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Original articles

The accuracy of portable peak flow meters

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Abstract

Background **The variability of peak expiratory flow (PEF) is now commonly used in the diagnosis and management of asthma. It is essential for PEF meters to have a linear response in order to obtain an unbiased measurement of PEF variability. As the accuracy and linearity of portable PEF meters have not been rigorously tested in recent years this aspect of their performance has been investigated.**

Methods **The response of several portable PEF meters was tested with absolute standards of flow generated by a computer driven, servo controlled pump and their response was compared with that of a pneumotachograph.**

Results **For each device tested the readings were highly repeatable to within the limits of accuracy with which the pointer position can be assessed by eye. The between instrument variation in reading for six identical devices expressed as a 95% confidence limit was, on average across the range of flows, ±8·5 l/min for the Mini-Wright, ±7·9 l/min for the Vitalograph, and ±6·4 l/min for the Ferraris. PEF meters based on the Wright meter all had similar error profiles with overreading of up to 80 l/min in the mid flow range from 300 to 500 l/min. This overreading was greatest for the Mini-Wright and Ferraris devices, and less so for the original Wright and Vitalograph meters. A Micro-Medical Turbine meter was accurate up to 400 l/min and then began to underread by up to 60 l/min at 720 l/min. For the low range devices the Vitalograph device was accurate to within 10 l/min up to 200 l/min, with the Mini-Wright overreading by up to 30 l/min above 150 l/min.**

Conclusion **Although the Mini-Wright, Ferraris, and Vitalograph meters gave remarkably repeatable results their error profiles for the full range meters will lead to important errors in recording PEF variability. This may lead to incorrect diagnosis and bias in implementing strategies of asthma treatment based on PEF measurement.**

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Portable devices for measuring peak expiratory flow (PEF) were pioneered by Martin Wright, who in 1959[1] had engineered a variable orifice PEF meter. Subsequently many lightweight PEF meters have become available and these devices are now of proved value in the diagnosis[2] and management[3 4] of asthma. The clinical value of PEF meters has now been fully recognised and they are of low cost with a high utility.

It has been accepted that readings from these portable PEF meters are sufficiently accurate and repeatable for clinical purposes. Many of the newer devices have been tested in human subjects by comparison with the original Wright meter as the accepted standard.[5–8] Experiments designed to validate the accuracy of meters by using human subjects are limited by their lack of an absolute standard of flow. Other studies have used PEF meters in series with a pneumotachograph to check their accuracy but this can mean that one device affects the performance of the other.

With these devices now more widely used in the management of asthma their exact performance characteristics need to be determined. The accurate measurement of gas flow, however, is considerably more demanding than that of volume and in the past methods of establishing absolute standards of gas flow have been poor. The original Wright meters were calibrated against a pneumotachograph that had been calibrated by a rotameter. Rotameters require their own calibration (which is open to challenge) and they work under conditions of constant flow that are not pertinent to a device for measuring a peak of flow. In recent years it has been possible to generate known dynamic flows by using computer driven pump systems,[9 10] and others have used the decompression of pressurised gas systems.[11 12] These latter devices are limited in not being able to generate flow profiles of different shapes.

We have undertaken a study of the accuracy of PEF measurement by several PEF meters using computer driven pump systems to determine whether the performance of the meters is satisfactory for clinical applications.

Methods

We have used two pump systems, which are schematically presented in figure 1, to see if both could satisfactorily test these meters. One

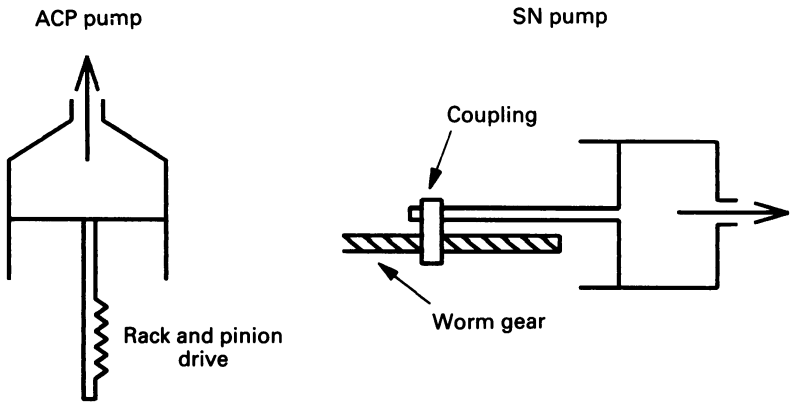

Figure 1 Schematic representation of the design of the two pumps.

