Eur Respir J, 1996, 9, 828–833
DOI: 10.1183/09031936.96.09040828
Printed in UK - all rights reserved

European Respiratory Journal
ISSN 0903 - 1936

TECHNICAL NOTE

Peak expiratory flow and the resistance of the mini-Wright peak flow meter

O.F. Pedersen*, T.R. Rasmussen*, Ø. Omland*, T. Sigsgaard*, Ph.H. Quanjer**, M.R. Miller+

Peak expiratory flow and the resistance of the mini-Wright peak flow meter. O.F. Pedersen, T.R. Rasmussen, Ø. Omland, T. Sigsgaard, Ph.H. Quanjer, M.R. Miller. ©ERS Journals Ltd 1996.

ABSTRACT: The purpose of this study was to examine whether the resistance of the peak flow meter influences its recordings.

One hundred and twelve subjects, (healthy nonsmokers and smokers and subjects with lung diseases) performed three or more peak expiratory flow (PEF) manoeuvres through a Fleisch pneumotachograph with and without a mini-Wright peak flow meter added in random order as a resistance in series.

The results were as follows. In comparison with a pneumotachograph alone, peak flow measured with an added mini-Wright meter had a smaller within-test variation, defined as the difference between the highest and second highest values of PEF in a series of blows. The mean (SE) variation was 14 (1.3) L·min^{-1} and 19 (1.5) L·min^{-1} with and without meter added, respectively. In comparison with the pneumotachograph alone, the addition of the mini-Wright meter caused PEF to be underread, especially at high flows. The difference (PEF with meter minus PEF without meter) = -0.064 * (average PEF) -8 L·min^{-1}; R^2=0.13. The mean difference was -7.8 (1.1) %, and increased numerically for a given PEF, when maximal expiratory flow when 75% forced vital capacity remains to be exhaled ($MEF_{75\%FVC}$) decreased. The reproducibility criteria for repeated measurements of peak flow are more appropriately set at 30 L·min^{-1} than the commonly used 20 L·min^{-1}, because a within-test variation of less than 30 L·min^{-1} was achieved in 76% of the subjects without PEF meter inserted and in 88% with meter inserted, with no difference between healthy untrained subjects and patients.

The resistance of the peak expiratory flow meter causes less variation in recordings but reduces peak expiratory flow, especially at high values and when the peak is large as compared with the rest of the maximal expiratory flow-volume curve.

Eur Respir J., 1996, 9, 828–833.

*University of Aarhus, Dept of Environmental and Occupational Medicine, Aarhus, Denmark. **Dept of Physiology, Leiden University, Leiden, The Netherlands. +Dept of Medicine, University of Birmingham, Good Hope Hospital, Sutton Coldfield, West Midlands, UK.

Correspondence: O.F. Pedersen
IMA, Building 180
University of Aarhus
DK-8000
Aarhus C
Denmark

Keywords: Added resistance
peak expiratory flow
peak flow meters
peak flow reproducibility

Received: May 18 1995
Accepted December 26 1995

This study was supported by the European Steel and Coal Community (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 for quality control by the manufacturers, and to ensure that the values obtained can be used in treatment plans and for scientific purposes.

Peak expiratory flow (PEF) is the maximal flow achieved during an expiration delivered with maximal force, starting from the level of maximal lung inflation (European Respiratory Society (ERS), Peak Flow Working Group, to be published). In order to measure a correct PEF, three main requirements must be satisfied with regard to the recording equipment.

Firstly, the accuracy of the readings must comply with values agreed upon. 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], and the accuracy of the readings of more or less steady flows can be made satisfactory.

Secondly, the frequency response must be adequate. Previous calibration studies have applied slowly rising flows [1]. Due to the nature of the meters, their response to high frequency content in the input is not well described. Conventional testing by use of sine wave inputs with increasing frequencies cannot be used. Therefore, an alternative method has been developed. The meter response to a flow pulse was defined by the rise time from 10 to 90% of PEF, PEF itself and peak duration ("dwell time"). The pulse was delivered by an explosive decompression calibrator [2]. By use of an adequate pneumotachograph the test requirements have been defined from a population study of mostly normal people. This study indicated that in 95% of the subjects studied the frequency response of the variable orifice type peak flow meter seemed to be adequate with regard to rise time and peak duration. Subjects with lung diseases may have shorter rise times and dwell times [3] than healthy subjects. This should be taken into account in setting of the standards.

