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OFFICIAL ERS STATEMENT

Peak expiratory flow: conclusions and recommendations of a Working Party of the European Respiratory Society

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The use of peak flow meters has been widely adopted for monitoring patients with asthma. The Working Party of the European Respiratory Society (ERS) has solely addressed technical and physiological issues relating to peak expiratory flow (PEF) (flow describes the rate of change of volume (volume rate), so that flow rate is equivalent to volume acceleration. Hence, PEF should be used in preference to peak expiratory flow rate (PEFR)). Monitoring schemes, or comparison of PEF with other indices, such as the forced expiratory volume in one second (FEV_1), do not form part of these recommendations.

Measurements of PEF are of value in identifying airflow limitation. The correlation between airflow and symptoms is variable, some patients being poor perceivers of changes in airway patency, whereas others quickly perceive small changes [1–6]. Recording the PEF is, therefore, of value in clinical practice where it can be helpful in monitoring the progress of airflow limitation and the effects of treatment, and in epidemiological and occupational studies for identifying the presence of airflow limitation, assessing its severity and variation.

Various types of instrument can be used to measure PEF, including pneumotachometers, spirometers, turbines and anemometers. By far the most suitable and commonly used instruments in clinical practice are flow meters which measure PEF only and, hence, may be referred to as peak flow meters. Since they are mass-produced, they are relatively inexpensive; furthermore, they are portable and do not require electrical power for their operation.

Most handheld peak flow meters employ the principle of a variable orifice to measure airflow indirectly. The pressure exerted by a forced expiration causes a diaphragm or vane to move and, in so doing, to open a progressively larger area of the orifice. The point at which no further movement of the diaphragm occurs depends on the maximal pressure and, hence, on the peak expiratory flow that has been generated.

Definition

PEF is the maximum flow achieved during an expiration delivered with maximal force starting from the level of maximal lung inflation. The value obtained may differ depending upon the physical properties of the instrument used to measure it.

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Factors affecting PEF

Physiological factors

In a subject whose lungs have not been affected by any pathological condition (see below), the factors which determine PEF are as follows:

1. The dimensions of the large intra- and extrathoracic airways. The length and calibre of intrathoracic airways increases with lung volume during growth; within an individual, the calibre is a function of transbronchial pressure and, hence, of the volume and the elastic properties of the lung, and of the compliance of the airways. Both thoracic airway diameter and compliance are influenced by flexion and extension of the neck [7].
2. The force generated by the expiratory muscles, primarily abdominal. This is dependent on the force-length relationship and, hence, varies with the level of lung inflation.
3. The speed with which maximal alveolar pressure is reached, which depends on the force-velocity properties of the expiratory muscles [8].
4. The "volume history" of the lung, *i.e.* how the lung was stretched prior to the PEF manoeuvre; stress relaxation of viscoelastic lung elements is time-dependent, so that peak expiratory flow immediately after stretching the lungs is higher than after a pause at total lung capacity [9, 10]. It is generally assumed that PEF in healthy subjects is not determined by a flow-limiting mechanism in intrathoracic airways. If this is the case, PEF is dependent on: the alveolar pressure generated by the subject; the flow resistance of intra- and extrathoracic airways; and by the added resistance due to the instrument. In some subjects, the determinants of PEF may be the same as those which determine effort-independent flow [11], when expiratory flow is limited by the speed with which a pressure wave propagates in a dynamically compressed airway segment [12]. The determinants are then: the elastic properties of the large intrathoracic airways; lung elastic recoil; and the resistance of the smaller intrathoracic airways. In that case, the PEF is still effort-dependent because greater effort during early expiration causes flow limitation at a higher lung volume, where elastic lung recoil is greater and airways resistance lower, permitting a higher PEF. MEAD *et al*. [13] showed that with increasing resistance at the mouth there was a decline in PEF. Thus, within an individual subject, PEF may be influenced by the instrument used for measuring it; however, such an interaction between subject and instrument may not be the same

for all subjects. Another study [14] showed that PEF assessed with a low resistance pneumotachometer gave a lower reading when a mini-Wright peak flow meter was added as a resistance in series with the pneumotachometer, than it did without. However, the difference between the two largest peak flow readings in a series of measurements was significantly smaller with the resistance added.