was developed in our laboratory[10] by the late Archie Pincock (ACP pump), being designed to have low mass and a fast response. It comprises a Perspex cylinder of known dimensions, mounted vertically to act as the barrel of the pump with a carbon fibre piston, which has a double knife edged Teflon seal. This seal was ensured by flooding the piston head with silicon oil. The pump was driven by a rack and pinion attached to a servo controlled 100 watt DC motor with a permanent magnet printed armature to reduce its inertia. Digital output from a computer was converted to an analogue signal, which positioned the piston head to within 3 ml of the desired volume. The instantaneous position of the piston head could be monitored via the servo control system and it was statically verified and volume calibrated by means of an optical vernier microscope mounted on the side of the pump. The timing of the delivery of flow was effected by a programmable clock within the computer. The position of the head of the pump was updated every 4 milliseconds (ms) to give a smooth flow profile. The outflow from the ACP pump was of a conical design to reduce gas compression effects and to house a fan and heating element for determining temperature effects.[10]

The second pump was one of an early design by Steven Nelson[9] (SN pump), which was endorsed by the American Thoracic Society[13] for use in testing spirometers and flow measuring devices. This device has a horizontally mounted piston and flat ended chamber of 8 litres. The piston is driven by a wide gauge worm gear with a plastic coupling to a stepper motor. The stepper motor was driven by a pulse frequency from the computer calculated to give the desired flow. The piston had a ring seal and the position of the piston could not be verified independently. Pressure ports were tapped into the chambers of each pump and at their outlets. Pressures were measured from these with a Statham transducer (damping factor 0·3, damped frequency response 144 Hz), whose signal was amplified (100 Hz low pass three pole Butterworth filter) and sampled every 4 ms. An independently calibrated Fleisch pneumotachograph, whose characteristics have been described,[14] was also used to measure the flows generated by the pumps.

The following devices were tested:

Wright (W)	Wright peak flow meter, Airmed Ltd, Harlow, UK
Mini-Wright (MW)	Mini-Wright peak flow meter, Clement Clarke Ltd, Harlow, UK
Vitalograph (V)	Peak flow monitor, Vitalograph, Buckingham, UK
MicroMedical (MM)	Portable spirometer (turbine device), MicroMedical Instruments, Rochester, Kent, UK (1986)
Assess (AS)	peak flow meter, Healthscan Inc, New Jersey, USA
Ferraris (F)	Pocket peak flow meter, Ferraris Medical Ltd, London, UK
Pneumotachograph (PT)	An optimised Fleisch pneumotachograph
Ventilometer (VM1)	Wright Ventilometer VM1, Clement Clarke Ltd, Harlow, UK

These devices were tested when placed directly on to the pump without any connecting tubing to avoid resonance effects.

The American Thoracic Society has recommended using a scaled version of its flow profile 24 (ATS 24)[13] for testing flow measuring devices. This profile is a true recording from a subject. We were concerned with the possibility that gas compression within the pumps would distort the flow produced. We therefore tested each pump with scaled ATS 24 profiles, scaled single exponentials whose run up to PEF varied from 130 ms for a PEF of 730 l/min to 570 ms for PEF 120 l/min, and scaled cusp profiles such that PEF was generated half way through the manoeuvre to minimise gas compression and avoid effects due to the unknown frequency response of the devices tested. For each profile the PEF was held constant for at least 10 ms. Differently scaled versions of each profile are shown in figure 2. The exponential, cusp, and ATS profiles were used with one PEF meter to

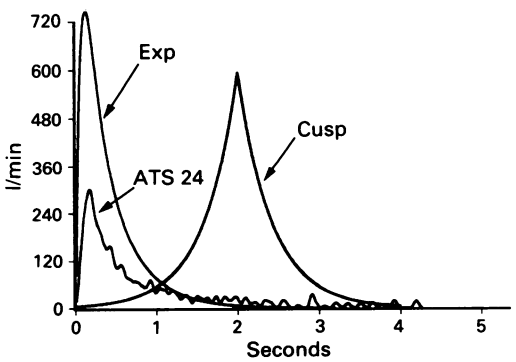

Figure 2 Flow-time plots of the cusp, exponential, and American Thoracic Society (ATS 24) profiles. For clarity the scaling of each is different.

