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TECHNICAL NOTE

Portable peak flow meters: physical characteristics, influence of temperature, altitude, and humidity

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Portable peak flow meters: physical characteristics, influence of temperature, altitude, and humidity. O.F. Pedersen, M.R. Miller, T. Sigsgaard, M. Tidley, R.M. Harding. ©ERS Journals Ltd 1994.

ABSTRACT: Little is known about the linearity of portable peak flow meters, or about physical gas factors affecting peak expiratory flow (PEF) readings. We therefore tested five portable peak flow meters of three types in an altitude chamber (sea level to 5,500 m) and in a climate chamber at sea level (7–37°C) to determine the influence of the physical conditions of the gas on the reading of the meters.

The nonlinear response of the variable orifice meters was confirmed and, when this was corrected for, the readings of these meters were found to be significantly reduced by higher altitude and lower temperature. The readings from a turbine type of peak flow meter were not affected by altitude but were reduced at low temperature. A mathematical model for the variable orifice meters could correct for both their nonlinear behaviour and the effect of gas density (altitude, temperature and humidity). The model showed that correction is not necessary for the differences in gas conditions between calibration and taking of measurements under normal laboratory conditions. All the meters tested had impedances higher than recommended (0.05 kPa·l^{-1}·s) and this may influence PEF at high flows. The mean uncorrected PEF of six healthy subjects when measured with a Mini Wright peak flow meter at sea level and at 3,000 m fell by 5%, but the mean corrected PEF increased by 12%. This increase in PEF was about 60% of that predicted for fully density-dependent flow and agreed with the findings of other similar studies.

We conclude that orifice meters give satisfactory PEF readings at different altitudes and temperatures, provided adequate correction is made for their nonlinearity and the influence of gas density.
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The extensive use of portable peak flow meters for monitoring of peak expiratory flow (PEF) in clinical and occupational medicine makes it important to standardize the performance specification of such meters. The repeatability of variable orifice meters is very good [1–3], but their response is not linear, with considerable overestimation of PEF in the mid-range [2]. For comparison of results obtained by different types of meter, it is essential to correct for any nonlinearity. Little is known about the impedance of such meters, which may influence PEF measurement, or about their response to changes in temperature, altitude and humidity. The purpose of this study was to obtain such information for different types of peak flow meters under different ambient conditions.

Material and methods

Testing of meters

We used a computerized pump, as used by MILLER *et al.* [2], the performance of which is not influenced by temperature changes in the range of the measurements made. We tested five commercially available meters that could be divided into three groups: 1) variable orifice meters - mini Wright (Airmed, Clement Clarke International Ltd), Vitalograph (Buckingham, UK), fdE peak flow meter (Ferraris Medical Ltd, London, UK); 2) a fixed orifice meter - Assess meter (Healthscan, Inc. NJ, USA); and 3) a turbine meter - Micro Medical (Micro Medical Ltd, Rochester, UK).

The meters were mounted on the outlet of the pump and pressure was measured just upstream to the meter by use of a Statham pressure transducer. This transducer was calibrated by use of an incline plane, and had an amplitude gain of less than 2% at 20 Hz. A cusp volume time profile [2], with adjustable amplitudes from 60 to 800 $l\cdot\text{min}^{-1}$, was used for the pump to generate the desired PEF. This profile gives maximum flow in the middle of the manoeuvre and, thus, avoids abrupt acceleration (the rise time from 10 to 90% PEF was >500 ms). Corresponding values of true PEF (generated by the pump), PEF measured on the meter, and upstream pressure at PEF were recorded.

Table 1. – Experimental conditions in the climate chamber

	Day 1	Day 2	Day 3
Temperature °C	7	21	37
RH %	64	35	16
Pressure kPa	100.4	100.4	102.9

RH: relative humidity measured by a Vaisala instrument (HMI 32, Helsinki, Finland).

The meters were tested in a hypobaric chamber at the RAF Institute of Aviation Medicine in Farnborough. The temperature was 21°C and relative humidity was between 42 and 44%. Tests were performed at ambient pressures of 100 kPa, corresponding to sea level, and at 90, 80, 70, 60 and 50 kPa, the latter corresponding to about 5,500 m. At 70 kPa (3,000 m) a full range of flows was tested for the Mini Wright peak flow meter and the Micro Medical turbine. At the other pressures all of the meters were tested with only one flow (299 *l*·min^{-1}). The Mini Wright peak flow meter and the Micro Medical turbine were tested with the same equipment in a climate chamber at the University of Aarhus under the three conditions described in table 1.

