formula: *Q2 = [Q1 (P3 / P1)]/P2*
Where:

Q1 is the indicated or set flow at normal sea level atmospheric pressure,
Q2 is the predicted Actual flow in the chamber.
P1 is oxygen supply pressure at sea level atmospheric pressure,
P2 is the hyperbaric chamber pressure,
P3 is the oxygen supply pressure at chamber pressure P2.

With all pressure measurements being in atm abs (sea level = 1 atm abs).

Using these equations at 2.8 ATA Actual flow = [Indicated flow x (6.88 / 5.08)] / 2.8 or ~48% of Indicated flow.

This simplified choked flow formula is based upon an assumption of dry gas and no significant temperature change. We believe this simplification is reasonable as, in practice, the temperature of gas exiting a medical flowmeter will trend towards the temperature of the copper tubing supplying the medical gas outlet and the metal valve controlling flow. As a result, the flow changes resulting from relatively minor changes in absolute temperature are unlikely to be clinically significant (e.g., a 10°K increase in temperature would result in only a 3% change in flow).

It is also important to note that a flowmeter valve such as in the Ezi-flow is not a simple critical orifice such as occurs when gas flow is controlled by a hole of critical diameter drilled through an orifice plate. In the Ezi-flow control valve, one would expect some pressure drop to occur through the gas flow channels of the device, with the result that the pressure drop across the components that act as a 'critical orifice' will be expected to be somewhat less than the total pressure drop from supply to delivery.

Given that formulae for gas flow are expected to be only generally predictive, we considered it important to measure Actual flows with appropriate methods to enable clear guidance for clinical decision making in cases where flow rates are clinically important such as for patients receiving HECMO. This may be especially important for neonatal and paediatric patients for whom small proportional changes in flow may have greater physiological impact.[15,16]

Methods

HYPERBARIC SAFETY ASSESSMENT (IN-VITRO)

A test equipment safety assessment was performed prior to commencing analysis of flow rates under hyperbaric conditions. The flowmeter testing set-up involved the Comweld Ezi-Flow Oxygen flowmeters (model numbers 515800 and 515824); 0–15 L·min^{-1} and 0–2.5 L·min^{-1} respectively, fitted on to medical oxygen outlets in a Fink Engineering triple lock hyperbaric chamber and a FlowAnalyzer™ PF-300 (IMT Analytics AG, Buchs, Switzerland) gas flow analyser (PF-300) designed for biomedical engineering testing of medical ventilators. This analyser had been previously validated for use and approved safe under hyperbaric conditions. We nevertheless also assembled a small version of a Douglas bag type gas collection system to enable cross checking of analyser readings against flows measured by capturing gas over a timed period and measuring it with a 500 ml gas volume calibration syringe as commonly used to calibrate spirometry equipment. The Ezi-flow flowmeters were connected to the flow analyser with disposable small bore oxygen tubing long used in hyperbaric conditions.

COMPONENT SELECTION

Flowmeter

Comweld Ezi-Flow flowmeters were selected based on their being the general-purpose oxygen flowmeters in current use in our hospital and within our hyperbaric chambers. These are 'ball-in-tube' or 'Thorpe tube' type flowmeters. The Comweld Ezi-Flow standard flowmeter has an indicated flow range of 0–15 L·min^{-1} and is typically used for adult patients at our centre. The Comweld Ezi-Flow low flowmeter has an indicated flow range of 0–2.5 L·min^{-1} and is our flowmeter of choice for paediatric cases. The manufacturer specifies both flowmeters as having an error range of ± 5%.[9]

Tubing

The connecting tubing selected for our analyses was medical grade oxygen tubing with a 7 mm outside diameter and 5 mm inside diameter. This is the standard tubing used in our institution for delivery of sweep gas during ECMO and was used with the modified Rotaflow I device when we delivered HBOT to patients on ECMO.[4–6]

Gas flow analyser

The PF-300 gas flow analyser utilised is calibrated and certified yearly by the manufacturer for high precision flow rate recordings and has been previously validated for safety and accuracy in hyperbaric conditions at our centre. The device's low flow inlet port is used to record flow rates in L·min^{-1}, up to two decimal places.

SET UP

The gas flow analyser was allowed to warm up for at least 20 minutes prior to commencing testing, to ensure running temperature and flow rate recording were stable.