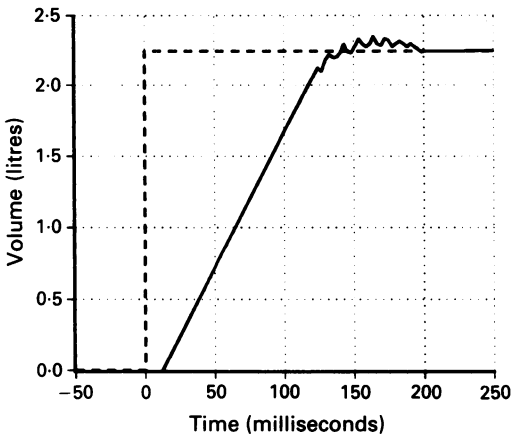

Figure 3 Plot of the response of the piston of the ACP pump to a square wave input (dashed line).

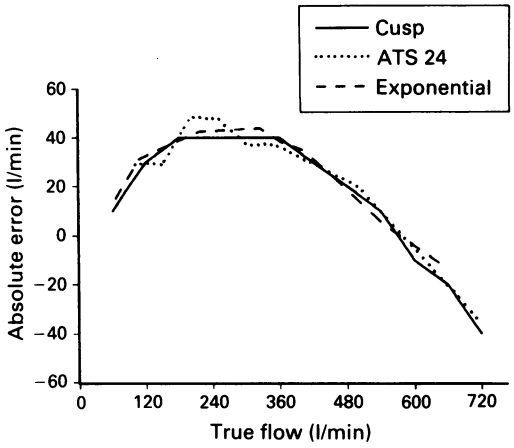

Figure 5 Absolute error in reading (recorded − true) for the Vitalograph meter with the three types of flow-time profile.

determine whether there was any substantial difference between the profiles. The cusp profile was subsequently used for testing all the devices except for the VM1. Because the VM1 will reject a blow if the time to PEF is too long the use of the cusp profile was precluded, and so the ATS 24 profile was used instead. The effect of temperature on a meter was investigated by cooling a meter to 6°C in a fridge and then testing it with the pump gas at an ambient temperature of 25°C. The effect of the position of the meter was explored by testing a meter with it mounted vertically, then horizontally, and finally at 45° down from horizontal.

Results

The SN pump could not be tested for power and acceleration because the high inertia of the system would cause the stepper motor to stall. The ACP pump when presented with a square wave input responded with a maximal flow of 21·9 l/s (slewing rate) with an internal pump pressure of 203 mm H_2O. With a Mini-Wright meter on the outlet of the pump the slewing rate was 20·0 l/s with an internal pump pressure of 649 mm H_2O and the mouth pressure (that is, immediately upstream of the meter) was 456 mm H_2O. Figure 3 shows the volume-time profile of the response of the pump with a Mini-Wright meter in place and a square wave input, where the displaced volume was calculated from the known position of the piston head. A delay of 12 ms was evident before the motor started to move the piston head and the effect of the servo controller in retarding the piston head at the end of its travel can be seen. Figure 4 shows the plot of the piston head position compared with the input signal for a cusp profile producing 20 l/s with a Mini-Wright meter in place. The piston head lagged the input signal by up to 18 ms but the maximal slopes of each curve are the same and are equal to a flow of 20 l/s.