With the chamber set to 37°C the effects of humidity and temperature on Mini Wright meters were tested, respectively, by discharging the pump through the meters having filled it with fully saturated air (relative humidity (RH) 94%) from a water containing bag-box system lined with blotting paper, or by cooling the meters to 10°C and discharging ambient air through the meters.

PEF at altitude

The effect of altitude on peak flow readings in human subjects was examined in the hypobaric chamber using six healthy subjects (1 female, 5 males; mean age 34 yrs, range 22–54 yrs), who each performed five peak flow manoeuvres with a Mini Wright meter at sea level and at a simulated altitude of 3,000 m.

Data analysis

All mathematical and statistical calculations were performed using the SPSS/PC+program (SPSS Inc, Chicago, USA). Significant differences were accepted based on a probability value of less than 0.05. We used regression analysis, analysis of variance, and nonparametric tests.

The error of the meters was defined as the measured peak expiratory flow (PEFM) minus true peak expiratory flow (PEF), and was plotted as a function of PEF for the different measuring conditions. The errors were compared with a standard proposed by a PEF working group [4], which currently states that the reading should be within ±5% or ±5 *l*·min^{-1} of the true flow, whichever is larger.

In order to correct for the nonlinearity of the meters and the influence of gas density, the data from the variable orifice meters were fitted to a model describing PEF as a function of PEFm (*cf.* Appendix). This model assumes that flow through the meter is turbulent and that changes in response due to altitude, temperature, and humidity are mediated *via* changes in gas density. The density correction factor is the square root of the ratio of gas density (SQDR) between calibration and the new situation.

The impedance, which was defined as peak upstream (mouth) pressure divided by PEF, was calculated for the different meters and plotted against PEF. The impedances were compared with 0.05 kPa·*l*$^{-1}$·s, the upper limit suggested by a working group for the European Community for Coal and Steel (ECCS) [5].

Results

Testing of meters

Figure 1a shows the curvilinear error for measured flows (PEFm minus PEF) for the variable orifice meters at sea level, whereas the fixed orifice meter and the

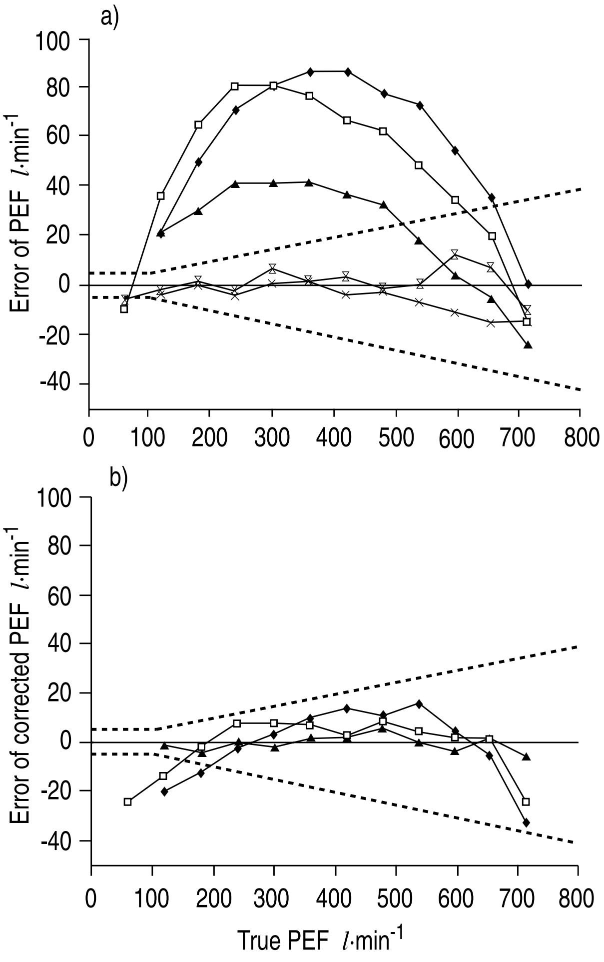

Fig. 1. – a) Errors of different peak flow meters expressed as measured minus true peak expiratory flow (PEF). b) Residual errors of the variable orifice meters defined as corrected minus true PEF. The dashed lines delineate the acceptable range of errors (±5% or 5 l min^{-1} of the true flow, whichever is larger) (*cf.* text). -□-: Mini Wright's; -▲-: Vitalograph; -◆-: Ferraris; -×-: Assess; -▽-: Micro Medical.