Thirdly, PEF should not be influenced by the internal resistance of the meters. A previous study [4] has shown that the resistance in different types of hand-held peak flow meters is up to six times the recommended value of 0.05 kPa·L^{-1}·s [5]. Such an increase in resistance creates a back pressure up to 3.5 kPa at high flows, and this may impede PEF, which is considered to be effort-dependent [6].

The purpose of the present study was to examine whether the added resistance of a typical variable orifice meter influences the magnitude of PEF when measured by a low resistance pneumotachograph with adequate linearity and frequency response.

Methods

Equipment

An unheated Fleisch type pneumotachograph with a diameter of 5 cm was used, together with a Vitalograph Compact (Buckingham, UK) unit. The pneumotachograph head is provided with a conical inlet containing a wire screen. The sampling rate was 100 Hz. A special device (fig. 1) was constructed so that a mini-Wright peak flow meter could be inserted upstream, in series with the pneumotachograph.

The linearity of the spirometer readings was tested in the range 120–900 $L \cdot min^{-1}$ with a servo-controlled precision pump, delivering slowly rising and decreasing flows with known peak flow values.

With a sampling frequency of 100 Hz the natural frequency of the system could not be tested properly by the step input test described previously [2]. Instead, the peak flows were read from the spirometer display for flow profiles with decreasing rise times (10–90% of PEF). These varied from 75 to 4 ms. The flow profiles were delivered by an explosive decompression device [2]. Firstly, the median PEF was measured for 10 blows with the rise time of 75 ms. Next, PEF was measured for 10 blows with each of the remaining rise times and the median values and ranges were calculated for the ratios of the measured flows to the median flow with the rise time of 75 ms. This gave an impression of the magnitude of error at the given shorter rise times. Finally, an estimation was made of whether the reading would be correct for peak flows with rise times in the range encountered in the population.

The resistance of a variable orifice meter varies with flow. In a previous publication [4], for a mini-Wright peak flow meter a curvilinear decrease was found from 0.3 $kPa \cdot L^{-1} \cdot s$ at 60 $L \cdot min^{-1}$ to 0.2 $kPa \cdot L^{-1} \cdot s$ at 700 $L \cdot min^{-1}$. At 600 $L \cdot min^{-1}$ it was 0.21 $kPa \cdot L^{-1} \cdot s$. To measure the resistance of the pneumotachograph assembly with and without the PEF meter included, an explosive decompression device was used to generate flow through the pneumotachograph assembly, which was connected to a Validyne MP45 transducer (Northridge, CA, USA). From here, the signal was amplified and fed to the Y-channel of an XY recorder (Graphtech WX2400, Japan). The pressure difference across the assembly was measured with another transducer calibrated with a water manometer and fed to the X-channel of the recorder. From the recorded pressure-flow curve, the pressure was read at 600 $L \cdot min^{-1}$, and the resistance calculated for the assembly with and without the PEF meter included.

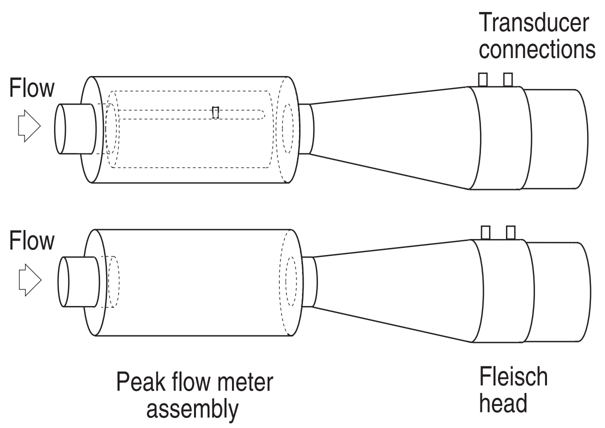


Fig. 1. – The pneumotachograph assembly with and without mini-Wright peak flow meter added as a resistance. The arrows indicate the direction of the flow.