A Vitalograph meter was tested through a range of flows with each of the three profiles; absolute errors are shown in figure 5 as the recorded flow minus the true flow, so that a positive error means an overreading. There was little difference in result between the three profiles, the greatest agreement being between the exponential and the cusp profiles. The two pumps gave identical results when they were used with these profiles in this manner. The difference in pressure measured in the chamber and at the outlet of the two pumps while a flow of 720 l/min was being generated was kept to a minimum of 8 mm H_2O by using the cusp profile. Figure 6 shows the pressure just upstream of the PEF meter when this was being used by a subject and when it was being tested by the pumps; the pressures were very similar. Above 300 l/min a subject tends to generate a higher flow than the ACP pump (by up to 33 l/min) for a given mouth (upstream) pressure.

With the use of the cusp profile (to minimise compression and frequency response effects)

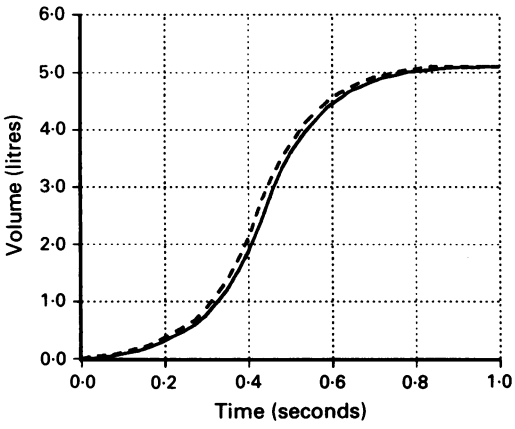

Figure 4 Plot of the reponse of the piston of the ACP pump to a cusp profile input (dashed line) generating 20 l/s.

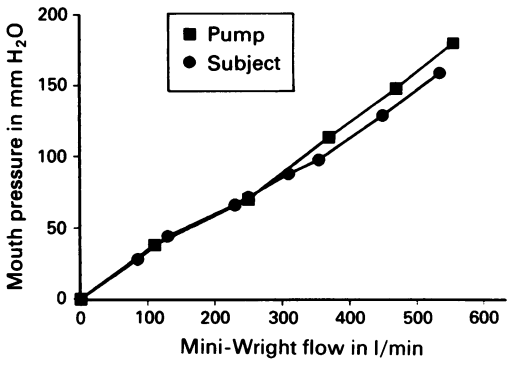

Figure 6 Upstream (mouth) pressure for a Mini-Wright meter when tested by the pump or by a subject.

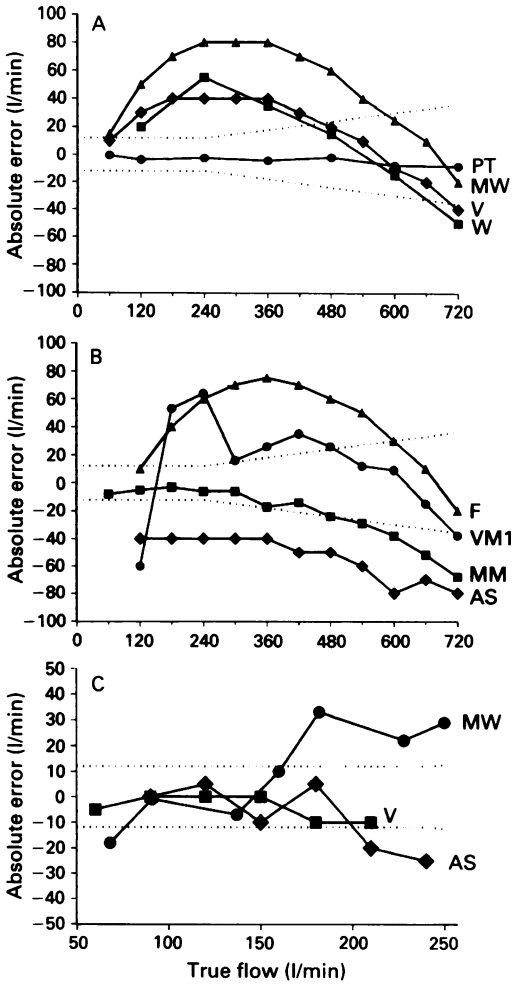

Figure 7 Absolute error plots for all the full range meters (A and B) and low range devices (C). The dotted lines indicate the American Thoracic Society guidelines for accuracy.