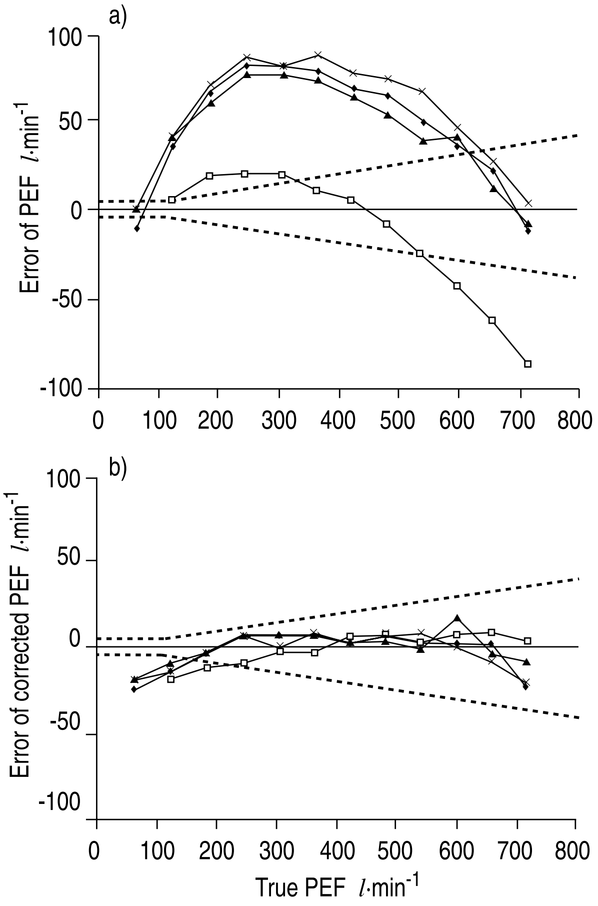

Fig. 2. – Temperature and altitude dependence of Mini Wright peak flow meter. a) Errors of measured peak expiratory flow (PEF) at different values of temperature (t) and pressure (P). b) Errors of corrected PEF. The dashed lines delineate the acceptable range of errors (±5% or 5 *l*·min-1 of the true flow, whichever is larger). –□– : t=21°C, P=70 kPa; –▲– : t=37°C, P=103kPa; –◆– : t=21°C, P=100 kPa; –×–: t=7°C, P=100 kPa.

