Eur Respir J, 1995, 8, 849–855
DOI: 10.1183/09031936.95.08050849
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European Respiratory Journal
ISSN 0903 - 1936

TECHNICAL NOTE

Frequency response of variable orifice type peak flow meters: requirements and testing

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Frequency response of variable orifice type peak flow meters: requirements and testing. O.F. Pedersen, T.R. Rasmussen, S.K. Kjaergaard, M.R. Miller, Ph.H. Quanjer. ©ERS Journals Ltd 1995.

ABSTRACT: Little is known about the response of variable orifice peak flow meters to high frequency flow input. The purpose of this study was to define and test dynamic requirements for such peak flow meters.

In a population sample we measured peak expiratory flow (PEF), rise time (t_r), from 10–90% PEF and the duration of the flow in excess of 97.5, 95 and 90% of PEF, by use of a carefully calibrated Fleisch pneumotachograph with known and adequate frequency response. Three peak flow meters (Mini Wright, Vitalograph and Ferraris) were tested with an explosive decompression calibrator adjusted to values for PEF and t_r as close as possible to the 95th and 5th percentile values, respectively, both for males and females, and with peak durations between 5 and more than 100 ms.

The 95th percentile values of PEF were 597 L·min^{-1} for females and 894 L·min^{-1} for males. The 5th percentile values of t_r were, respectively 55 and 45 ms. The duration of flow in excess of 95% PEF was longer than 10 ms in 99% of the subjects. For all meters, the deviation of PEF corrected for alinearity were less than 5% at a peak duration of 10 ms.

We conclude that PEF, rise time, and peak duration can be used for description of dynamic properties of variable orifice meters, and that the tested meters had a satisfactory frequency response for recording PEF in mostly normal subjects.
Eur Respir J., 1995, 8, 849–855.

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Keywords: Dynamic response
peak expiratory flow
peak flow meters

Received: November 21 1994
Accepted after revision February 26 1995

The study was supported by the European Community for Steel and Coal (agreement No. 7280/03/056) and the European Economic Community (agreement MAT1-CT 93032).

The widespread use of portable peak flow meters for clinical, occupational, and epidemiological purposes has made it necessary to establish calibration standards to be used for quality control for the manufacturers, and to ensure for the users that the values obtained can be used in treatment plans and for comparison between studies. The orifice type peak flow meters seem to have an excellent repeatability. Until recently, the scales have not been calibrated in terms of true flow, but this can easily be done [1].

Previous calibration studies have been performed by use of slowly rising flows [1]. Little is known about the response of the meters to higher frequency content in the input. Due to the nature of the meters, conventional testing by means of sine wave inputs with increasing frequencies cannot be used. The purpose of the present study is, therefore, to present and test an alternative method to determine whether the dynamic response of the peak flow meters is satisfactory.

The study had two parts. In the first part, we tried to define the requirements to be met by a peak flow meter. This was done by analysis of data from subjects who performed peak flow manoeuvres with a linear, low-resistance pneumotachograph, with known and satisfactory frequency response. For these subjects, the 95th percentile of peak expiratory flow (PEF), the 5th percentile of rise time (t_r) from 10–90% of PEF, and PEF duration were determined to define the requirements. In the second part, we tested different makes of variable orifice peak flow meters for adequate response to these values and different durations of the peak ("dwell time").

Methods

Subjects

The subjects participated in a previous study of maximal expiratory flow-volume curves obtained in a body plethysmograph [2]. Two hundred and fourteen subjects (89 females, aged 19–64 years (39±15 yrs) (mean±SD) and 125 males, aged 18–73 yrs (41±15 yrs)), 129 of whom were lifetime nonsmokers and 85 smokers and ex-smokers, were selected from 512 subjects who replied to an invitation sent to 1,309 randomly chosen subjects drawn by lottery from the city register. The subjects answered a questionnaire about health problems, especially respiratory symptoms and smoking habits (the (BMRC) questionnaire [3]) and underwent a medical examination. In addition to the measurements mentioned below, the following personal characteristics based on the answers to the questionnaires and the medical examination entered the analysis: sex, age, height, weight, chronic bronchitis, asthma, smoking habits in terms of daily tobacco consumption (DTC), pack-years (PY = DTC/20 × number of years smoked).