Subjects

Seventy five healthy subjects (40 females and 35 males; median age 23 yrs, range 16–64 yrs), mostly agricultural students participating in an epidemiological survey, and 37 patients with lung diseases examined at the Department of Respiratory Diseases at the University Hospital of Aarhus (22 females and 13 males; median age 60 yrs, range 20–84 yrs) entered the study. The patients were divided into two groups, one with emphysema and chronic obstructive lung disease (COPD) (19 cases), and one with asthma (10 cases), fibrosis (2 cases), and other diseases (4 cases). In two of the patients with lung diseases, the diagnosis was missing. Emphysema was defined as increased total lung capacity (TLC), residual volume (RV) and RV/TLC, and only minor response to bronchodilator therapy and steroids. COPD was defined as chronic airway obstruction with only minor response to bronchodilator therapy and steroids. Asthma was defined as airway obstruction with spontaneous remissions or reversibility of >20% forced expiratory volume in one second (FEV_1) after bronchodilator therapy or steroids.

Ethics

The agricultural survey study was approved by the local Ethics Committee, and informed consent was obtained from all participants.

Procedure

The spirometer was calibrated before each measurement session by blowing five strokes of room air from a 1 L syringe through the pneumotachograph assembly. The ambient temperature was entered and the readings were automatically corrected for body temperature, atmospheric pressure and water saturation (BTPS).

The subjects were carefully instructed to perform correct peak flow manoeuvres, *i.e.* to breathe in maximally, rapidly insert the mouthpiece between the teeth, close the lips around it, and without losing air breathe out as rapidly, forcefully and completely as possible, with a start "as if you are going to blow out a candle at a distance of 2 m". In the standing position, three or more peak flow manoeuvres were performed through the pneumotachograph, with and without the peak flow meter inserted. Meanwhile, the subjects were continuously encouraged. The three highest values from correctly performed manoeuvres were recorded in the order by which they were obtained. Very few blew more than five times. A complete forced vital capacity (FVC) manoeuvre was only attempted during one or two blows in the first series. The remainder of the tests were completed after 2–3 s. The sequence of the blows with and without the meter were randomized. To minimize errors due to condensation effects and temperature change [7], the pneumotachograph was placed in a flow stream of a fan blowing ambient air for 15 s between the blows. The three highest PEF values were recorded from the printout of the Vitalograph Compact, and the highest value was chosen for the analysis. Furthermore, maximal expiratory flows when 75, 50 and 25% FVC remained to be exhaled ($MEF_{75\%FVC}$, $MEF_{50\%FVC}$, $MEF_{25\%FVC}$), age, height, sex and disease were recorded. $MEF_{75\%FVC}$, $MEF_{50\%FVC}$, $MEF_{25\%FVC}$ were recorded from the test without the meter, giving the largest sum of FEV_1 and FVC in accordance with the American Thoracic Society (ATS) criteria [8].

Calculations

ΔPEF was defined as the difference between the highest PEF in a series of blows and the second highest PEF, and is a measure of the within-test variation between blows. ΔPEF was calculated separately for blows with and without PEF meter and plotted as a function of the highest PEF. On these plots, lines describing 40–90 percentiles of ΔPEF were drawn to indicate the percentage of the population having values smaller than or equal to the ΔPEF indicated by the line. Furthermore, the number of acceptable tests was calculated for ΔPEF <20 L·min^{-1}, a selection criterion suggested by BURGE [9], and for ΔPEF <30 L·min^{-1}, which we found more realistic.

The error was defined as (PEF with meter - PEF without meter). The error was related to the average PEF of the two [10], to examine for systematic difference between the peak flow measurements with and without PEF meter inserted. The error was also related to PEF (without meter) and other indices from the expiratory flow-volume curve, to examine any association with the shape of the flow-volume curve, sex, age, lung disease, and the sequence of measurements.