It follows, from the above, that in healthy subjects PEF is determined by: the volume of the lungs (which is a function of the thoracic dimensions and, hence, of stature); by the elastic properties of the lung; and by the power and co-ordination of expiratory muscles, these last being able to be enhanced by training. In general, males generate higher alveolar pressures than females [15–20]. Hence, males can achieve higher values of PEF than females, but up to about 13–15 yrs of age boys produce the same PEF as girls of corresponding stature and age, since the greater muscular power is probably off set by narrower airways [15, 21]. Expiratory muscle strength [22] and PEF [23] decline slightly with ageing.

Pathophysiological factors

Of the pathological situations which impair PEF, by far the most common is that of a disorder of the structure or function of the intrathoracic airways, which increases resistance to airflow within them. PEF may also be impaired by: obstruction in extrathoracic airways; conditions which limit chest expansion or which affect respiratory muscle function; and by the integrity of the neural system. In restrictive processes due to interstitial lung disease, the effect of a loss in lung volume on PEF may be offset by increased lung elastic recoil. In subjects with severe airflow obstruction, PEF may include air coming from the collapsing airway in addition to flow coming from the lungs. In that case, PEF may underestimate the degree of airway obstruction [24, 25].

Calibration

All instruments used to measure PEF should provide similar readings. A device (*e.g.* [26]) which is capable of generating known accurate flows between 0–900 $L \cdot min^{-1}$ (0–15 $L \cdot s^{-1}$) (corrected for gas compression between the calibrator and PEF meter) should be used; and correction factors needed to take account of altitude [27–31] should be applied. Such devices generate known flows by explosive decompression of known volumes of gas, or are motor-driven pistons under computer control, giving specific flows. The device should be capable of generating flows with a short rise time (30 ms) and short dwell time (10 ms), with an abrupt fall of flow after reaching PEF (fig. 1). The meter should, thus, be tested between 0 and at least 800 $L \cdot min^{-1}$, both under conditions of constant flow and with the flow patterns generated by the calibrating device. The rise time is the time required to go from 10 to 90% of PEF. In healthy male subjects and patients, the lower 5th percentile was 45 ms [32], which is in agreement with

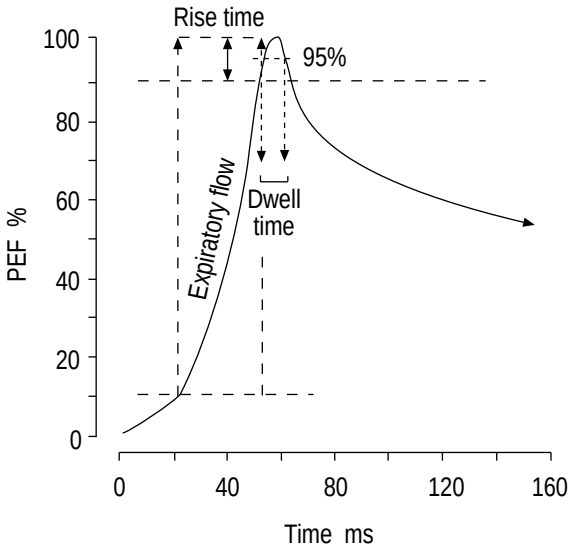

Fig. 1. – Rise time (the time required to go from 10 to 90% of peak expiratory flow (PEF)) and dwell time (the duration of time that flow is in excess of 95% of PEF), derived from an expiratory flow-time curve.

the lower 5th percentiles of time to PEF from back-extrapolated zero volume in males measured in a population study [33]. In females, the value is slightly higher, but there is evidence that in patients with chronic obstructive pulmonary disease (COPD) it may be as low as 30 ms [34]. We have defined the dwell time as the duration of flow in excess of 95% of PEF (fig. 1); a dwell time of 10 ms was exceeded by 99% of healthy subjects and patients with obstructive lung disease [32]. The same calibrating equipment should be used for assessing: accuracy between different makes of peak flow meter; the variability of readings within the same make of peak flow meter; and the repeatability within a given peak flow meter. Users of PEF meters (*i.e.* in patients, hospitals, some research studies) may have to rely on less expensive methods (secondary standards or biological controls) to provide a rough check of the function and accuracy of commercial PEF meters.

Specifications for pneumotachometers have been published previously [35]. The accuracy (closeness of agreement between measured and calibration value) of the PEF meter should come to 5% or 5 $L \cdot min^{-1}$, whichever is the greater [30, 36].