Ethics

The studies were approved by the Local Ethics Committee, and informed consent was obtained from all participants.

Equipment

We used an unheated Fleisch type pneumotachograph with a diameter of 5 cm, normally used by Vitalograph Compact (Buckingham, UK). The pressure across the pneumotachograph head was measured by a Validyne MP45 transducer (Northridge, Ca, USA) with a ±0.2 kPa diaphragm, *via* 10 cm long connecting tubes with 3 mm internal diameter. The pneumotachograph head was provided with a conical inlet containing a wire screen. The signal from the transducer was low-pass filtered at 40 Hz (no attenuation at 20 Hz) and led to an IBM AT3 computer supplied with an A/D conversion board (Dash-16, Metrabyte, Taunton, Ma, USA). For the measurements in subjects, the sampling rate was adjusted to be 400 samples·s^{-1} for the first 100 ms, and 100–150 samples·s^{-1} in the following period. For the measurements of frequency response, the signal was low-pass filtered at 60 Hz and sampled at 1,000 Hz for the first 100 ms. The body temperature, and pressure saturated with water vapour (BTPS) correction factor was determined experimentally by comparing integrated expired mouth flow with integrated flow into the plethysmograph, where the subjects were seated. It was ensured that the forced vital capacity (FVC) manoeuvres began and ended with complete relaxation of the respiratory muscles, and the two measured volumes, therefore, could be considered identical. The mean value was found to be 1.05, somewhat lower than traditionally calculated [4], possibly due to heating of the pneumotachograph. Data acquisition and calculation was performed with Asyst software, (version 1.56, McMillan, Ca, USA).

Static calibration was performed in the following manner: flow from a vacuum cleaner, with the hose on the exhaust side, could be regulated by use of a special transformer. Through a three-way stopcock and *via* a wide bore tubing (diameter=3.5 cm) the flow could be led through the pneumotachograph into a 50 L plastic bag. The vacuum cleaner was started at a given voltage. When flow was steady, the stopcock was turned to direct flow through the pneumotachograph and into the bag. Due to the low resistance in the system, this would lead to a step change in flow to a level that did not change notably during the sampling time, which was determined by the computer. After some time, the stop-cock was again turned, and the bag was emptied through a gas meter to give the exact volume. True flow was calculated as volume divided by time. This was carried out for a range of flows between 0 and 16 L·s^{-1}. Daily calibration of the system was performed by use of an explosive decompression device [5, 6], delivering a known volume (approximately 8 L) of air, having a rise time from 10–90% PEF lasting about 40 ms, and with a PEF of 732 L·min^{-1} in the 1988 part of the study and 1,068 L·s^{-1} in the 1992 part. From volume and time, the computer determined the calibration constant by the integration procedure [7].

The frequency response of the system was determined under the assumption that the pneumotachograph and connections behaved like a perfect second order electromechanical system (with resistance, capacitance and inertance in series). In that case, resonance frequency and damping factor can be determined from the response to a step change in flow [8] (see Appendix). The step change in the present study was created by explosive decompression of the calibrator, where the cone in the outlet valve (fig. 1), which determines the rise time, was replaced by a cylinder, permitting an opening of the

