Peak expiratory flow at increased barometric pressure: comparison of peak flow meters and volumetric spirometer

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ABSTRACT

Increasing numbers of patients are receiving hyperbaric oxygen therapy as an intensive care treatment, some of whom have pre-existing airway obstruction. Spirometers are the ideal instruments for measuring airway obstruction, but peak flow meters are useful and versatile devices. The behaviour of both types of device was therefore studied in a hyperbaric unit under conditions of increased pressure. It is important to have a non-electrical indicator of airway obstruction, to minimize the fire risk in the hyperoxic environment. The hypothesis was tested that, assuming that dynamic resistance is unchanged, both the Wright’s standard and mini-peak flow meters would over-read peak expiratory flow (PEF) under increased pressure when compared with a volumetric spirometer, as the latter is unaffected by air density. It was postulated that a correction factor could be derived so that PEF meters could be used in this setting. Seven normal subjects performed volume-dependent spirometry to derive PEF, and manoeuvres using both standard and mini PEF meters at sea level, under hyperbaric conditions at 303, 253 and 152 kPa (3, 2.5 and 1.5 atmospheres respectively; 1 atmosphere absolute = 101.08 kPa), and again at sea level. There was a progressive and significant decline in PEF with increasing pressure as measured by the spirometer (69.46±0.8% baseline at 303 kPa compared with 101 kPa), while the PEF meters showed a progressive increase in their readings (an increase of 7.86±1.69% at 303 kPa with the mini PEF meter). Using these data points, a correction factor was derived which allows appropriate values to be calculated from the Wright’s meter readings under these conditions.

INTRODUCTION

In view of the increasing number of patients who are receiving hyperbaric oxygen therapy (HBOT), we have assessed the performance of the Wright’s mini peak flow meter under the clinically relevant conditions of increased barometric pressure. This is a versatile and easily portable instrument for monitoring airway obstruction. It has been shown that a decrease in barometric pressure will alter the accuracy of this device, if uncorrected [1,2].

Until the late 1960s, hyperbaric medicine was largely confined to the treatment of divers who were suffering from decompression illness. Since then, HBOT has been advocated as an adjunctive intensive care therapy in an...
increasing number of conditions where tissue hypoxia is implicated, including carbon monoxide poisoning, radionecrosis, clostridial myonecrosis, chronic wounds and crush injuries [3]. HBOT is now an accepted therapy in these disorders, and the list is likely to grow as further indications are investigated.

Although airflow obstruction is a relative contraindication for HBOT, as applications for this therapy increase it becomes more likely that patients with airway obstruction will be exposed to increased ambient pressure. Currently, it is recommended that those with asthma, or airway obstruction which might lead to gas trapping, are excluded from self-contained underwater breathing apparatus (SCUBA) diving, and this has formed the traditional approach to acceptance for HBOT. Despite this consideration, many recreational divers have asthma, and the proportion who have asthma and who dive may even reach the predicted prevalence of asthma in the normal population [4]. Airway obstruction and gas trapping are recognized risk factors for barotrauma during the decompression from hyperbaric conditions [5]. As ambient pressure is decreased, gas will expand and must be equilibrated with the ambient pressure, or barotrauma will result. In the lungs, rupture of the substance of the lung and pneumothorax, pneumomediastinum or arterial gas embolism may occur. Increasingly, the benefits of HBOT will result in clinical situations where asthmatic and other subjects with airway obstruction are considered for treatment. Such individuals require monitoring under hyperbaric conditions in order to conduct such treatment safely. Monitoring should ideally be non-electrical in order to minimize the risk of fire in the hyperoxic environment of HBOT. Both the Wright’s peak flow meter and the mini-peak flow meter are therefore useful in this situation, as they require no electrical supply, and are reliable and portable [6,7].

We investigated the changes in peak expiratory flow (PEF) at simulated depth and compared the performance of Wright’s peak flow meter and Wright’s mini-peak flow meter with that of a rolling-seal spirometer. We hypothesized that the peak flow meters would over-read, as they are density-dependent, while the spirometer should correctly indicate a decrease in peak flow as the density of air rises at increased pressure [8,9], if dynamic airways resistance remains unchanged.

METHODS

The protocol was approved by the South East Sydney Area Health Service Research Ethics Committee, and informed consent was obtained from all subjects. The experiment was carried out in the Department of Hyperbaric Medicine at the Prince of Wales Hospital.

Subjects

Seven subjects (three female), mean age 36.4 years (range 29–42 years), were studied. All had been passed as being fit to be subjected to hyperbaric pressures according to the ‘Fitness to Dive’ Medical Examination based on the South Pacific Underwater Medical Society Diving Medical Examination [10]. None had evidence of asthma, airway obstruction or other concurrent medical problems. Baseline spirometry of all subjects was within 15% of predicted. Three were ex-smokers, each with less than a 5 pack year smoking history (1 pack year = 20 cigarettes per day for 1 year).