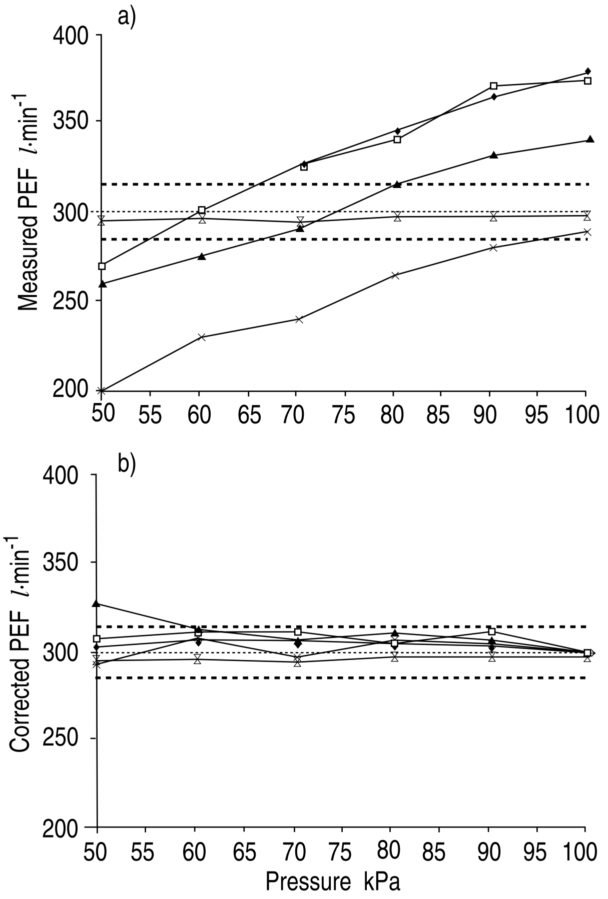

Fig. 3. – a) Measured peak expiratory flow (PEF); and b) corrected PEF at altitudes ranging between 5,500 m (50 kPa) and sea level (100 kPa) for different peak flow meters (*cf.* text). –□– : Mini Wright; –◆– : Ferraris; –⧖– : Micro Medical; –▲–: Vitalograph; –×–: Assess; --- :Acceptable PEF range (±5% of the true flow);······: true PEF=299 *l*·min-1.

turbine meter were satisfactory except for the lowest value measured with the turbine. When the variable orifice meters were corrected for nonlinearity according to Equation (4) in the Appendix (fig. 1b) their results were acceptable for PEF above 200 *l*·min-1, but in the low flow range the residual error for the Mini Wright and Ferraris meters was larger than acceptable.

Figure 2a shows the effect of temperature and altitude on Mini Wright meters. The differences between the curves disappear (fig. 2b) when the correction in the Appendix is applied with proper values for temperature and pressure substituted into Equation (5). The fixed orifice meter readings followed the same pattern with a reduced reading for higher temperatures and lower pressure, but this could be similarly corrected. The turbine was much less affected by altitude than any of the orifice meters, with a minimal under-reading for high flows at 3,000 m. Low temperature, however, caused an under-reading of 10–50 *l*·min-1, mostly at high flows, where high temperature also seemed to have an effect in the same direction.

The results above only describe the influence of pressures at sea level and about 3,000 m. The results of measurements at a number of altitudes at 299 *l*·min-1 are shown in figure 3a. The turbine meter readings are all well within the accepted limits. For the other meters, the values all fall with decreasing pressure in a parallel way. The parallel shift reflects the initial differences between the meters due to nonlinearity. When the readings for all the orifice meters are corrected firstly by a factor to normalize the initial values for nonlinearity and then by a factor equal to the square root of the ratio of air density at sea level to air density at the given altitude, the results are within the accepted limits, as shown in figure 3b.

Examination of three different Mini Wright meters at 37°C and at a flow of 299 *l*·min-1 did not give different readings when the meters were cooled to 10°C in a refrigerator, 362.0±2.7 (mean±SD) *versus* 365.0+6.2 *l*·min-1, respectively, (p=0.2, Mann Whitney). The readings were not affected by changing the air in the pump from 37°C saturated with water vapour (RH=94%) to 37°C dry (RH=16%), 360.2±0.4 *versus* 361.7±7.5, respectively, (p=0.8, Mann Whitney).

The impedances for all the meters are shown in figure 4. The Mini Wright and Vitalograph show reduction

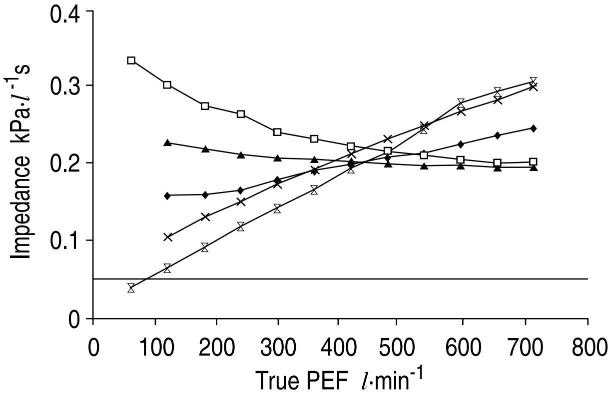

Fig. 4. – Impedance of portable peak flow meters. The solid horizontal line is the accepted maximum according to [5]. -□- : Mini Wright; -▲- : Vitalograph; -◆- : Ferraris; -×- : Assess; -⧖-: Micro Medical; —— : upper ECCS limit. PEF: peak expiratory flow; ECCS: European Community for Coal and Steel.

in impedance with increasing flow, indicating that the increase in the size of the orifice counterbalances the rise in impedance caused by increased flow across the orifice. For the fixed orifice meters, such as the Assess and turbine meter, the impedance increased with flow, as expected. However, the impedance of the Ferraris meter was more like that of a fixed orifice device.

