Effect of Altitude on Hand-held Peak Flowmeters*

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Objective: To quantify the effect of altitude on the operational characteristics of hand-held peak flowmeters.

Design: Altitude simulation within a hypobaric chamber combined with five constant simulated peak flows delivered from a computerized pump were used to test commercially available peak flowmeters.

Setting: F.C. Hall Hyperbaric/Hypobaric facilities located at Duke University School of Medicine.

Measurements: Two each of nine models of commercially available hand-held peak flowmeters and a volume spirometer were tested at six simulated altitudes (100, 500, 1,000, 1,500, 2,000, and 3,000 m) using five target peak flows. Each peak flow was injected into each meter twice. Forward stepwise regression was used to check for nonlinear relationships between altitude and peak expiratory flowmeter readings. Linear regression equations were fit to the data at each target flow across altitude. Effect of absolute peak flow was tested by analysis of covariance.

Results: For these altitudes, linear relationships were found between altitude and measured peak flow. For all meters tested, the average decrease in peak flow ranged from −8.7% at the lowest target flow (123 L/min) to −6.5% at the highest target flow (702 L/min) for each 100 mm Hg decrease in barometric pressure (Pb). Individual meters ranged from −12.3% at the lowest target flow to −4.4% at the highest target flow for 100 mm Hg decrease in Pb. The spirometer had no significant changes associated with changes in Pb. In all cases, the magnitude of the altitude effect, measured by percent change, decreased with increasing peak flow.

Conclusions: Peak expiratory flowmeters underread PEF as a function of both increasing altitude and increasing target peak flow.

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Several studies suggest small portable peak expiratory flowmeters (PFM) underestimate peak expiratory flow (PEF) as altitude increases. Forster and Parker1 studied 19 workers who lived at sea level and commuted daily to Hawaii's Mauna Kea observatory at an altitude of 4,200 m (13,780 feet). PEF was measured with a PFM (Mini-Wright) on 44 separate trips to the summit. The effects of altitude and gas density were further investigated by delivering constant flows into a PFM using a mechanical pump filled with either oxygen or helium. Average PEF in the subjects fell 6.5%, from 601 L/min at sea level to 560 L/min at 4,200 m. PEF measured from the mechanical pump fell as a function of relative gas density. Using the gas density experiment results, Forster and Parker1 estimated that if true PEF in the subjects did not change, measured PEF would fall 10% at 4,200 m. Since measured PEF fell only 6.5%, they concluded that PEF rose in humans with increasing altitude and suggested that the effect of air density on the performance of pulmonary function equipment should be considered before using it for altitude physiology studies.

Using a spirometer in an altitude chamber, Kryger et al2 found PEF in nine subjects increased 2.0% with ascent to 762 m; 6.3% at 1,515 m; and 12% at 2,272 m. Thomas et al3 studied nine men in a decompression chamber at barometric pressures of 760 mm Hg (sea level), 520 mm Hg (3,030 m), 447 mm Hg (4,242 m), and 380 mm Hg (5,455 m). Measurements were made with a dry rolling seal spirometer and a PFM (Mini-Wright). The spirometer was assumed to measure accurately at all altitudes. PEF measured with the spirometer increased as altitude increased while PEF measured with the PFM fell. The changes in both instruments as a function of barometric pressure were approximately linear. Thomas et al estimated the spirometer PEF reading could be approximated by increasing the PFM (Mini-Wright) reading by +6.6% for every 100 mm Hg drop in barometric pressure from 760 mm Hg.

Together, these studies show that PEF increases with increasing altitude in humans. PFM (Mini-Wright) underread PEF by about 7% per 100 mm Hg fall in barometric pressure. Although the effect of altitude has been studied only on a specific PFM (Mini-Wright), all PFM based on technologies affected by gas density should be affected by changes in

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ATS=American Thoracic Society; NAEP=National Asthma Education Program; Pb=barometric pressure; PEF=peak expiratory flow; PFM=peak expiratory flowmeter; PH2O=water vapor pressure; RH=relative humidity
altitude. The magnitude of the altitude effect, however, may not be the same for other PFM models. Previous studies have not examined the magnitude of the altitude effect as a function of absolute peak flow.

We studied nine models of PFMs to determine the altitude effect on measured peak flow and to determine whether the altitude effect varies as a function of the magnitude of peak flow.