PT—pneumotachograph
MW—Mini-Wright
V—Vitalograph
W—Wright
F—Ferraris
VM1—Ventilometer
MM—MicroMedical Turbine
AS—Assess.

each device was tested five times at a flow of 60 l/min, and at 60 l/min increments up to 720 l/min. All the meters with needle readings gave identical results every time within the limits of accuracy for reading the scale by eye, ie to the nearest 5 l/min. The digital readings on the VM1 had a maximum SD of ±15 l/min at 660 l/min, for the MM this was ±6 l/min at 720 l/min and for the pneumotachograph ±3 l/min at 660 l/min.

Figure 7 presents the absolute error of PEF measurement for single instruments of the various devices. The Wright, Mini-Wright, Ferraris, and Vitalograph have similar shaped error curves, with a maximal overreading for the Mini-Wright and Ferraris of 80 l/min at 360 l/min. These errors would mean that a true PEF variability of 20% at a mean flow of 200 l/min would be recorded by a Mini-Wright as 25% variability, whereas a true variability of 20% at 600 l/min would be recorded by this device as 13% variability.

Six new Vitalograph, Mini-Wright, and Ferraris devices were tested and the results are presented in the table. Up to 600 l/min the Vitalograph meters were significantly closer to the true flow than the Mini-Wright meters, the Ferraris meters being significantly closer than the Mini-Wright to the true flow up to 300 l/min but not being significantly different from the Mini-Wrights at higher flows (two sample t test, $p > 0.05$). The 95% confidence limits for identical devices were on average ±8·5 l/min for the Mini-Wright, ±7·9 l/min for the Vitalograph, and ±6·4 l/min for the Ferraris meters. The results for four Mini-Wright devices that had been used for monitoring asthma for more than six months are shown in figure 8 and indicate that two devices were now reading significantly below the lower 95% confidence limit for the six new devices.

When Mini-Wright meters were tested horizontally and then at 45° down from the horizontal the readings were unchanged. The readings for flows above 180 l/min were significantly lower when the devices were placed vertically upwards than when they were tested horizontally, but this was only by 10 l/min or less (t test, $p < 0.001$). The mean (SD) of the readings for five tests of a Mini-Wright in the mid range of flows was 420 (0·0) l/min when the device was at an ambient temperature of 25°C, and the readings were unchanged when the device had been cooled in a fridge to 6°C (test gas still at 25°C). For the Ferraris the results were 424 (2·2) l/min and to 420 (0·0) l/min and for the Vitalograph 388 (4·5) and 394 (2·2) l/min. The resistance of each device was calculated and for the low range devices, the pneumotachograph and the original Wright, this was well below the 15 mm H_2O/l/s guideline set by the ATS[13] for spirometers. For the other devices the resistance ranged from

True flow and mean recorded flow (Rec) for six meters of each type, with 95% confidence interval (95% CI) for the reading calculated as 1·96 SE

	Mini-Wright			*Vitalograph*			*Ferraris*		
True l/min)	*Rec (l/min)*	*95% CI (±)*	*Max diff (%)**	*Rec (l/min)*	*95% CI (±)*	*Max diff (%)**	*Rec (l/min)*	*95% CI (±)*	*Max diff (%)**
68	65·0	7·2	25 (37)	62·5	4·9	10 (15)	†	†	†
137	160·8	7·4	20 (15)	142·5	4·9	15 (11)	126·7	8·3	30 (22)
182	245·0	4·4	10 (5)	214·2	7·4	25 (14)	216·7	6·0	20 (11)
251	314·2	7·8	25 (10)	275·0	7·2	25 (10)	292·5	5·5	20 (8)
296	377·5	6·6	20 (7)	332·5	6·6	25 (8)	360·8	5·9	20 (7)
365	429·2	8·6	25 (7)	387·5	7·5	25 (7)	427·5	5·5	15 (4)
433	479·2	8·6	25 (6)	439·2	5·3	20 (5)	486·7	5·5	15 (3)
479	525·0	10·1	30 (7)	488·3	9·0	30 (6)	535·8	5·3	15 (3)
547	571·7	9·0	25 (5)	534·2	9·6	35 (6)	581·7	10·2	35 (6)
593	612·5	10·0	30 (5)	577·5	10·7	40 (7)	628·3	5·5	20 (3)
661	651·7	9·4	30 (5)	621·7	11·8	40 (6)	658·3	6·0	20 (3)
730	692·5	12·8	45 (6)	661·7	9·4	30 (4)	690·8	6·9	25 (3)

*The absolute maximum difference in l/min between meters of the same type (Max diff) is shown together with this difference expressed as a percentage of the true flow shown in parentheses.
†No reading obtained.