Measurements

Spirometry was performed using a specially adapted Morgan Spiroflow rolling seal spirometer (P. K. Morgan, Chatham, U.K.) within the chamber, interfaced with an external personal computer (Digital Corp.) using a validated program [11] written to integrate signal into flow volume curves for expiration. From these data were derived PEF, expiratory flow volume curves and forced expiratory volume (FEV1). PEF readings were also measured on both the Wright mini-peak flow meter and the standard Wright peak flow meter (Clement Clarke, London, U.K.).

Protocol

Subjects performed two expiratory spirometric manoeuvres, and took the best of three PEF readings on each of the peak flow meters at approximately sea level (1 atmosphere absolute; = 101.08 kPa). The chamber was pressurized with air to 303 kPa (3 atmospheres; equivalent to an approximate diving depth of 20 m), and the readings were repeated. The chamber was then decompressed to 253 kPa (2.5 atmospheres), and the same measurements repeated, and again at 202 kPa (2 atmospheres), 152 kPa (1.5 atmospheres) and finally again at 101 kPa (1 atmosphere). The procedure took approx. 15 min for each level, and the pressure profile lay within the accepted limits of depth and time in order to minimize the risk of decompression illness.

Statistical analysis was performed using t-tests for paired data, while multiple comparisons were analysed by analysis of variance (ANOVA) with post-hoc corrected t-test, or by comparisons of area under the curve [12].

RESULTS

No subject noted untoward effects during the experiment except for slight lightheadedness. Euphoria was noted in one subject.
Increasing pressure led to a progressive fall in both FEV₁ and PEF as measured by the spirometer (Figures 1 and 2). In contrast, both peak flow meters demonstrated a slight increase in the measured PEF with increasing pressure (Figure 1). FEV₁ decreased significantly when comparing sea-level values with those at 202, 253 and 303 kPa (sea-level, 3.78 ± 0.27 litres; 303 kPa, 3.44 ± 0.24 litres, means ± S.E.M.; P < 0.005 by ANOVA). The forced vital capacity increased slightly with pressure (sea-level, 4.51 ± 0.35 litres; 303 kPa, 4.69 ± 0.34 litres; P < 0.001 by paired t test).

Modelling the relationship of PEF with pressure using results from either the spirometer or the PEF meters indicated that all relationships were linear, with a positive slope for the PEF meters and a negative slope for the spirometer (Figure 1).

**DISCUSSION**

A progressive fall in PEF with increasing pressure was demonstrated by the spirometer, which, being a volumetric instrument, is unaffected by changes in air density. Under conditions of 303 kPa, PEF decreased by approx. 30%. These spirometric PEF values are in agreement with previous studies [8,9], and would fit the curve which Schilder et al. [13] constructed for PEF using gases of differing densities at sea level (Figure 3). This would suggest that gas density is the principal factor dictating the decrease in spirometric or ‘true’ PEF that was demonstrated in the present study. Figure 1 demonstrates that there is a linear relationship between pressure and change in PEF for both types of instrument. From Boyle’s law, absolute change in pressure is linearly related to volume or density, and this would explain such a relationship.

The Wright peak flow meters over-read by approx. 40% at 303 kPa compared with the values derived from the spirometer. Thus, to derive a correction factor for using PEF indicated by a PEF meter, change in pressure can be plotted against difference between true and recorded PEF (as given by the spirometer and mini-peak flow meter), as in Figure 4. This plot uses data derived from the present study and from the previous study under hypobaric conditions [1]. These data suggest that an equation can be derived that applies to both hypo- and hyper-baric situations and describes the line in Figure 4:

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\text{Change in mini-PEF reading to give ‘true’ PEF (\%) = } -77.92 \times \log(\text{pressure}) - 1.61
\]

where pressure is expressed in absolute atmospheres (1 absolute atmosphere = 101.08 kPa).

As there is close agreement between the Wright mini-PEF and standard PEF meters, the equation might be
Figure 4 Plot of pressure against percentage change required to derive ‘true’ peak flow, as measured by the spirometer, from the Wright’s mini-PEF meter values

Data were derived from the present study (○) and from Thomas et al. [1] (□), using identical devices. The equation derived to describe this curve is presented in the Discussion section. Conversion factor: 1 absolute atmosphere (ATA) = 101.08 kPa.

used for both devices, but the standard PEF meter was not studied under hypobaric conditions. The above equation differs from the correction factor derived in the previous study [1], as it is now apparent that the relationship between pressure and correction to mini-PEF readings is curvilinear, and can be applied to both hyper- and hypo-baric situations (Figure 4).

It should be realized that the ‘true’ PEF will fall under hyperbaric conditions, and such a fall in true PEF may be critical in those with airway obstruction. Airflow limitation is a recognized risk factor for barotrauma. PEF is, however, a measure limited to the early phase of the expiratory manoeuvre, and so may underestimate airway obstruction in those with chronic obstructive pulmonary disease. These individuals show greater attenuation of flow with increased dynamic resistance at the end of expiration, which cannot be measured by the PEF meter. The risks and benefits of HBOT should be carefully considered in such patients. Spirometers are not usually used in this setting unless specially adapted, and, if monitoring of a patient with airway obstruction is required, a correction factor should be applied to PEF meter readings. The peak flow meter remains a versatile instrument, and for subjects who are undergoing therapy in a hyperbaric chamber the results should be adjusted for ambient pressure.

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