The statistical examination involved analyses of variance, multiple linear regression analysis, and nonparametric tests (Statistical Package for the Social Sciences (SPSS)/PC+; SPSS Inc., Chicago, USA). A p-value equal to or less than 0.05 indicated significance.

Results

Test of the equipment

Linearity. For the pneumotachograph assembly without the PEF meter, the mean of the differences between measured flow and calibrator flow was 6.6 L·min^{-1} (range -1–13 L·min^{-1}). The percentage deviation was correspondingly 2% (range 0–4%). The difference between the calibrations with and without PEF meter was less than 1% at flows up to 600 L·min^{-1}. At 720 L·min^{-1} it was 3%, and at 900 L·min^{-1} it was 4%.

Frequency response. Figure 2 displays the influence of decreasing rise times on the spirometric readings of PEF. It can be seen that at rise times below 35 ms the median values increased with decreasing rise time. At 30 ms, the error was about 5% overestimation. In addition, the scatter of measurements increased. Both the overestimation and the scatter was considerable for rise times below 10 ms. With the PEF meter included, this picture did not change. With the explosive decompression calibrator, a flow profile with a rise time of 30 ms, which is shorter than the 5 percentile value in population studies [2, 3], PEF for five blows came to 632 L·min^{-1} (SE 2.7 L·min^{-1}) without the meter and to 628 L·min^{-1} (SE 3.6 L·min^{-1}) with the meter. This difference was not significant (p>0.05). This indicates that the presence of the PEF meter did not change the frequency response for this low rise time.

Resistance. The resistance of the pneumotachograph assembly without PEF meter included was 0.06 kPa·L^{-1}·s at 600 L·min^{-1}, which is slightly more than recommended [5]. With the meter included, it was 0.29 kPa·L^{-1}·s, *i.e.* about six times the recommended value. As the resistance of the PEF meter was 0.21 kPa·L^{-1}·s, the resistance of the assembly with the meter included was slightly larger than the sum of the two measured separately.

Measurements in subjects. The median value of ΔPEF without the meter was 15 L·min^{-1} (mean (SE) 19 (1.5) L·min^{-1}), which was significantly larger (p=0.004, Wilcoxon matched pairs signed-ranks test) than that with the PEF meter, which was 11 L·min^{-1} (mean (SE) 14 (1.3) L·min^{-1}). The standard deviations for all three measurements in a series without the meter was 20 L·min^{-1} (SE 1.3 L·min^{-1}). This was significantly larger (p=0.05) than that with the meter, which was 18 L·min^{-1} (SE 1.2 L·min^{-1}).

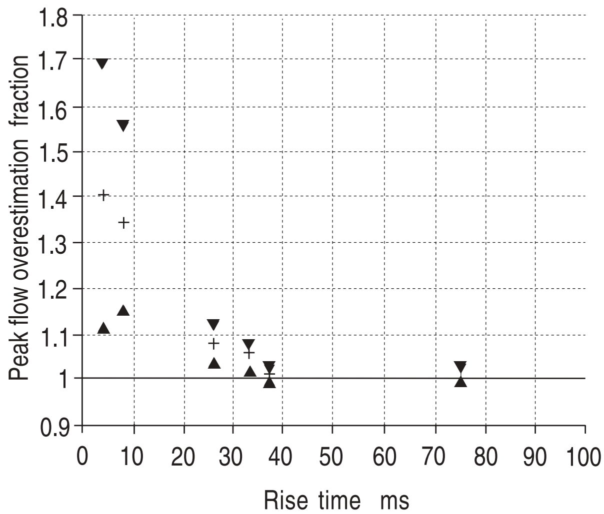
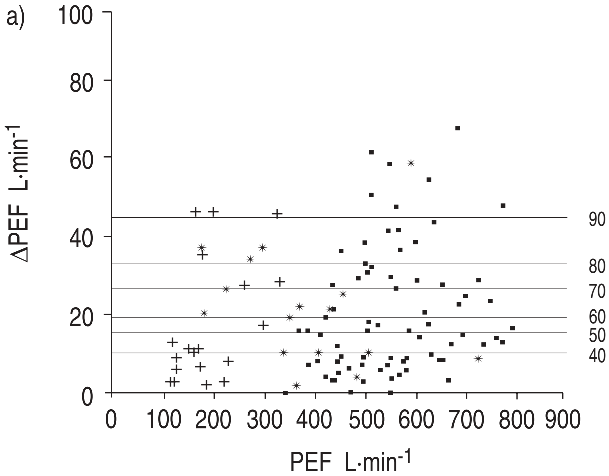