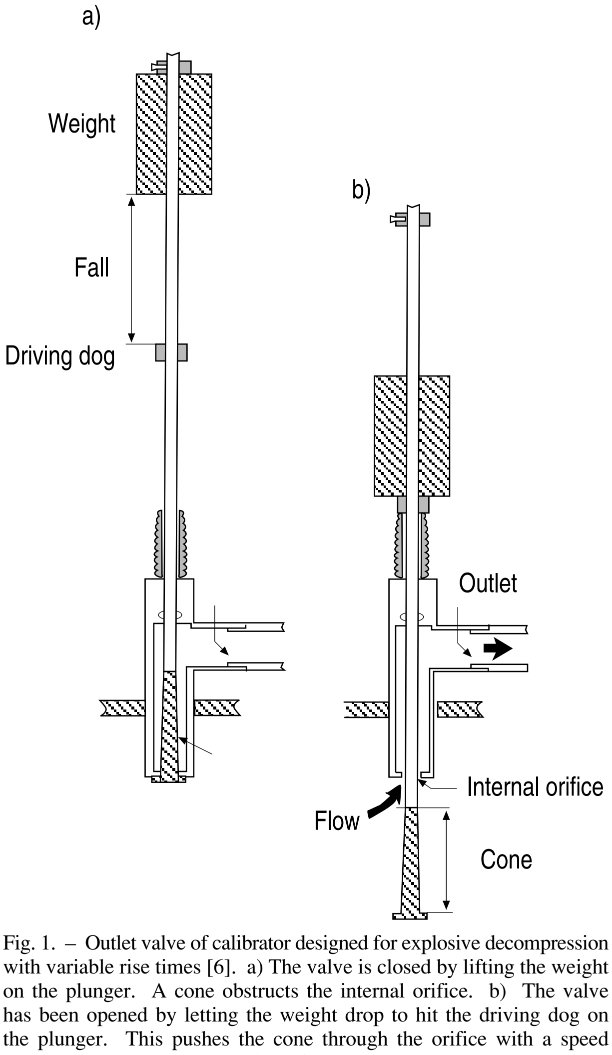

Fig. 1. – Outlet valve of calibrator designed for explosive decompression with variable rise times [6]. a) The valve is closed by lifting the weight on the plunger. A cone obstructs the internal orifice. b) The valve has been opened by letting the weight drop to hit the driving dog on the plunger. This pushes the cone through the orifice with a speed that depends on the height of the fall. The rise time also depends on the shape of the cone. To create a step increase in flow, the cone was replaced by a cylinder with the same dimensions as the shaft of the plunger. Different "dwell times" were generated by putting sleeves of different lengths on the shaft above the cone. This creates a partial obstruction after the initial full opening of the valve.

valve in less than 1 ms. From the response to this step change, a curve showing amplitude gain as a function of frequency of a sine-wave flow change was calculated, as described in the Appendix. The resistance of the pneumotachograph-mouthpiece assembly was determined at 12 L·s^{-1}.

Measurements in subjects

The subjects were seated and performed three or more vital capacity manoeuvres. At least three satisfactory curves, as judged from the appearance of the maximum expiratory flow-volume curves, were stored in the computer.

PEF was chosen as the highest flow among the flow values recorded during the technically satisfactory forced expirations. As shown in figure 2, the corresponding rise time (t_r) between 10–90% PEF was calculated and so were the durations of the flows in excess of 97.5, 95, and 90% PEF, in order to obtain indices for the duration of the peak ("dwell times"). An interpolation procedure secured minimal errors most importantly when PEF occurred after the first 100 ms, and the sampling rate decreased to 100–150 samples·s^{-1}.

For the statistical analysis we applied the SPSS/PC package (Norusis, Chicago, IL, USA). A p-value less than 0.05 was considered statistically significant.

Test of the peak flow meters

Three different meters were tested: Mini Wright (Airmed, Clement Clarke International Ltd), Vitalograph (Buckingham, UK), fdE peak flow meter (Ferraris Medical Ltd, London, UK). For the testing, we used the calibrator on which the same pneumotachograph as used in the population study was mounted on the outlet, and in series with that the peak flow meter to be tested. The dynamic properties of the entire system were tested as described for the population study. Different dwell times could be obtained by putting sleeves on the piston of the calibrator (*cf.* fig. 1), so that, after the initial opening, a further descent of the piston would cause the sleeve to partially obstruct the outlet.