MATERIALS AND METHODS

Two each of nine commercially available PFM models and a dry rolling seal spirometer interfaced to a computer with an optical shaft encoder were studied in the F.G. Hall Hyperbaric/Hypobaric Environmental Laboratory at Duke University, Durham, NC (Table 1). Each device was studied at six simulated altitudes: 100, 500, 1,000, 1,500, 2,000, and 3,000 m at measured barometric pressures of 752 mm Hg, 717 mm Hg, 674 mm Hg, 640 mm Hg, 597 mm Hg, and 526 mm Hg, respectively. A computerized pump was used to deliver simulated patient expiratory waveforms. The pump was initially developed to reproduce digitized spirometry waveforms for testing spirometry equipment. Nine multiples of the American Thoracic Society's (ATS) standard spirometry waveform 24 were selected by the National Asthma Education Program as the set of standard waveforms for PFM testing. We chose five of these standard waveforms for our study (flow range 123 to 702 L/min) (Table 2).

The PFMs were tested in a sequence randomized first for altitude, second for peak flow, and third for the individual meters. In practice, we first went to a simulated altitude specified by the randomization, randomly selected a target peak flow, and delivered that flow into the dry rolling seal spirometer four times. We then tested all 18 PFMs in random sequence. The selected peak flow was injected four times into each PFM and read by two observers for a total of eight readings. We then randomly selected a new target peak flow and retested the 18 PFMs choosing the models in a new random sequence. After all five peak flows had been tested on all meters, we randomly selected a new altitude, the chamber was pressurized accordingly, and the process was repeated.

Simulated altitudes were obtained by decreasing the pressure in the hypobaric chamber to a pressure that represented the target altitude. The chamber was continuously refreshed with atmospheric gas. The chamber concentration of CO2 was less than 0.5% and concentration of O2 was held to within ±0.5% of room air. The computerized pump, volume spirometer, PFMs, computers, and four individuals operating the testing equipment, recording data, and managing communications to the exterior were placed in the hypobaric chamber for each experiment. Pressure inside the chamber was maintained within ±1 mm Hg at each simulated altitude. Temperature and relative humidity were recorded during testing of each target flow at each altitude.

Statistical Analysis

Analysis was performed with statistical programs (ABSTAT; Anderson Bell; Parker, Colo; and SPSS; SPSS; Chicago). Examination of the individual meter data showed no significant differences between identical models so data from the two meters were combined for each model type. At each target peak flow, the 16 observations (4 measurements in 2 of each model PFM read by two observers) were averaged. All statistical analysis was performed on these average values. Data for each PFM model were first analyzed by graphing measured peak flow against barometric pressure. Linearity over the range of experimental pressures of peak flow vs barometric pressure was tested with forward stepwise regression starting with a linear term then adding first a quadratic and then a cubic term for barometric pressure. Only terms with significant coefficients (p<0.05) were retained. In addition, for each PFM model, we regressed the measured values for each target flow against barometric pressure using a simple linear model. At any given target flow, the average decrease in peak flow reading with increasing altitude is represented by the slope coefficient from regression equations. The regression data are also represented as percent decrease per 100 mm Hg change in barometric pressure.

### Table 1—PFMs Studied*

<table>
<thead>
<tr>
<th>Meter</th>
<th>Manufacturer and Operation Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferraris:</td>
<td>Ferraris Medical Limited; London, England</td>
</tr>
<tr>
<td>Low range</td>
<td>(Deflected leaf spring)</td>
</tr>
<tr>
<td>High range</td>
<td>(Deflected leaf spring)</td>
</tr>
<tr>
<td>Wright</td>
<td>Ferraris Medical Limited; London, England</td>
</tr>
<tr>
<td>(0-900 L/min)</td>
<td>(Deflected leaf spring)</td>
</tr>
<tr>
<td>Mini-Wright</td>
<td>Clement Clarke, Inc; Columbus, Ohio</td>
</tr>
<tr>
<td>Low range</td>
<td>(Linear spring extended by flow)</td>
</tr>
<tr>
<td>High range</td>
<td>(Linear spring extended by flow)</td>
</tr>
<tr>
<td>Vitalograph</td>
<td>Vitalograph, Inc; Lenexa, Kan</td>
</tr>
<tr>
<td>Low range</td>
<td>(Linear spring extended by flow)</td>
</tr>
<tr>
<td>High range</td>
<td>(Linear spring extended by flow)</td>
</tr>
<tr>
<td>Spiro</td>
<td>Respiratory Care Center, Hameenhuuna, Finland</td>
</tr>
<tr>
<td>(0-750 L/min)</td>
<td>(Deflected leaf spring)</td>
</tr>
<tr>
<td>Assess</td>
<td>Healthscn Products, Inc; Cedar Grove, NJ</td>
</tr>
<tr>
<td>(60-780 L/min)</td>
<td>(Linear spring extended by flow sampling)</td>
</tr>
</tbody>
</table>

*Note: Product scales for some products have since been adjusted to conform to NAEP guidelines, and new models have become available since the time of the study.