Fig. 2. – Peak flow overestimation for decreasing rise times of calibrator flow. +: median values of 10 blows; ▼: maximum values; ▲: minimum values.



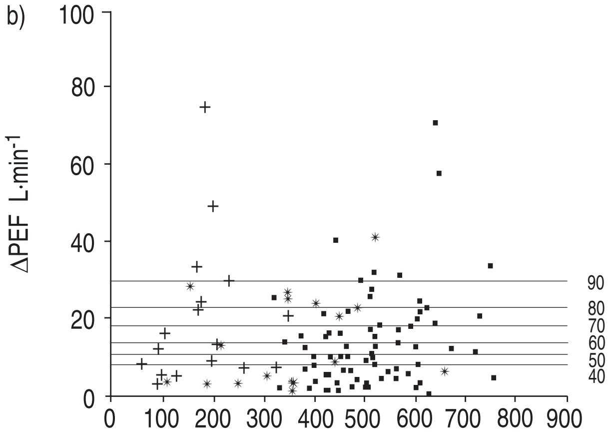


Fig. 3. – Within-test peak flow variation (ΔPEF = difference between highest and second highest PEF): a) for blows without PEF meter inserted; and b) for blows with PEF meter inserted. The horizontal lines indicate the percentage of the population having ΔPEF equal to or lower than the ordinate values of the lines. ■: normal young subjects; +: patients with emphysema or chronic obstructive pulmonary disease (COPD); ∗: patients with asthma and other disease (see text).

Figure 3a and b shows the relationship between ΔPEF and the maximum PEF obtained without and with PEF meter inserted, respectively. It is seen that ΔPEF does not systematically depend on PEF or presence of lung disease. The horizontal lines indicate the percentage of the examined population with ΔPEF equal to or below the ordinate values of the lines. Table 1 shows that if the criterion for an acceptable test is that ΔPEF is less than 20 L·min^{-1}, then 41% of this untrained population blowing through the pneumotachograph alone and 30% blowing through the pneumotachograph with the peak flow meter will fail. If, instead, 30 L·min^{-1} is used as a criterion, the corresponding figures are 24 and 12%.

Figure 4 shows the error, defined as PEF with meter minus PEF without meter as a function of the average of the two, for all the subjects (healthy and two groups of patients) and the 95% prediction interval for an individual error [11]. In almost all healthy subjects, the peak flow meter caused a decrease of PEF. However, among patients with emphysema and COPD, 7 out of 19 subjects showed an increase. Regression analysis showed that the error = -0.064 * (average PEF) -8 (L·min^{-1}); R^2=0.13 (p<0.0001). The mean (SE) numerical error was

Table 1. – The effect of different criteria on selection of acceptable peak flows

Subjects	Subjects remaining when ΔPEF <30 L·min^{-1}				Subjects remaining when ΔPEF <20 L·min^{-1}			
	without meter		with meter		without meter		with meter	
	n	%	n	%	n	%	n	%
Total (n=112)	85	76	98	88	66	59	78	70
Healthy (n=75)	58	77	68	91	46	61	58	77
Emphysema (n=19)	15	79	15	79	13	68	11	58
Asthma and other# (n=16)	12	75	15	94	7	44	9	56

#: the diagnosis was missing in two patients. ΔPEF: maximum difference between the highest and second highest peak expiratory flow during three to five blows.

36 (2.9) L·min^{-1} for all subjects. The mean (SE) error for healthy subjects was 43 (3.2) L·min^{-1} and was larger than the error for the patients, which was 21 (5.6) L·min^{-1}. This difference between healthy subjects and patients was significant (p=0.004, Wilcoxon rank sum W Test). The corresponding numerical percentage error was 7.8 (SE 1.1%) and was not influenced by disease.