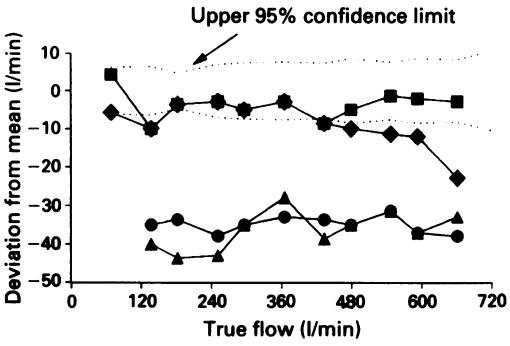

Figure 8 Plot of the readings for four old Mini-Wright meters, with dotted lines indicating the 95% confidence limits for the readings obtained from six new meters.

21 mm H_2O/l/s for the Vitalograph to 31 mm H_2O/l/s for the Assess meter.

Discussion

The data we have presented indicate that some portable PEF meters are not accurate across their whole range, with a non-linearity that could lead to important distortion of measures of PEF variability. We have to consider, however, whether the pump systems we have used are the best means for testing portable PEF meters. The original work by Wright and McKerrow[1] used a human calibration, their view being that their new device must give a result as close as possible to that obtained by their subjects through a low resistance mesh screen (Lily) type of pneumotachograph. There are several disadvantages to this approach. Individuals have their own inherent variability in PEF in repeated blows, and the blows from a selected group of human subjects cannot be applied elswhere in the world. Furthermore, the linearity of the Lily type of pneumotachograph is not as good as that of the capillary (Fleisch) type of pneumotachograph,[15 16] and the effect of both temperature and condensation on the pneumotachograph calibration by Wright and McKerrow is not available. Their Lily pneumotachograph was calibrated by using a constant flow rotameter and then making a comparison of integrated forced expiratory volumes with those achieved by subjects blowing into another device. This method is not as accurate as calibration by the numerical integration of an absolute volume discharged through the pneumotachograph.[17] There are therefore grounds for believing that, in the light of advances in our knowledge, the original calibration could be improved.

With this in mind both Archie Pincock and Steve Nelson with his coworkers independently produced pump systems for this purpose. We have compared these two pumps and found that with simple profiles they give the same results. The ACP pump can accelerate its piston faster than can the SN pump. When the ACP pump is tested with a severe resistance the pressure generated and flow achieved are much greater than are required for testing portable PEF devices. We conclude that the ACP pump is "strong" enough to produce the range of flows seen in human subjects. It may be argued that such a pump will deliver a given flow irrespective of the resistance of the device whereas a human subject could not. This raises the suggestion that portable PEF meters may inhibit the PEF that could be achieved by a human because of their resistance. The maximal mouth pressures found in human subjects[18] are about eight times higher than the mouth (upstream) pressures we have recorded with the pump or a subject, and the upstream pressure for the pump generating a flow of 12 l/s (720 l/min) is only 6 mm H_2O higher than that for a human. This small difference in pressure in only the higher flow range cannot explain the observed curvilinear error profile of overreading by the meters in the mid flow range, and it may be due to the higher gas temperature and humidity for the subject, leading to a greater pointer movement for a given high driving pressure. If the observed small pressure difference with the pump in the higher flow range was "falsely" raising the recorded flow with the PEF devices, then the "true" degree of non-linearity of these devices would be greater than we have presented. An alternative explanation for the error profile we have observed has been derived from applying the Bernoulli equation and the known dimensions of these devices to predict the way in which variable orifice meters work. This approach has accurately predicted our observed error profile (O F Pedersen, personal communication), indicating that this non-linearity is intrinsic to the design of these variable orifice meters.