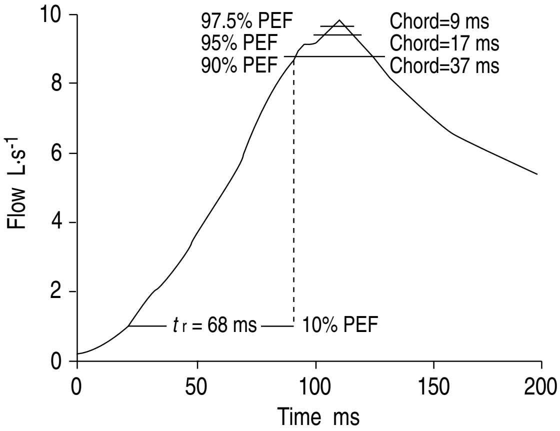

Fig. 2. – The first 200 ms of flow from a forced vital capacity manoeuvre. Rise time (t_r) is the time from 10–90% peak expiratory flow (PEF). The duration of flows in excess of 97.5, 95 and 90% PEF are determined by the lengths of the respective chords, *i.e.* the lines joining corresponding points on the flow-time curve (*cf* text).

By using outlets and cones of different dimensions with and without sleeves, it was possible to create different peak flows and rise times. The settings actually used depended on the findings in the population study. The test values were the 95th percentile of PEF, and the 5th percentile of t_r found for males and females. For each dwell time, three measurements were performed. The ratios of the meter readings to true PEF measured by the pneumotachograph were calculated and then divided by the similar ratio for the longest dwell time (>100 ms). In that way, the influence of errors due to the inherent scale inaccuracy of the meters [1] was removed, and the results could be compared nondimensionally for the different dwell times shorter than 100 ms.

Results

Characteristics of the pneumotachograph used in the population study

The steady flow calibration of the pneumotachograph gave a linear response with r^2=0.9994, and the residual standard deviation (RSD) for a regression line through the origin was 0.11 L·s^{-1}. The dynamic response during the first 50 ms after the opening of the valve is shown in figure 3a. There is an overshoot with damped oscillations.

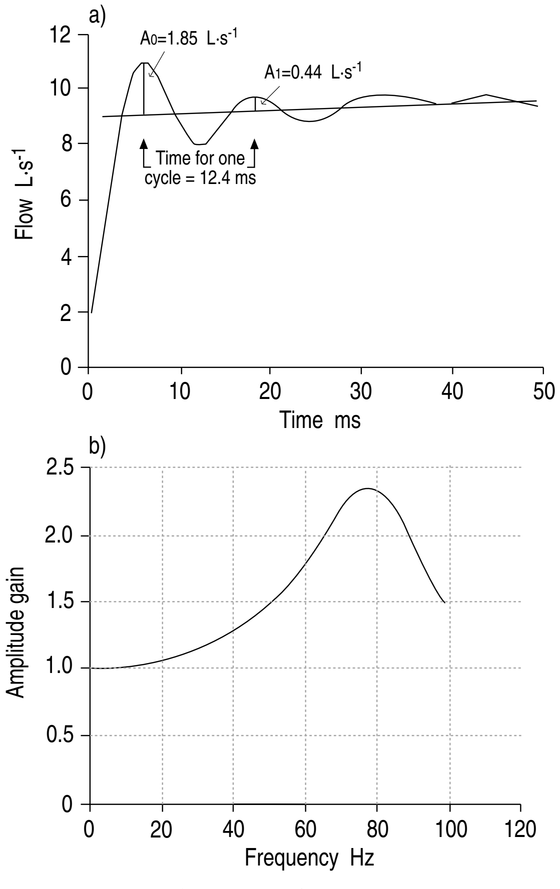

Fig. 3. – a) Dynamic response of the pneumotachograph to a step change in flow. b) Calculated amplitude gain as a function of frequency for the step change response above (*cf.* text).

After the step, there is a slightly sloping plateau considered of minor importance in the present context. Under the assumption of a 2nd order electromechanical system, the equation in the Appendix was used to calculate the amplitude gain as a function of frequency from the overshoots of the first and second oscillation and the time for one cycle. This is shown in figure 3b. The system is underdamped, with a damping factor of 0.22 and a damped resonance frequency of 81 Hz. The amplitude gain at 20 Hz is 6%, but at 10 Hz it is only 1%.