A multivariate analysis of variance estimating the influence of sex, disease and the sequence of the measurements, and with parameters from the maximum expiratory flow-volume curve as covariates, revealed that the error was determined by PEF and $MEF_{75\%FVC}$ only. The numerical error increased with PEF (p<0.001) and decreased with increasing $MEF_{75\%FVC}$ for a given PEF (p=0.01). Seventy nine percent of the curves from which the spirometric parameters entering this analysis were taken, had a sum of FEV_1 and FVC that deviated less than 5% from the curves with the next highest sum or by less than 0.2 L, whichever was the greater, indicating that the performance was not much influenced by the manoeuvres, although full expirations were only encouraged in the first two.

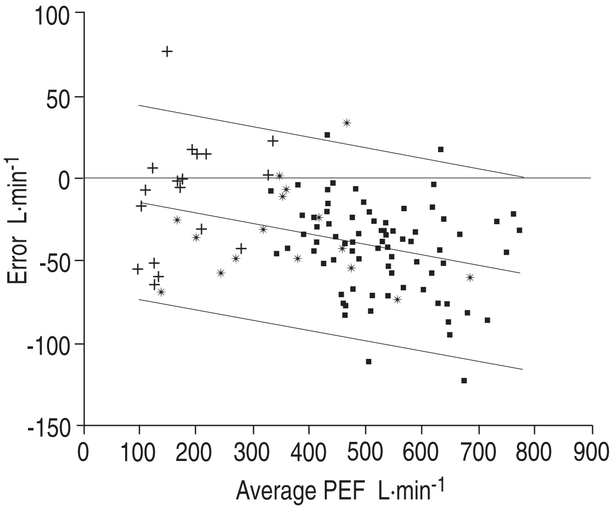


Fig. 4. – Measurement error defined as (peak expiratory flow (PEF) with meter - PEF without meter) as a function of the average of the two. The regression line and the 95% prediction interval for an individual error are also shown. ■: normal young subjects; +: patients with emphysema and chronic obstructive pulmonary disease (COPD); ∗: patients with asthma and other diseases (see text).

Including only subjects with a ΔPEF <20 $L \cdot min^{-1}$ would rule out 30% of the tests with the meter and 41% without the meter. A ΔPEF <20 $L \cdot min^{-1}$ in both tests would rule out 55% (found in a separate analysis). This indicates that a certain level of variation without the meter does not necessarily imply a similar variation with the meter. Table 1 shows the number of subjects remaining after each test separately to be 70 and 59% with and without the meter, respectively. A random variation would rule out 100% - (70% of 59%) = 59%, which is close to the value that was actually found.

Discussion

We assume that the reading of a correctly calibrated variable orifice meter is identical to the reading of a correctly calibrated pneumotachograph with increased resistance equal to the resistance of the peak flow meter. Previous investigations indicate that this may be correct [1, 4]. We, therefore, only used the mini-Wright peak flow meter as a resistance in the pneumotachograph recording system, as we assumed that the PEF measured with the pneumotachograph assembly including the peak flow meter should be equal to the PEF meter reading itself, had it been correctly calibrated. The most widely-used variable orifice meters have very similar resistance profiles [4]. Therefore, the mini-Wright meter has been assumed to be representative of this group of meters.

In the present study, it was important that the equipment was adequate with regard to calibration and frequency response. The deviation from linearity was minimal up to 900 $L \cdot min^{-1}$. The inclusion of the PEF meter as a resistance had only minor influence on the readings below 600 $L \cdot min^{-1}$. When the PEF meter was included, the error is likely to be less than measured, due to gas compression in the pump, especially at high flows due to increased back pressure created by the increased resistance. The accuracy appeared to be satisfactory compared with the ERS standard [5]. The frequency response of the pneumotachograph was determined as the response to flow profiles with decreasing rise times (fig. 2) as described previously [2]. Ideally, the ratio should be one for all rise times. The median values increase above one when the rise times decrease, because the pneumotachograph is underdamped. Also the scatter increases. This is due to rapid events measured with too slow a sampling frequency. The question is whether this would invalidate the measurements in the present study. That depends on the range of rise times expected in the study. In healthy male subjects and patients, the lower 5 percentile of rise time was 45 ms [2] which is in agreement with the lower 5 percentile of time to PEF from back extrapolated zero volume in males in a population study [12]. In women, the value was slightly higher, but there is evidence that in patients with obstructive lung disease it may be as low as 30 ms [3]. In that worst case, we can expect that for six subjects in the present study PEF may be overestimated by more than 5%.