Others have found that Mini-Wright meters overread in part of their range. Shapiro *et al*[6] used a Mini-Wright in series with a Pneumotach and adjusted the calibration of the Pneumotach to take into account the effect of the Mini-Wright on its performance. They found the Mini-Wright would overread up to 400 l/min and then underread in the high range. Two other groups of workers[5 7] have found a larger overreading by the Mini-Wright in the range 180–300 l/min by comparison with 480 l/min. Two separate studies have compared the Mini-Wright with the previously accepted standard of the Wright meter, using patients or normal subjects blowing into the devices in random order. Despite the additional noise introduced by using human subjects in this way these studies have shown that the Mini-Wright tends to overread when compared with the Wright.[19 20] We have now presented further evidence to confirm these findings.

Hand held PEF devices are inexpensive and for their cost they are remarkably robust and give repeatable results. They are, however, increasingly being used to monitor patients' asthma, and treatment strategies are being based on recorded changes in PEF. It is therefore important to recognise and correct any errors in the readings of PEF meters so that there is no inadvertent bias introduced into treatment strategies or experimental results. Such bias may occur because some of these meters falsely enlarge a given change in one range of PEF and reduce the true change in another range of PEF. Although it may be thought that in following the progress of an individual patient's asthma these errors should not cause any problem, the trigger points for treatment strategies will be affected and so lead to an unintentional bias. Although a large body of work has accumulated from the use of the

Wright, Mini-Wright, or similar devices for recording PEF the accuracy of such devices must now be improved and any distortion of PEF variability thus be eliminated. With the substantial investment in developing new treatments for asthma, we should ensure that the testing of their efficacy in patients uses methods free from error. A simple correction for this non-linearity would be for the manufacturers to change the reading scales so that they become accurate. Such changes to the scales would not be obvious to the user (the scales are already non-linear), and if there were any loss of visual appeal it would still be worth making the change for the benefit of removing the distortion of the readings with the current scales.

As the manufacturers serve an international market there is a genuine concern that they may faced with trying to match many different standards for accuracy and repeatability. It is therefore essential that an agreed single standard for these devices prevails. The UK Drug Tariff Specification No 51[21] has indicated that such devices should have an accuracy of $\pm 10\%$ or $\pm$measurement scale interval (whichever is the greater) when their readings are compared with readings from the Wright meter. Some devices clearly fail this standard, and these criteria for accuracy would still include the absolute inaccuracy of the Wright meters that we have shown. A recent statement from the American National Asthma Education Program[22] has requested an absolute accuracy of $\pm 10\%$ with ATS waveform 24 as the testing signal on a pump system. The disadvantage of this limit for accuracy is that it would still be acceptable for a device to have an underreading of 60 l/min at a PEF of 600 l/min but an overreading of 70 l/min at 700 l/min. Although this may seem an unlikely occurrence it would lead to serious distortion of PEF variability and yet fulfil the crtieria for accuracy. We have found that most of the devices we have tested had a within device short term repeatability that easily satisfied both the UK recommendation[21] of $\pm 3\%$ or 10 l/min (whichever is the greater) and the US recommendation[22] of $\pm 5\%$ or 10 l/min. As the Mini-Wright, Vitalograph, and Ferraris devices have an extremely high degree of repeatability they should be able to achieve a high degree of absolute accuracy if the reading scales were adjusted. The original ATS guidelines[13] for accuracy of flow measurement, which we have shown in our figures, would seem to be eminently achievable and less permissive than the others.

The important question of long term stability of these meters cannot yet be adequately answered. Normal use by a patient over some months would be a more valid test of durability than just retesting after a standard number of actuations, which has been proposed by some.[6] The response of some of these devices is affected by certain factors that should be avoided. For instance, a change in reading will occur if the exhaust vents on the Wright, Mini-Wright, Ferraris, or Vitalograph are covered or if the barrel or body of the device is squeezed because this will attenuate the movement of the pointer. Collection of moisture and grime on the channel of the pointer may also retard the movement of the pointer, and the manufacturers' recommendations on regular washing of the devices should be strictly followed. In devising tests of durability over time the effect of accumulation of grime must be considered and further work in this area is necessary.