For each flow rate tested, the desired flow was initially set at atmospheric pressure according to the Ezi-Flow flowmeter indicator, and then fine-tuned according to the flow displayed (to two decimal points) on the PF-300 gas analyser. Intervals of 0.30 L·min^{-1}, 0.60 L·min^{-1}, 0.90 L·min^{-1} and 1.20 L·min^{-1} were analysed using the low flowmeter and intervals of

3.00 L·min^{-1}, 6.00 L·min^{-1} 9.00 L·min^{-1} and 12.00 L·min^{-1} were analysed using the standard flowmeter.

The chamber was then pressurised at a rate of 10 kPa·min^{-1} from 101.3 kPa (1 atm abs) to 284 kPa (2.8 atm abs). Recordings of flow rate (L·min^{-1}), chamber temperature (°C) and humidity (%) were recorded at 10 kPa intervals. The chamber was subsequently decompressed, at a rate of 10 kPa·min^{-1}. The compression and decompression rates of 10 kPa·min^{-1} were chosen for comparative consistency. To confirm that the change in flow rate phenomena was not due to a faulty flowmeter, other flowmeters of same make and model were also tested to confirm consistent findings with the primary test flowmeters.

CROSS VERIFICATION

Flow rates displayed by the PF-300 analyser were cross verified with a Douglas bag test type procedure to confirm reliability at hyperbaric pressure. At interval pressure and set flow rate, oxygen gas was allowed to flow into an emptied reservoir bag for sixty seconds. Gas flow was then immediately closed off. The set-up included control valves to prevent gas loss. A 500 mL calibration syringe was used to extract and record the volume of gas that had entered the reservoir bag during the timed period enabling the Actual gas flow rate to be calculated prior to the next pressure change.

CALCULATIONS

Both percentage and absolute change in Actual gas flow rate from that at atmospheric pressure was calculated during compression, isopressure and decompression phases. The percentage difference between the flow rate during chamber compression and decompression was calculated.

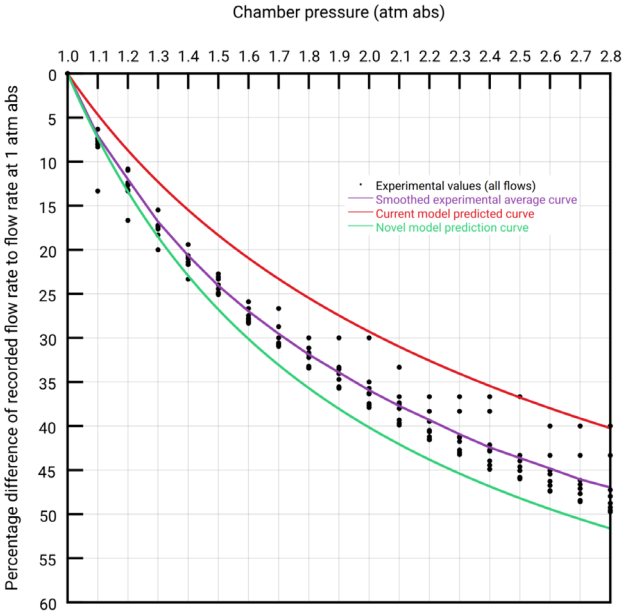
Results

Numerical results of the Actual gas flow rates through the standard and low flow assessments can be found in online *Appendix 1, and are presented graphically in online *Appendices 2 and 3, respectively .

STANDARD FLOW ASSESSMENT

Actual gas flow rates through the standard flowmeters reduced as the pressure in the chamber increased from 1 atm abs to 2.8 atmabs, characterised graphically by non-linear curves. At 2.8 atm abs flow delivered was approximately 50% less than set and indicated on the flowmeter (*Appendix 1).

Figure 2
Decrement in Actual flow from Ezi-flow (standard and low) oxygen flowmeter at hyperbaric pressures



LOW FLOW ASSESSMENT

The Actual flow of oxygen through the low flow flowmeter reduced and gradually tapered as chamber pressure increased in a similar fashion to that seen with the standard flowmeter. At the lowest flow rates we assessed (0.30 L·min^{-1} and 0.60 L·min^{-1}), reductions in oxygen flow rates of 40.0% and 43.3% were demonstrated respectively, whereas at all other flows approached a 50% reduction.

The percentage reductions of flow at various pressure intervals, are presented as a scatter plot in Figure 2 overlaid with the smoothed average, variable orifice-based prediction model and a new model based off the choked flow behaviour characteristics which was identified as appropriate for this design of flowmeter. Details of the modelling will be presented in a separate manuscript.