The frequency characteristics, however, did not change when the meter was inserted. Therefore, the difference in PEF with and without peak flow meter inserted is unlikely to be attributed to change of the frequency response of the system.

For the PEF meter included, it is remarkable that even after careful instruction and coaching only about 70% of the tests with at least three blows each could be accepted if a within-test variation of less than 20 $L \cdot min^{-1}$ was required, but that 90% could reproduce it within 30 $L \cdot min^{-1}$ in three technically acceptable blows.

A similar study of untrained subjects [13], showed that after the first two days 95% of within-test PEF readings with mini-Wright PEF meters matched within 30 $L \cdot min^{-1}$, and that within-test variation was slightly larger during the first 2 days of testing, which is in agreement with our study.

Without the added PEF meter resistance, only 60% of untrained subjects could reproduce PEF within 20 $L \cdot min^{-1}$. Therefore, such a criterion is obviously not useful. Under these circumstances, we suggest a value of 30 $L \cdot min^{-1}$, which can be accomplished by about 80% of the subjects.

The presence of the peak flow meter increased the within-test peak flow reproducibility, but a subject with little variation of measurements with a meter inserted did not necessarily have little variation when the meter was removed or *vice versa*. The variation seemed almost randomly distributed between the two series of measurements. The training associated with the first series did not decrease the variation within the second series in this study. The effect of training over days, however, is well-known in other studies [13, 14].

The better reproducibility when using the PEF meter may be explained if the increased back pressures impede the effort-dependent flow coming from the airway in association with dynamic compression ("the Knudson Transients") [15]. It is interesting to note that if the standard deviations for the individual test sessions are used instead of ΔPEF as an estimate of within-test variation, then the difference caused by the meter became less significant. This could be explained if the meter changes the shape of the PEF distribution without much changing the standard deviation. This could happen, if the meter caused very high values to become less high. This was examined but was not the case.

Due to the resistance of the peak flow meter, it could be expected that especially at high PEF the back pressure might cause a smaller PEF. Our data support this assumption, showing a mean difference of 36 $L \cdot min^{-1}$ (7.8% of the average PEF). It is our hypothesis that the reason for the lower PEF with the added resistance is due to gas compression. In a plethysmographic pilot study, we examined the effect of a PEF meter used as an added resistance to mouth flow. We obtained flow-volume curves with mouth flow as a function of box volume changes. We found that the lower PEF obtained with the meter than without occurred when the flow hit the perimeter of the flow-volume curve without the meter. This happened at a lower lung volume. The set-up made it possible to calculate the alveolar pressure from the degree of gas compression in the lungs by use of Boyle's law. The alveolar pressure at peak flow was slightly larger with the meter than without. The lower peak flow with the meter, therefore, could be explained by more gas compression at peak flow leading to a lower elastic recoil and, therefore, a lower peak flow, if the latter is determined by wave-speed flow. However, this needs further investigation.

The fact that ΔPEF depends on $MEF_{75\%FVC}$ independent of PEF indicates that the shape of the flow-volume curve is also of significance. A high peak compared with the rest of the flow-volume curve will increase the difference. The reason for this is unclear, but could be related to the increased back pressure with the peak flow meter, causing less dynamic compression of the airways and, hence, reduced flow coming from the collapsing airway.

Figure 4 shows that proportionally more patients than healthy subjects get a higher PEF with the peak flow meter than without. This is partly a statistical phenomenon, because the patients have smaller PEF but unchanged standard deviation. Another explanation of positive errors may be that the back pressure created by the resistance of the peak flow meter may prevent airways from collapsing in certain situations.