Portable, mechanical handheld PEF meters should be robust. They are best used, cleaned and stored at room temperatures ranging between 15–30°C, because temperature changes influence gas density and accordingly peak flow meter reading [30]. During the normal lifetime of the meter, its performance should conform with the specifications. The reading from the meter should be linearly related to the flow delivered by the calibration device. Flow meters should be capable of giving values in the range 60–800 $L \cdot min^{-1}$. Some current commercial devices perform poorly at and below 100 $L \cdot min^{-1}$ [36]. The scale should be graduated to 10 $L \cdot min^{-1}$, and allow estimates of 5 $L \cdot min^{-1}$.

Manufacturers should provide clear instructions about the care, cleaning and disinfection of the instrument and mouthpieces.

Measurement procedure

It is essential to pay close attention to the correct performance of the test. If a subject is tested for the first time, an explanation should be given of the purpose of the test followed by a demonstration of the manoeuvre, and the subject should make two practice attempts. Adequate rest must be allowed before the test, especially if the subject has been hurrying. The test may be performed in a standing or sitting position, but the neck must not be flexed. Having taken a maximal inspiration, and after a maximum pause of 2 s at total lung capacity (TLC) [35], the subject blows as hard as possible, maintaining an airtight seal between the lips and the mouthpiece. Unlike the forced vital capacity (FVC) manoeuvre, the PEF manoeuvre need last for only about 1 s. Dentures need not be removed, unless they fit very badly. Spuriously high readings can be caused by explosive decompression occurring during forced expiration, due either to sudden opening of a previously closed glottis, or to the release of the tongue which was previously obstructing the mouthpiece, or by "spitting" into the PEF meter. It is most important that close attention is paid to the directions, supplied by the manufacturers concerning the correct handling of the instrument; details differ, according to differences in design between types of meter. If the test provokes coughing, readings need be rejected only if this occurred at the start of the manoeuvre or if it interfered with a full inspiration. Further testing may be needed in patients in whom the manoeuvre itself induces or enhances airflow limitation [37–45]. The latter may be suspected if there is a fall in successive readings; this phenomenon should be recorded. A fall in PEF of ≥10 $L \cdot min^{-1}$ during each of three successive PEF manoeuvres occurred in 4.4% of children and adults with asthma, and in 3.3% of those without asthma [45].

The highest value of PEF from three correctly performed blows is recorded. For practical purposes, in patient-administered PEF measurements, if the largest two out of three acceptable blows are not reproducible within 40 $L \cdot min^{-1}$, it is recommended that up to two additional blows are performed to try and obtain better agreement. Ninety five percent of healthy subjects and patients with lung disease can reproduce the highest PEF, assessed with a handheld PEF meter, within 40 $L \cdot min^{-1}$, and 90% can reproduce it within 30 $L \cdot min^{-1}$ in three technically acceptable blows [14]. A similar study of trained subjects [45] showed that after the first 2 days, 95% of within-session PEF readings matched within 30 $L \cdot min^{-1}$, and that within-session reproducibility was slightly less during the first 2 days of testing. Successive blows give somewhat less reproducible results with low resistance pneumotachometers than with PEF meters [14]. If five manoeuvres have not led to a set of satisfactory blows, further tests are unlikely to be helpful [46]. Inability to reach good agreement between blows may, for instance be due to bronchoconstriction induced by the respiratory manoeuvres and, should not therefore, be used to reject the data [35, 47]. If successive blows do not reproduce within 40 $L \cdot min^{-1}$, a note to that effect should be recorded beside the highest reading. Electronic PEF meters can use the rise time or the time to peak flow as good indices of the quality or acceptability of the effort exerted by a subject to generate PEF [48].

Interpretation of observed values

There are different strategies for interpreting observed values of PEF.

Reference values

Since PEF is influenced by a subject's sex, ethnic origin, age and stature, interpretation of observed values of PEF requires that they be compared with the values which "normal" subjects with the same anthropometric characteristics would be expected to attain [23, 49]. In clinical practice, reference values (often called "predicted" or "normal" values) can be obtained from tables, nomograms and regression equations. In addition to mean values, authors of PEF reference studies should provide the standard deviations or the 5th percentiles in order to allow lower limits of the normal PEF range to be established.