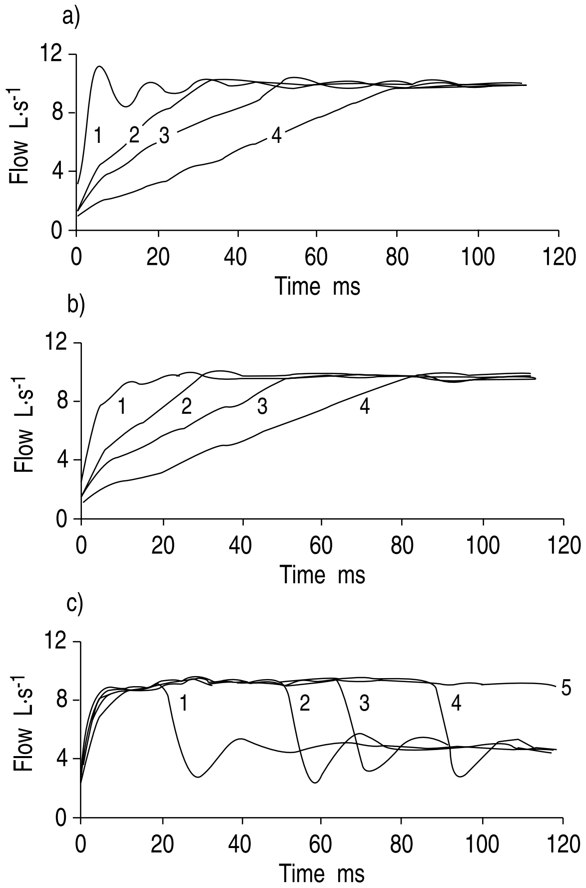

Fig. 4. – a) Response of pneumotachograph to flow profiles with different rise times. Curves Nos. 1–4 have rise times of 6, 28, 47, and 74 ms, respectively. b) Response of pneumotachograph in series with peak expiratory flow (PEF) meter to flow profiles with the same rise times as above. c) Response of pneumotachograph in series with PEF meter to flow profiles with short rise time and different dwell times. Curves Nos. 1–5 have dwell times of 16, 47, 60, 85 and >100 ms, respectively.

Table 1. – PEF, rise times and chord lengths ("dwell times") expressed as medians and critical percentile values (95th or 5th)

	Males		Females	
	Median	95th	Median	95th
PEF L·min^{-1}	636	894	427	597
	Median	5th	Median	5th
Rise time ms	70	45	88	55
Chord length ms				
97.5% PEF	14.7	7.0	17.4	8.7
95% PEF	22.8	12.5	28.6	15.6
90% PEF	39.8	20.5	49.9	25.1

PEF: peak expiratory flow.

Figure 4a shows the same time curve as in figure 3a, but three other curves with longer rise times are shown on top of it. These curves were obtained with the cone in the calibrator outlet valve, by adjusting the fall of the weight to 18, 10 and 3 cm. These curves indicate a very small overshoot for rise times greater than 30 ms and, consequently, a satisfactory dynamic response (see below).

The resistance of the pneumotachograph-mouthpiece assembly was 0.06·kPa·L^{-1}·s, slightly larger than the recommended value of 0.05 kPa·L^{-1}·s [4].

Measurements in subjects

Peak expiratory flow (mean±SD) measured with the pneumotachograph was 444 (±90) L·s^{-1} for the females and 660 (±126) L·s^{-1} for the males. Residuals were calculated as (observed - predicted PEF)/RSD [4] and were 0.62 (±1.44) for the females and 1.45 (±1.56) for the males, indicating higher than average PEF both for the females and the males.