The implication of these findings is that even if the accuracy of the PEF meter is satisfactory in terms of linearity and frequency response, the magnitude of the internal resistance is sufficiently large to cause a systematical underreading of PEF especially at high flows. The higher peak flows obtained with the pneumotachograph alone, however, vary more than when the peak flow meter is inserted. The rather poor reproducibility, even during well instructed and well coached peak flow manoeuvres, indicates that criteria that are too restrictive for reproducibility cannot be met without a considerable loss of tests. The present study indicates that a difference of less than 30 $L \cdot min^{-1}$ between the highest and second highest peak flows from a series of 3–5 blows can be achieved by 80–90% of untrained subjects, and therefore seems to be a more realistic measure than 20 $L \cdot min^{-1}$, which can only be achieved by 60–70%.

In conclusion, PEF measured by variable orifice meters, even when correctly calibrated, cannot be immediately compared with PEF obtained by pneumotachographs. The significance of this should be considered when reference equations for PEF are established.

***Acknowledgements*:** G.J.J.M. Borsboom, Leiden University, is acknowledged for suggestions in the analysis of within-test peak flow reproducibility.

References

1. Miller MR, Dickinson SA, Hitchings DJ. Accuracy of portable peak flow meters. *Thorax* 1992; 47: 904–909.
2. Pedersen OF, Rasmussen TR, Kjærgaard SK, Miller MR, Quanjer PhH. Frequency response of variable orifice type peak flow meters: requirements and testing. *Eur Respir J* 1995; 8: 849–855.
3. Miller MR, Pedersen OF. The rise and dwell time for peak expiratory flow in normals and subjects with airflow limitation. *Eur Respir J* 1994; 7: 53s.
4. Pedersen OF, Miller MR, Sigsgaard T. Portable peak flow meters: physical characteristics, influence of temperature, altitude, and humidity. *Eur Respir J* 1994; 7: 991–997.
5. Quanjer PhH, Tammeling GJ, Cotes JE, *et al.* Lung volumes and forced ventilatory flows. Report, working party, standardization of lung function tests, European Steel and Coal Community. *Eur Respir J* 1993; 6 (Suppl. 16): 6–40.
6. Fry DL, Hyatt RE. Pulmonary mechanics: a unified analysis of the relationship between pressure, volume and gas flow in the lungs of normal and diseased human subjects. *Am J Med* 1960; 29: 672–689.
7. Miller MR, Sigsgaard T. Prevention of thermal and condensation errors in pneumotachographic recordings of the maximal forced expiratory manoeuvre. *Eur Respir J* 1994; 7: 198–201.
8. American Thoracic Society. Standardization of spirometry: 1987 update. *Am Rev Respir Dis* 1987; 136: 1285–1298.
9. Burge PS. Single and serial measurements of lung function in the diagnosis of occupational asthma. *Eur J Respir Dis* 1982; 63 (Suppl. 123): 47–59.
10. Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet* 1986; i: 307–310.
11. Gardner MJ, Altman DG (eds). Statistics with confidence: confidence intervals and statistical guidelines. London, British Medical Journal, 1989; p. 40.
12. Enright PL, Johnson LR, Connett JE, Voelker H, Buist AS. Spirometry in the lung health study. 1. Methods and quality control. *Am Rev Respir Dis* 1991; 143: 1215–1223.
13. Enright PL, Sherrill DL, Lebowitz MD. Ambulatory monitoring of peak expiratory flow: methods and quality control. *Chest* 1995; 107: 657–661.
14. Siersted HC, Hansen HS, Hansen NCG, Hyldebrandt N, Mostgaard G, Oxhøj H. Evaluation of peak expiratory flow variability in an adolescent population sample: the Odense schoolchild study. *Am J Respir Crit Care Med* 1994; 149: 598–603.
15. Knudson RJ, Mead J, Knudson DE. Contribution of airway collapse to supramaximal expiratory flows. *J Appl Physiol* 1974; 36: 653–667.