PEF at altitude

The results of the human study are shown in table 2. The fall in uncorrected mean PEF of 5% was significant (analysis of variance: p=0.0001), but when the PEF was corrected for density effects it had, instead, increased significantly by 12% (p=0.0001).

Discussion

Testing of meters

We have presented the first data comparing the effect of altitude and temperature on the readings from different peak flow meters. Our findings mean that these instruments can be used under a wide range of ambient conditions and still obtain true readings, with the use of a mathematical model to correct the data. Investigators can now make an informed choice concerning the ideal instrument for their needs and how best to ensure correct readings.

We have previously presented a model for the correction of variable orifice meter readings that was based on the precise measurement of the various components of the meters and the mechanical performance of their springs [3]. The present study does not involve dimensional measurements of the individual meters, but the parameters that describe the new model are derived from the statistical analysis of the relationship between measured flow, true flow, driving pressure at peak flow, and knowledge of gas density. Application of the Bernoulli equation implies assumptions about losses that cannot be calculated, but only determined experimentally [6]. These losses may be pooled into a discharge coefficient, to be multiplied by the true area of the orifice, to obtain the area of the jet through the orifice determined by the present method. Therefore, the constants derived by the statistical method that we have used here may not necessarily be equal to the constants derived by the previous method, although they give acceptable fits to the measured curves. The goodness-of-fit to the model is expressed by the residual standard deviation, which is the standard deviation of the measured minus the predicted peak flow readings. This standard deviation is only 3.2 l·min^{-1} for the Vitalograph meter, but somewhat higher for the Mini Wright meter and for the Ferraris meter at 12.0 and 15.2 l·min^{-1}, respectively. Figure 1 showed that flows after correction were underestimated in the lower flow range by the latter two meters, and the error in this region accounts for the higher standard deviation. For the Mini Wright meter this was probably due to the fact that the scale is not completely linear, as assumed in the calculations. There is a slightly shorter distance between the marks up to 350 l·min^{-1}, with a zero reading about 4 mm from the proximal end of the variable orifice. For the Ferraris peak flow meter, our analysis indicated a poorer correlation between pointer position and distending pressure than for the two other meters, indicating that Hooke's law may not apply as well to the bending of a blade as to the stretching of a spring.

Because the primary purpose of this study has been to evaluate how variable orifice meters work, and how portable peak flow meters are influenced by altitude, temperature and humidity, we examined only very few meters of each kind. Therefore, the accuracy of the

Table 2. – PEF at altitude

				Measured PEF l·min^{-1}			Corrected PEF l·min^{-1}		
Sbjt.	Sex	Age yrs	Ht cm	Sea level	3000 m	%Δ	Sea level	3000 m	%Δ
MM	M	43	188	521 (16)	506 (14)	-3	463 (19)	534 (21)	15
MT	M	29	169	713 (7)	678 (5)	-5	707 (9)	792 (7)	12
DP	M	22	177	720 (9)	671 (5)	-7	716 (13)	781 (9)	9
VL	F	26	168	489 (13)	489 (11)	-0	426 (15)	511 (16)	20
OP	M	54	178	676 (17)	631 (17)	-7	658 (22)	719 (26)	9
DG	M	31	167	526 (5)	489 (10)	-7	469 (6)	511 (14)	9
Mean (SD)				608 (106)	577 (92)	-5 (3)	573 (134)	641 (137)	12 (4)

Results are mean±SD. PEF: peak expiratory flow; %Δ: percentage change; M: male; F: female.

meters examined in this study may not necessarily be generally valid for all meters of the same kind, although it has previously been shown that the variation in reading between meters of the same type is small [2]. We found that the fixed orifice meter examined (Assess) did not need any correction when used under normal circumstances, whereas SHAPIRO *et al.* [7] found that the Assess meter generally underestimated PEF at values below 350 $l\cdot\text{min}^{-1}$ and overestimated at higher flows. They tested the meters in series with a pneumotachograph with human subjects blowing through the combination of both meters. It is possible that their results include an error estimate due to the effect one meter may have on the performance of the other, and also there may be frequency response differences between the meters. The turbine meter in this study did not need any correction, although MILLER *et al.* [2] previously found a slight underestimation at high flows.