Table 1 presents the medians and 95th percentile values of PEF in males and females. It also presents the medians and 5th percentile values for rise time and chord lengths at 97.5, 95, and 90% PEF. The duration of flow in excess of 90% PEF was longer than 10 ms in all subjects. The duration of flow in excess of 95% was longer than 10 ms in 100% of the females and in 98.6% of the males. The similar figures for 97.5% PEF were 90.8% of the females and 82.7% of the males.

Statistical analyses show negative correlation between PEF and t_r. The explained variation (r^2) for women was 38% but for men only 9%. Multiple linear regression analysis revealed that the dependence of t_r on PEF was also influenced by FEV$_1$, FVC and age, as it increased with FEV$_1$ and age, but decreased with increase of FVC. By including these variables, the overall r^2 increased from 24 to 33%. There was no influence of sex and smoking habits.

The chord lengths at 97.5 and 95% PEF decreased with increasing PEF, and increased with FEV$_1$, but did not vary with sex, age or smoking habits (r^2=0.15 and 0.21, respectively). At 90% PEF, the chord length in addition increased with age and decreased with FVC (r^2=0.30).

Examination of the peak flow meters

Flow-time curves obtained from the calibrator-pneumotachograph-Mini-Wright meter setup are shown in figure 4b. Curve No. 1 depicts the response to a step change. Curves Nos. 2, 3 and 4 were obtained with increasing rise times set with the calibrator. Curve No. 1 seems almost optimally damped. True PEF varies by less than 5% between the different curves. Figure 4c shows curves with different "dwell times" obtained for the same setup with different lengths of sleeves mounted on the plunger, as described in the Methods section. For the study of meter performance in relation to the percentile values for women shown in table 1, a combination of settings corresponding to curve No. 3 in figure 4b (t_r=47 ms) and sleeves 2, 3, 4 and 5 (no sleeve) in figure 4c was chosen. As curve No. 3 in figure 4b reaches a peak after approximately 50 ms, the corresponding dwell times by use of sleeves 2, 3, 4 and 5 in figure 4c are approximately 50 ms shorter than indicated by the times for the abrupt decrease of flow, *i.e.* about 5, 20, 40 and >100 ms. The settings for men were obtained by substituting a wider orifice and cone in the calibrator outlet. That would give approximately the same rise times and dwell times but higher PEF. Table 1 shows that the upper 95th percentile of PEF is 894 L·min^{-1}, but the scale of the meters all stop at 800 L·min^{-1}. Therefore, a lower value was chosen.