COMPRESSION VS DECOMPRESSION

The maximum differences in flow rates between chamber compression and decompression were a few percent at all but the lowest flows from the low flowmeter, where up to 22% discrepancy was demonstrated at 1.4 atm abs (*Appendix 3).

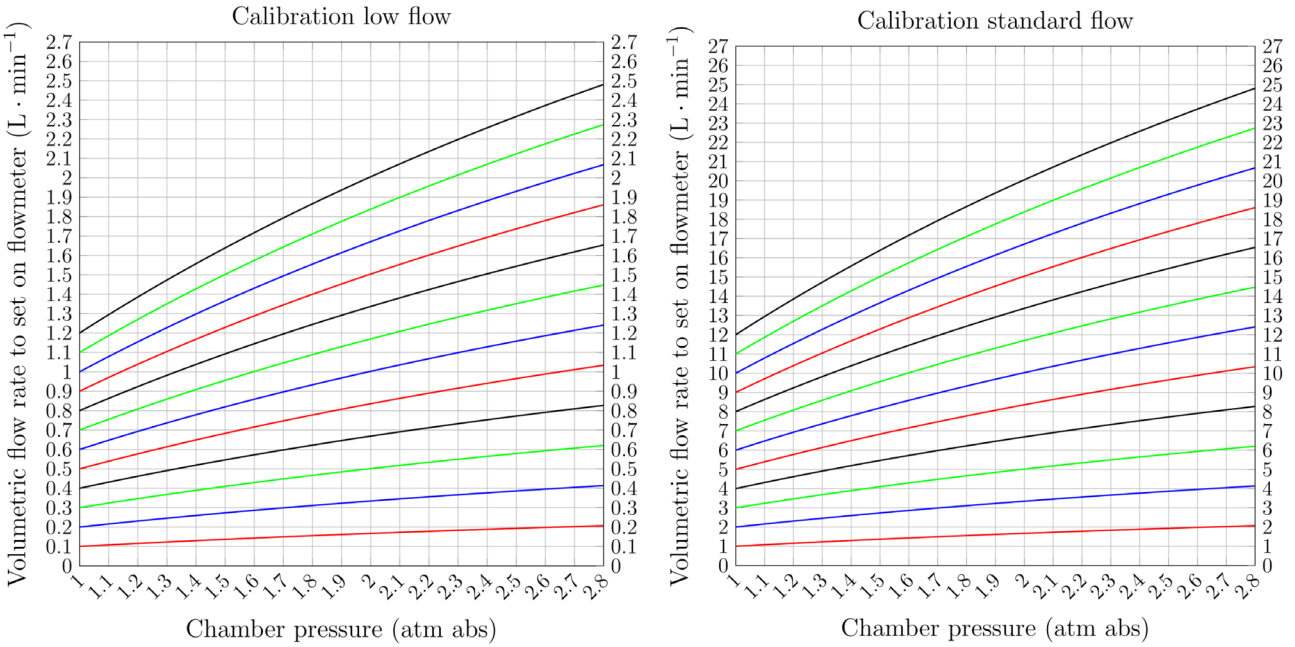
GAS ANALYSER CROSS VALIDATION

Douglas bag type testing at a variety of pressure and flow points cross-validated the performance of the PF-300 gas

***Footnote:** Appendix 1–3 are available online on our website https://www.dhmjournal.com/index.php/journals?id=418

Figure 3

Correction charts for clinical use of Ezi-Flow flowmeters in hyperbaric conditions at The Alfred, Bayside Health. To use the correction charts, select your desired Actual flow rate, e.g., 1.2 L·min^{-1}. On the Y-axis of the appropriate chart (standard or low flow), find the curve that begins at your desired Actual flow rate (e.g., 1.2 L·min^{-1}). Follow the curve to the pressure at which you will be operating (e.g., 2.8 atm abs). Move horizontally from this point to the axis on the right, which will indicate the flow rate you will need to set at normal atmospheric conditions in order to obtain your desired Actual flow rate at pressure (approximately 2.5 L·min^{-1} in this example)



analyser within the two decimal place/L·min^{-1} precision of this instrument.