In the model presented here, the function of the meters is expressed by three well-defined constants, but correction of existing meters should probably be based on polynomial fits of recorded flows to true flows for a sufficient number of meters to take into account small differences between meters and situations where the model fit is not completely adequate. The square root of the gas density ratio (SQDR) seems to be the main factor accounting for the influence of altitude, temperature and humidity on orifice meters, indicating that any effect of temperature or humidity can be best explained by its consequent effect on gas density. From this, one can easily calculate whether it is necessary to correct for the influence of difference between two gases. For air with 50% saturation with H_2O at sea level and alveolar gas of 5% CO_2, 15% O_2, 80% N_2 and 100% saturated with H_2O at sea level, the correction factor is 0.97 [8], which would counterbalance the correction of ATPS to BTPS (ambient temperature and pressure, saturated, to body temperature and pressure, saturated). The exact magnitude of this is not known because of lack of data about the gas temperature in the meter. Change of humidity alone, from dry to fully saturated air at 37°C in the climate chamber, would be predicted to give a 1.2% lower reading, but we were unable to detect this small change. The influence of temperature and altitude on the turbine meter is less than for the orifice meters, and may be caused by the mechanical properties of the vane and change in viscosity of the gas in addition to density.

In order to record a true PEF, the impedance of the meter must not be so big that it influences the measurement itself. The impedances of the different meters are too high to satisfy the requirements of the ECCS standard of 0.05 $\text{kPa}\cdot l^{-1}\cdot\text{s}$. The impedances of the variable orifice meters do not vary much with flow and are in accordance with those of MILLER *et al.* [2], who did not specify the flow at which they were measured. For a fixed orifice with turbulent flow through it, pressure is proportional to the square of the flow, and so the impedance should be proportional to flow. We found this to be the case for the fixed orifice meter and the turbine meter, and JONES *et al.* [9] found this to be true in a study of another make of fixed orifice meter. For the variable orifice meters, the impedance does not increase with flow, because the larger opening counteracts the increase of pressure. The maximum impedance we found of 0.3 $\text{kPa}\cdot l^{-1}\cdot\text{s}$ at 700 $l\cdot\text{min}^{-1}$ will create a back pressure of 3.5 kPa. At high flows, the back pressure can, therefore, be considerable with some of the meters, and this may be sufficient to influence PEF because of the force-velocity properties of the respiratory muscles [10]. At lower flows, as in the case of obstructive lung disease, the back pressure is smaller, and any influence on peak flow will probably be less. Further work is needed to clarify whether the observed impedance of the meters could be limiting PEF.

Impedance is the sum of the resistances due to elastance, friction and inertia. The elastance in our experiments will be negligible because it is mostly related to gas compression. Because our measurements were performed using a cusp-shaped flow profile, which progressively accelerates up to PEF [2], the impedance described above is comprised mostly of frictional resistance. The ECCS working group standard [5] allows for an inertia of 0.001 $\text{kPa}\cdot l^{-1}\cdot\text{s}^2$. With an average PEF of about 600 $l\cdot\text{min}^{-1}$ and a 10 to 90% rise time of 60 ms (unpublished observation from the present study) the volume acceleration would be approximately 130 $l\cdot\text{s}^{-2}$, creating a back pressure of 0.13 kPa. This is small compared with the maximally allowed resistive pressure of 0.5 kPa at 600 $l\cdot\text{min}^{-1}$. The inertia of these meters is related to the mass of the moving parts of the meters. This has not been measured, but can be assumed to be negligible because the moving parts of the meters have very little mass.