Examination of the reference values for adults which have been reported by various authors reveals substantial differences between them, both in mean values and standard deviations [21, 23, 35]. In part, these differences are attributable to the employment of different criteria in the selection of supposedly "normal" subjects and to different methods of analysing the data to derive regression equations [21, 23, 35]. Reference values might also differ based upon the performance of the meter.

The essential criterion which constitutes "normality" in the context of reference values is the absence of any past or present factor that is recognized to have an adverse effect either upon the structure or function of the airways. Such factors include a previous or present history suggestive of asthma, COPD, emphysema, bronchiectasis, bronchiolitis and other lower respiratory tract infections. Since it has been shown that PEF is impaired by previous or current smoking, even when unaccompanied by hypersecretion of mucus or any other symptoms [50], any smoker or ex-smoker must be excluded from a reference group.

Even if every subject in a reference group fulfils the above criteria, and allowance has been made for differences in age, ethnic group and stature, there will still be a wide scatter of values around the mean, due to other variables that are not ascertainable; this must be taken into account in assessing an individual's peak flow. By subtracting 1.64·SD from the predicted mean, a figure is obtained for the lower 95% confidence limit, below which the values of only 5% of the "normal" subjects will fall.

Very few of the published reference equations have been based on a sufficiently large series of healthy subjects to warrant recommending a single set of equations for adult males and females or for children [51]; the most widely-used seem to meet the above criteria for adults [21]. PEF reference values derived from spirometric readings should not be applied to readings from PEF meters; this is because spirometers are usually

unsuited for measuring PEF, and standard flow-time waveforms commonly used to assess spirometers and PEF meters do not adequately evaluate the frequency characteristics of the instruments. In addition, PEF derived from volume-time recordings is sensitive to the filtering and smoothing algorithms applied [52–54]. Because of the considerable scatter around mean predicted values of PEF [23, 49], these should be regarded as providing no more than an approximate guide to the value which should be attainable by a subject who has no airflow limitation. A value in the "lower range of normal" does not exclude airflow limitation.

There is no statistical or physiological justification for regarding a reading of 20% less than mean predicted in adults as a lower limit of "normal". It has been recommended that the percentage predicted, or the best value of PEF attained by a subject, be used to classify asthma into mild, moderate and severe categories [55]. In adults, the scatter around the predicted mean value is independent of the mean; this lack of proportionality precludes the expression of results as a percentage of predicted [23, 35, 51, 56–59]. In children and adolescents, however, there is evidence that the scatter is proportional to the mean, so that in this age range it is justifiable to express observed values as a percentage of predicted mean [60].

Maximal attained value

A single value of PEF is of very limited use, though it may sometimes suffice to exclude the presence of airflow limitation at the time of the measurement. Clearly, sequential measurements of PEF are essential for monitoring the progress of disease and the effects of treatment upon it. The most valuable index for this purpose is the maximal attained value (MAV) that a subject has previously achieved. In the case of patients with asthma, MAV must have been recorded either during a remission or while they were taking optimal treatment. Since the decline in PEF with age is very small in normal adults, a patient's MAV remains valid for at least 5 yrs after it is recorded. In normal adolescents and young adults, however, PEF rises steeply due to growth, and allowance must be made for this if MAV was recorded more than 6 months previously.

Variability

Exaggeration of the endogenous circadian variation of airways patency is a particular feature of asthma [61]. Serial measurements of PEF may be helpful in confirming the diagnosis of asthma, assessment of risk factors, such as in occupational medicine [62], and in assessing the effectiveness of asthma therapy in poorly-controlled asthma, especially the "morning dip". In general, values of PEF tend to be lowest during the night and on waking, and to reach maximal values between about noon and early evening. In addition to measurements made on rising and at night, it is important that at least one other measurement is made in the early afternoon [61]. In patients using a bronchodilator, measurements should be made prior to taking the drug.