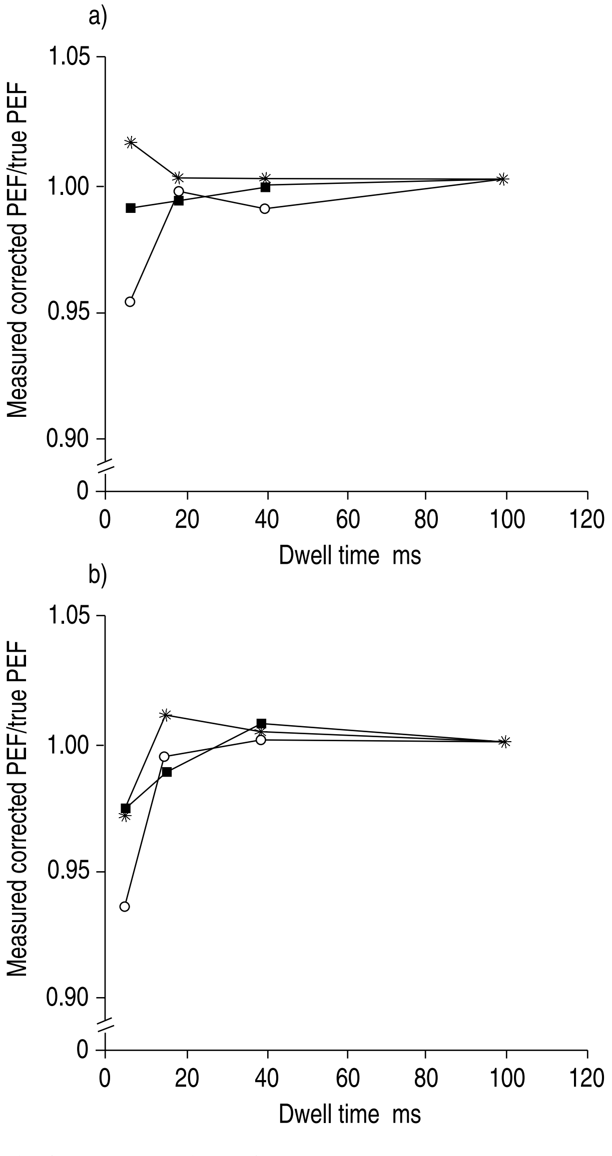

Fig. 5. – a) Peak expiratory flow (PEF) meter response to PEF=818±11 L·min^{-1} (13.6±0.2 L·s^{-1}) and t_r=40±4 ms, and different dwell times (compare with table 1, 95th percentile PEF and 5th percentile t_r for males). b) Similar response to PEF=573±8 L·min^{-1} (9.55±0.14 L·s^{-1}) and t_r=46±3 ms, and different dwell times (compare with table 1, 95th percentile PEF and 5th percentile t_r for females). ■: mini-Wright meter; ○: vitalograph meter; ✳: Ferraris meter.

The results of the meter testing are shown in figure 5. Figure 5a describes the results of the testing with settings adequate for approximately 95% of the males. A small but significant under-reading ($p<0.05$, one-way analysis of variance) is seen for all three meters, but only for the shortest dwell time, which is 5–10 ms. Figure 5b similarly describes the results with settings adequate for most females. Although the peak flow is higher, the deviation is not significant, except for the Ferraris meter that slightly over-reads. In both situations, the response appears satisfactory for dwell times longer than 10 ms.

Discussion

In order to determine whether a peak flow meter has a satisfactory frequency response, there are three main problems. The first is how to define frequency response. The second is to give quantitative values for the chosen parameters, and the third is to test the meters to see if the response is satisfactory. In the present approach, we have compared the meter response to the response of a pneumotachograph in series with the peak flow meter. The system could be defined as a 2nd order electromechanical system, characterized by total rise time to peak (or from 10 to 90% PEF), overshoot, damped resonance frequency, and degree of damping. The main contributions are from the tubing and the transducer. The flow head itself has a very short response time (2.2 ms) and can be considered a 1st order system [9]. The fact that the plateau had a slight positive slope in figure 2a, was considered insignificant in the present context. For a perfect 2nd order system, amplitude does not enter the determining equations, but for peak flow meters the acceleration (amplitude divided by total rise time) may influence the motion of the pointer. Therefore, PEF (amplitude) was also considered.

With regard to the definition of the requirements, results from a population studied previously were available. But it had to be ensured that the results were obtained with a satisfactory technique. Therefore, the pneumotachograph was retested with regard to linearity and frequency response. The linearity was excellent, probably due to the conical inlet and the upstream wire screen. The resonance frequency was sufficiently high, so that the rise times observed in the study could not be affected by this. Furthermore, underdamping will cause rise times to be underestimated and peak flow to be overestimated, and therefore imply more restrictive standards than necessary. However, figure 4a shows that with t_r of 28 ms, PEF was correctly measured. Only one person had t_r shorter than 28 ms. For these reasons, the measurements seem adequate. The negative correlations between t_r and PEF may be due to effort dependence of PEF, because larger effort may lead both to higher PEF and shorter t_r. The multiple regression analysis indicated that t_r and chord lengths correlated with PEF, FEV_1 and FVC, but not with sex and smoking habits. The opposite influences by FEV_1 and FVC remains to be explained. The population examined here does not include subjects with severe obstructive lung disease.