PEF at altitude

Our results for PEF in humans at sea level and at 3,000 m are consistent with those of THOMAS *et al.* [11], and FOSTER and PARKER [12], who made empirical corrections without paying attention to causal relationships. If the PEF out of the lungs is turbulent or determined by the wave-speed flow limiting mechanism, then the maximal increase in true PEF due to change in gas density can be estimated from SQDR [13, 14], which for an altitude of 3,000 m equals $\sqrt{(100.4/70)}=1.20$, corresponding to a 20% increase in PEF. We found a mean increase in PEF of 12±4% (table 2). The reason for this lower than theoretical increase in PEF may be that there are viscosity-dependent pressure losses in the airway, creating a smaller pressure at the choke points, and consequently smaller wave-speed flows [15]; or, the force-velocity properties of the respiratory muscles may limit the ability to achieve wave-speed at PEF when breathing a low density gas. In a previous unpublished study, we used a pneumotachograph to measure density dependence of PEF in 15 healthy subjects of similar age when breathing a mixture of 21% O_2 in He at sea level. In that study, we found an increase by 34±8% out of the maximum theoretical increase by 63% (SQDR=1.63 [16]). The ratios of observed increase in PEF to predicted increase were roughly the same in the two studies, suggesting that similar mechanisms operate to limit PEF at altitude and when breathing a low density gas mixture at sea level.

We conclude that the variable orifice meters show the previously described systematic errors in their readings, and that these can be corrected for. We have developed a mathematical model to explain the function of variable orifice meters, and their readings can be corrected for changes in altitude, temperature, and gas composition by reference to the square root of the ratio of gas densities. In ordinary laboratory working conditions such adjustments are not necessary. The impedances of all the meters were higher than the current recommendation, and it is possible that this may make it difficult for some subjects to record true peak flow values, especially at high flows, but more information is needed about this.

Appendix

Correction of flow from variable orifice meters

In the Mini Wright and Vitalograph meters, a diaphragm loaded by a coiled spring is positioned as a piston in a pump. During the blow, it opens up a variable orifice, the size of which is proportional to the distension of the spring. Following Hooke's law, the orifice size will be proportional to the force applied to the spring. The orifice is a slit with a moving pointer that indicates the maximal aperture obtained during a given blow. The slit is supplied with a nearly equidistant scale, with units expressed in $l \cdot \text{min}^{-1}$. In the Ferraris meter, the spring-loaded diaphragm is replaced by a metal blade. This blade bends, giving increased tension with increased opening of the variable orifice, which is curved to fit the movement of the peripheral end of the blade. The meter is supplied with an equidistant scale.

Airflow through a variable orifice peak flow meter is governed by the Bernoulli equation:

$$P_{\text{PEF}}=0.5\times\rho\times\text{PEF}^2/A^2 \qquad (1)$$

where P_{PEF} is the driving pressure at peak flow, ρ is the density of the gas, PEF is the true peak expiratory flow, and A the area of the orifice. As explained above, P_{PEF} is proportional to the magnitude of the variable orifice, and can be written as $P_{\text{PEF}}=K_1\times A$, where K_1 is a constant.

Around the piston of the meter there is a leak with constant dimensions=A_0. This leak decreases mechanical friction but has to be taken into account in the equation, which by inclusion of A_0 and substitution of $P_{\text{PEF}}=K_1\times A$ becomes:

$$A=0.5\times\rho\times\text{PEF}^2/(K_1\times(A+A_0)^2) \qquad (2)$$

If Equation (2) is solved for PEF, we get:

$$\text{PEF}=(A+A_0)\times(2\times A\times K_1/\rho)^{0.5} \qquad (3)$$

If the scale along the variable orifice is linear, then measured peak flow (PEFm) will be proportional to the magnitude of this orifice and we get $\text{PEFm}=K_2\times A$. If this equation is used to substitute for A in Equation (3), then the corrected PEF (PEFm), if the constants A_0, K_1 and K_2 are known, is given by:

$$\text{PEFc}=(2\times K_1/(\rho\times K_2))^{0.5}\times[\text{PEFm}^{1.5}/K_2+A_0\times\text{PEFm}^{0.5}] \qquad (4)$$

In order to determine the constants A_0, K_1, and K_2, the following procedures were undertaken:

1. The coefficients of $\text{PEFm}^{1.5}$ and $\text{PEFm}^{0.5}$ were obtained by a multiple linear regression analysis, with true peak flow as the dependent variable and measured peak flow raised to 1.5 and 0.5, respectively, as the independent variables, with the curve forced through the origin.
2. As $P_{\text{PEF}}=(K_1/K_2)\times\text{PEFm}$, we obtained K_1K_2 from a linear regression forced through the origin of P_{PEF} as a function of PEFm.
3. For the given ambient pressure and temperature, ρ was calculated from a combination of Boyle's and Charles' laws:

$$\rho=1.293\times B\times 273/(T\times 101.3) \qquad (5)$$

where the constant 1.293 is the density of air in $\text{kg}\cdot\text{m}^{-3}$ at 273° Kelvin and a pressure of 101.3 kPa, B is the ambient pressure (kPa), and T the ambient temperature (° Kelvin).

The constants A_0, K_1 and K_2 are finally determined, by first finding the proper value of ρ from Equation (5), then K_1/K_2 from the regression analysis under Point 2, and finally substituting into the coefficients of Equation (4), determined by the regression analysis under Point 1. For the three variable orifice meters, these constants were determined to be:

	A_0 cm^2	K_1 kPa·cm^{-2}	K_2 $l\cdot\text{min}^{-1}\cdot\text{cm}^{-2}$	RSD $l\cdot\text{min}^{-1}$
Mini Wright	0.25	1.42	435	12.0
Vitalograph	0.41	1.45	448	3.2
Ferraris	0.30	1.56	477	15.2

RSD: residual standard deviation.

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References

1. Gardner RM, Crapo RO, Jackson BR, Jensen RL. Evaluation of accuracy and reproducibility of peak flow meters at 1,400 m. *Chest* 1992; 101: 948–952.
2. Miller MR, Dickinson SA, Hitchings DJ. The accuracy of portable peak flow meters. *Thorax* 1992; 47: 904–909.
3. Pedersen OF, Miller MR. Tests of portable peak flow meters by explosive decompression. *Eur Respir J* 1994; to be published.
4. Quanjer PhH, *et al.* (eds). Peak expiratory flow. Draft conclusions and recommendations of a Working Party of the European Respiratory Society. *Eur Respir J* 1994; to be published.
5. Quanjer PhH, *et al.* (eds). Standardized lung function testing. Lung volumes and forced ventilatory flows. 1993 Update. *Eur Respir J* 1993; 6 (Suppl. 16): p.29.

6. Streeter VL. Fluid Mechanics, 4th edition. NY, McGraw-Hill Book Co. 1966; p.420.
7. Shapiro SM, Hendler JM, Ogirala RG, Aldrich TK, Shapiro MB. An evaluation of the accuracy of Assess and Mini Wright peak flow meters. *Chest* 1991; 99: 358–362.
8. Radford ER Jr. The physics of gases. *In*: Handbook of Physiology. Section 3. Vol. I. Washington DC, American Physiological Society, 1964; pp. 125–152.
9. Johns DP, Abramson M, Bowes G. Evaluation of a new ambulatory spirometer for measuring forced expiratory volume in one second and peak expiratory flow rate. *Am Rev Respir Dis* 1993; 147: 1245–1250.
10. Hyatt RE, Flath RE. Relationship of airflow to pressure during maximal respiratory effort in man. *J Appl Physiol* 1966; 21: 477–482.
11. Thomas PS, Harding RM, Milledge JS. Peak expiratory flow at altitude. *Thorax* 1990; 45: 620–622.
12. Foster P, Parker RW. Peak expiratory flow at high altitude. *Lancet* 1983; ii: 100.
13. Dawson SV, Elliott EA. Wave speed limitation on expiratory flow: a unifying concept. *J Appl Physiol: Respirat Environ Exercise Physiol* 1977; 43: 498–515.
14. Pedersen OF. Physiological determinants of peak expiratory flow. *Eur Respir J* 1994; to be published.
15. Pedersen OF, Castile RG, Drazen JM, Ingram RH Jr. Density dependence of maximum expiratory flow in the dog. *J Appl Physiol: Respirat Environ Exercise Physiol* 1982; 53: 397–404.
16. Schilder DP, Roberts A, Fry DL. Effect of gas density and viscosity on the maximal expiratory flow-volume relationship. *J Clin Invest* 1963; 42: 1705–1713.