CLINICAL CORRECTION CHARTS

For greater accuracy of gas flow via Ezi-flow flowmeters in our service, we developed correction charts for clinical use, using our test results and mathematical modelling (Figure 3). The mathematical model is based on mass choked flow behaviour; details are be reported separately in a dedicated manuscript. Importantly, these correction charts have been developed specifically for our local hyperbaric systems and may not be applicable to other chamber configurations.

Discussion

In normal clinical practice, decisions about and control of oxygen administration is often imprecise with tolerance of significant variability, with low flow anaesthesia and ECMO being examples of areas where more precise control is required. There is normally an expectation that displayed gas flows will be consistent with actual gas flow and the small differences resulting from definitional differences of what is 'sea level' or 'standard' or 'normal' gas supply conditions are generally ignored as too small to be relevant. Under hyperbaric conditions, however, much greater changes occur than are seen with atmospheric pressure variability and with altitude. This study demonstrates clearly the need to consider and allow for the changes associated with hyperbaric pressurisation.

FLOW RATE TRENDS

Our results confirm that Actual volumetric flow of oxygen falls substantially below the set flow rates as chamber pressure is increased, in a manner consistent with that predicted by the equation shown in the introduction above.

The low flowmeter was demonstrated to be susceptible to greater variations in flow rate with respect to chamber compression and decompression compared to the standard flowmeter which delivered relatively stable results. This is not unexpected given that increasing imprecision at low flows is a commonly observed phenomenon in syringe driver pumps and in pressure control regulators, likely driven by mechanical factors such as 'stiction' preventing truly linear control of the movement of components within devices. In our installation, the supply pressure of medical gases into the hyperbaric chamber is controlled by variable output pressure regulators which are least accurate at low flows.

Although clinical utilisation of therapeutic oxygen is often pragmatic and imprecise, variability between flowmeter settings and Actual gas flow in a hyperbaric setting is particularly important to understand when delivering HBOT to a patient supported by ECMO. The determining factor for appropriate fresh gas flow into an ECMO oxygenator is

to remove carbon dioxide at rates that maintain the desired PCO_2 for the patient. These flow rates deliver multiple times more oxygen than is required for metabolic demand and CO_2 clearance therefore drives the fresh gas flow requirements during ECMO.

A minor but consistent trend observed during testing was movement of the bobbin. The bobbin was observed to move upward, but only very slightly, as chamber pressure increased. This is not inconsistent with the decreased volumetric flow and decreased gas velocity being balanced out by increased gas density. Given that small movements of the bobbin are sometimes seen in non-hyperbaric clinical practice, likely due to supply pressure variations and flow harmonics in the gas pipeline, this finding was concluded as having insignificant clinical impact for hyperbaric practice. Importantly, the mathematical model used in the development of the correction charts in Figure 3 works irrespective of errors that could be associated with this observation, as bobbin mechanics are subject to local drag, weight and buoyancy forces, whereas the model we have used is not.

GAS SUPPLY PRESSURE

The Comweld Ezi-flow flowmeters are designed for an inlet pressure of 400 kPa,[9] and our service has pressure compensation regulators which maintain flowmeter supply pressures at the gas port at the appropriate level above chamber pressure. Chambers without this feature will experience different patterns of variability in gas flow rates compared to what is reported here.

LIMITATIONS

Testing was performed in the hyperbaric chamber at The Alfred (Bayside Health). Variations in hyperbaric chamber designs may mean that the equations described here may not be applicable to hyperbaric chambers with differences in configuration, or without instruments to maintain steady supply pressure.

Another potential limitation of this work could be the consideration that our testing was inconsistent with clinical use of the flowmeters e.g., the flow was set prior to starting compression and not adjusted, as would be done clinically if required, during pressurisation. However, given the slight increase in bobbin height, any adjustments to restore the bobbin back to baseline Set flow by an inside attendant would be in the downward direction, further reducing flow and exaggerating the direction of the trend which we have described.

Conclusions

Our study demonstrated a nonlinear inverse relationship between chamber pressure and actual gas flow delivered by both standard and low-flow Comweld Ezi-flow flowmeters under hyperbaric conditions. These very significant changes are consistent with a shifted hyperbolic or exponential decay type relationship as would be expected based on the flowmeters' control of flow being characterised as a mass choked flow phenomenon. To deliver clinically desired gas flow rates under hyperbaric conditions, appropriate performance testing of gas flowmeters is required. We have used performance data and mathematical modelling to develop correction charts for the clinical use of Ezi-flow flowmeters in our hyperbaric chamber.

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