We conclude that some of the commonly used portable PEF meters are non-linear in their measurement of PEF and that this could lead to important errors in the recording of PEF variability. These devices are cheap, compact, and relatively robust and give repeatable results, which makes them ideal for patients for monitoring their asthma. Once internationally agreed standards for the performance and testing of these instruments are adopted the problem with their non-linear response can readily be corrected.

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1 Wright BM, McKerrow CB. Maximum forced expiratory flow rate as a measure of ventilatory capacity with a description of a new portable instrument for measuring it. *BMJ* 1959;ii:1041–7.
2 Hetzel MR, Clark TJH. Comparison of normal and asthmatic circadian rhythms in peak expiratory flow rate. *Thorax* 1980;**35**:732–8.
3 Beasley R, Cushley M, Holgate ST. A self management plan in the treatment of adult asthma. *Thorax* 1989;**44**:200–4.
4 Charlton I, Charlton G, Broomfield J, Mullee MA. Evaluation of peak flow and symptoms only self management plans for control of asthma in general practice. *BMJ* 1990;**301**:1355–9.
5 Chiaramonte LT, Prabhu SL. Comparative evaluation of five peak flow devices. *J Allergy Clin Immunol* 1982;**69**:509–15.
6 Shapiro SM, Hendler JM, Ogirala RG, Aldrich TK, Shapiro MB. An evaluation of the accuracy of Assess and miniWright peak flowmeters. *Chest* 1991;**99**:358–62.
7 Eichenhorn MS, Beauchamp RK, Harper PA, Ward JC. An assessment of three portable peak flow meters. *Chest* 1982;**82**:306–9.
8 Perks WH, Tams IP, Thompson DA, Prowse K. An evaluation of the mini-Wright peak flow meter. *Thorax* 1979;**34**:79–81.
9 Nelson SB. Commercially available spirometers: a performance evaluation. M S.thesis, University of Utah, 1987.
10 Miller MR, Pincock AC. The effect of temperature on recording spirograms. *Am Rev Respir Dis* 1983;**128**:894–8.
11 Pedersen OF, Naeraa N, Lyager S, Hilberg C, Larsen L. A device for evaluation of flow recording equipment. *Bull Eur Physiopathol Respir* 1983;**19**:515–20.
12 Glindmeyer HW, Anderson ST, Kern RG, Hughes J. A portable, adjustable forced vital capacity simulator for routine spirometer calibration. *Am Rev Respir Dis* 1980;**121**:599–602.
13 American Thoracic Society. Standardization of spirometry—1987 Update. *Am Rev Respir Dis* 1987; **136**:1285–98.
14 Miller MR, Pincock AC. Linearity and temperature control of the Fleisch pneumotachograph. *J Appl Physiol* 1986;**60**:710–5.
15 Fry DL, Hyatt RE, McCall CB, Mallos AJ. Evaluation of three types of respiratory flowmeters. *J Appl Physiol* 1957;**10**:210–4.
16 Finucane KE, Egan BA, Dawson SV. Linearity and frequency response of pneumotachographs. *J Appl Physiol* 1972;**32**:121–6.
17 Varene P, Vieellefond H, Sauman G, Lafosse JE. Etalange des pneumotachographes par method integrale. *Bull Eur Physiopathol Respir* 1974;**10**:349–60.
18 Wilson SH, Cooke NT, Edwards RHT, Spiro SG. Predicted normal values for maximal respiratory pressures in caucasian adults and children. *Thorax* 1984;**39**:535–8.
19 Perks WH, Tams IP, Thompson DA, Prowse K. An evaluation of the mini-Wright peak flow meter. *Thorax* 1979;**34**:79–81.
20 Brown LA, Sly RM. Comparison of mini-Wright and standard Wright peak flow meters. *Ann Allergy* 1980; **45**:72–4.
21 Department of Health. *Peak flow meters (PFM) for single patient use, non-powered—hand held.* London: Department of Health, 1990. (Drug tariff specification No 51.)
22 National Heart, Blood, and Lung Institute. *Statement on technical standards for peak flow meters. National Asthma Education Program.* Washington DC: NHBLI, 1991.