Multiple days of PEF are useful for assessing both diurnal variability and day-to-day variability. As there is a learning effect during the first 2–3 days [45, 63], these days should be ignored in evaluation of the variability. For diagnostic and monitoring purposes, variability can be expressed as an index, in which amplitude (*i.e.* the difference between the highest and lowest values of PEF) is divided by the mean of all measurements of PEF recorded during a day [1, 63, 64]. An initially low mean PEF, excessive variability, or both, may change to a higher mean without excessive variability as asthma improves; the reverse may occur if the asthma deteriorates [1]. In population samples in nonasthmatics, the 95th percentile of this index has been found to be <20% in adults [63, 65], and <31% in children [63]. Of adults and children with mild asthma, 51 and 60% respectively, were correctly identified by this index. There should, therefore, be no over-reliance on the diagnostic value of this index, as the false-negative ratio was 40 and 24%, respectively [63, 64]. If variability of PEF is used in the clinical context for diagnosis, the discriminatory power of the test is likely to improve if testing is restricted to patients in whom asthma is suspected.

Occupational medicine

In occupational medicine, serial measurements are invaluable for identifying subjects who react to environmental factors [66]; they are also helpful in studying the magnitude and the timing of the response, and its relationship to the level of exposure. It is recommended that assessment of serial measurements is based on at least four equally spaced daily measurements. At the present time, no quantitative guidelines can be given for distinguishing between responders and nonresponders, and this must, therefore, be based on inspection of the data. More detailed descriptions have been published previously [66]. In the case of patients suspected of having occupational asthma, a minimum positive record should include 2 weeks at work and 2 weekends away from work; and a minimum negative record should include at least 2 work periods separated by at least 10 days away from work, to provide an adequate representation of days at work and days away from work [62].

Diagnostic and therapeutic interventions

Measurements of FEV_1 are the established index of changes in airway calibre and obstruction. In patients, such as those with emphysema, PEF underestimates the degree of airway obstruction. If one cannot measure FEV_1, measurements of PEF can be used in exercise challenge tests, where a fall of 15% or more from the resting value is indicative of increased bronchial liability. In adults, an increase in PEF of 60 $L \cdot min^{-1}$ after administration of a bronchodilator drug has been suggested to indicate a clinically significant improvement [67].

Areas in which future research is required

Ideally different meters should give the same reading for PEF, whether from the same or a different manufacturer. This is not only a matter of linearity and accuracy, it also relates to the resistance to flow of the instrument and the dynamic performance. At the present time, there is insufficient knowledge of an acceptable upper limit

for flow resistance. This should be clarified in future research, in which the influence of instrument resistance on PEF is assessed. Based on one study of five brands of PEF meter [30], it is provisionally recommended that the back pressure should not exceed 5 kPa at 800 $L \cdot min^{-1}$, and 2 kPa at 400 $L \cdot min^{-1}$, or a maximum resistance of 0.4 $kPa \cdot L^{-1} \cdot s$. How the rise time to PEF and the dwell time at PEF may affect PEF meter readings needs to be established.

Flows are currently being measured with instruments based on different measuring principles: the temperature, the composition of the gas, including its viscosity, and the gas pressure do not affect the reading of different instruments in the same way [27–31]. Some of the complexities of relating calibrations made at room temperature to measurements of exhaled gas obtained with pneumotachometers have been reviewed previously [23, 30, 68–70]; similar considerations apply to other instruments employing other principles. In view of these problems, manufacturers should give guidance to the user concerning the effects of differences in gas temperature and gas composition on the readings obtained with their meter. Clarification of this and the above issue is indispensable in arriving at equipment specifications, which will make readings from peak flow meters of different makes comparable.

Present prediction equations are based on measurements obtained with nonlinearized meters, and, therefore, need updating with meters that comply with the specification presented in these recommendations. More information is needed about: the relationship between PEF, anthropometric variables and age in young children and adolescents; and also in males and females of different ethnic groups; and in every case about the confidence limits for the regression equations.

More information is required about the use of PEF measurements in clinical practice: how often are they needed in management, and how should they best be applied for their various functions? In addition, when PEF measurements are used as a diagnostic test, other indices than those reviewed here are useful [71, 72]. In view of patient recording compliance, recording instruments might improve the clinical utility of PEF measurements [73].

Clinical experience and current recommendations on asthma management have been derived using meters with a scale that does not linearly relate to flow. Changing the scales on meters to a linear relationship would remove any possible bias in the management of individual patients resulting from the present "nonlinear" scales, and would improve on the current expertise rather than negate it. Whilst mathematical corrections can be applied to data from the current meters, these are too cumbersome for individual patients monitoring their asthma. The issue needs to be resolved by an internationally agreed single standard for PEF meter scales [74].

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