It is likely that the percentiles described in table 1 can be used as guidelines for setting standards for frequency response of peak flow meters needed for recording PEF in normal subjects. It is remarkable that more than 5% of men in the present study had peak flows too high to be measured with the meters. This is in accordance with results from a much larger study, where 3% of 6,227 males and none of 5,439 females had PEF larger than 800 L·s^{-1} (Quanjer, personal communication). There can be two reasons for this: firstly, the meters under-read at high flows [1, 10]. In the present study, at 812 L·min^{-1}, the mini-Wright meter under-read by 54 L·min^{-1}, the Vitalograph meter (with corrected scale) under-read by 48 L·min^{-1} and the Ferraris meter under-read by 31 L·min^{-1}. Another factor of importance may be that the meter resistance is too high. A recent study [10] has shown that, especially at high PEF, the back pressure may become substantial (3.5 kPa at 700 L·min^{-1}). This may make it impossible to achieve true peak flow when blowing into the meter. A third possibility seems less likely after this study, namely that at high PEF the meters under-read due to inadequate dynamic properties.

Very short dwell times in the upper mid ranges of PEF, cause slight under-reading of PEF (fig. 7). Contrary to expectations, this was less pronounced at higher PEF. The explanation could be that at very high accelerations the pointer gains so much kinetic energy that it continues to move, when the "piston" in the meter has reached its maximum excursion. But the errors were small.

In the original definition of PEF, it was assumed that the duration of the peak was 10 ms [11], but this statement has never been confirmed by systematic measurements. The present population study seems to support the assumption that 10 ms is a key value. Only very few subjects will get an under-reading by more than 5%, if the dwell time required by the meter is less than 10 ms.

It is concluded, that the dynamic response of variable orifice meters can be adequately described in terms of response to calibration flows with well-defined peaks and dwell times, obtained with given rise times. In the present study, three types of variable orifice peak flow meters responded adequately to PEF, rise times, and peak durations in a study population. The data from this study, however, are not representative for subjects with lung disease. Before setting definite standards, data from patients should also be considered.

Appendix

The step test method

An ideal system should reproduce a step signal, but in practice the response will be a damped oscillation around the flow level at the entrance to the recording system, where the step is generated. The system responds with ringing around this value, with amplitudes depending on the degree of damping of the system. In an overdamped system no oscillations will occur.

The damping factor, d, is a measure of how quickly the oscillation is damped. The damping factor is mathematically defined as:

$$d = \frac{k}{\sqrt{(4\pi^2 + k^2)}} \quad \text{where } k = \ln\left(\frac{A_n}{A_{n+1}}\right) \tag{1}$$

A_n and A_{n+1} are the amplitudes of two oscillations following each other in the same direction. The damping factor is zero when the two oscillations following each other are equal. On the other hand it approaches infinity when the ratio decreases towards zero.

The natural frequency f_n, is the system's resonant frequency if the system is undamped. The correlation between the natural resonant frequency and the damped resonance frequency f_d is:

$$f_d = f_n \sqrt{(1 - d^2)} \tag{2}$$

from which f_n can be calculated, if f_d and d are known. f_d is the frequency of the damped oscillations, which can be derived from the recording of the reaction to the step pulse as $1/t_d$, where t_d is the time for a damped cycle.

In the frequency domain, the amplitude of the oscillations ($H(\omega)$) relative to that of the step change can be described by the following equation:

$$H(\omega) = \frac{\omega_n^2}{\sqrt{((\omega_n^2 - \omega^2)^2 + (2d\,\omega_n\,\omega)^2)}} \tag{3}$$

where $\omega_n = 2\pi f_n$, and $\omega = 2\pi f$.

There is a relationship between the damping factor and the overshoot O_p above the level around which the oscillations occur:

$$O_p = \exp\left(-\frac{d\pi}{\sqrt{(1 - d^2)}}\right) \tag{4}$$

Equation (4) reveals that this overshoot can maximally be 1 (*i.e.* equal to the step change) when d=0. Equation (3) states that $H(\omega)$ becomes infinite when d=0. This discrepancy is explained by the fact that the step change does not continuously add energy to the system, whereas a frequency input will.

Acknowledgements: The authors gratefully acknowledge R. Peslin for review of the manuscript, T.F. Pedersen for Asyst programming, and J. Gormsen for help with the electromechanical equations.

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