### Table 2—Average Peak Flow at 100 m Altitude for Spirometer and All PFMs (Mean ± SD)*

<table>
<thead>
<tr>
<th>Target, L/min</th>
<th>Spirometer</th>
<th>All PFMs</th>
</tr>
</thead>
<tbody>
<tr>
<td>123</td>
<td>118.1±0.91</td>
<td>121.3±18.5</td>
</tr>
<tr>
<td>246</td>
<td>243.8±1.01</td>
<td>249.8±18.5</td>
</tr>
<tr>
<td>369</td>
<td>388.0±0.89</td>
<td>361.4±18.5</td>
</tr>
<tr>
<td>491</td>
<td>400.2±0.52</td>
<td>469.5±40.1</td>
</tr>
<tr>
<td>702</td>
<td>690.6±1.07</td>
<td>632.1±43.9</td>
</tr>
</tbody>
</table>

*Averaged measured peak flow for the volume spirometer and all PFMs±SD showing average accuracy of the PFMs that is similar to the spirometer at all peak flows except 702 L/min target.

### Table 3—Change in PEF With Altitude (Averages for All Nine PFMs Tested)*

<table>
<thead>
<tr>
<th>Flow (L/min)</th>
<th>Near Sea Level Average Slope, L/min/mm Hg</th>
<th>Average Percent Change per 100 mm Hg</th>
<th>Decrease in PEF</th>
</tr>
</thead>
<tbody>
<tr>
<td>121.3</td>
<td>-0.11</td>
<td>-8.7</td>
<td>-8.7</td>
</tr>
<tr>
<td>249.8</td>
<td>-0.18</td>
<td>-7.4</td>
<td>-7.4</td>
</tr>
<tr>
<td>361.4</td>
<td>-0.25</td>
<td>-7.0</td>
<td>-7.0</td>
</tr>
<tr>
<td>469.5</td>
<td>-0.33</td>
<td>-6.9</td>
<td>-6.9</td>
</tr>
<tr>
<td>632.1</td>
<td>-0.41</td>
<td>-6.5</td>
<td>-6.5</td>
</tr>
<tr>
<td>All flows</td>
<td>-0.26</td>
<td>-7.3</td>
<td>-7.3</td>
</tr>
</tbody>
</table>

*Average slope coefficient (L/min/mm Hg) for tested meters decreases consistently as the absolute target peak flow increases.
Table 4—Regression Results for Each Meter at Each Target Flow*

<table>
<thead>
<tr>
<th>Device</th>
<th>Target, L/min</th>
<th>Slope, L/min/mm Hg</th>
<th>$r^2$</th>
<th>Change per 100 mm Hg, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferraris (high)</td>
<td>123</td>
<td>-0.12</td>
<td>0.94</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td>246</td>
<td>-0.19</td>
<td>0.91</td>
<td>8.0</td>
</tr>
<tr>
<td></td>
<td>369</td>
<td>-0.24</td>
<td>0.91</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>491</td>
<td>-0.43</td>
<td>0.95</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>702</td>
<td>-0.47</td>
<td>0.83</td>
<td>6.8</td>
</tr>
<tr>
<td>Ferraris (low)</td>
<td>123</td>
<td>-0.10</td>
<td>0.94</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>246</td>
<td>-0.12</td>
<td>0.97</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>369</td>
<td>-0.33</td>
<td>0.93</td>
<td>9.2</td>
</tr>
<tr>
<td>Mini-Wright (high)</td>
<td>123</td>
<td>-0.15</td>
<td>0.94</td>
<td>12.3</td>
</tr>
<tr>
<td></td>
<td>246</td>
<td>-0.22</td>
<td>0.96</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>369</td>
<td>-0.25</td>
<td>0.97</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>491</td>
<td>-0.29</td>
<td>0.98</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>702</td>
<td>-0.35</td>
<td>0.99</td>
<td>5.1</td>
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<tr>
<td>Mini-Wright (low)</td>
<td>123</td>
<td>-0.13</td>
<td>0.95</td>
<td>10.8</td>
</tr>
<tr>
<td></td>
<td>246</td>
<td>-0.19</td>
<td>0.96</td>
<td>7.8</td>
</tr>
<tr>
<td>Vitalograph (high)</td>
<td>123</td>
<td>-0.11</td>
<td>0.45</td>
<td>9.0</td>
</tr>
<tr>
<td></td>
<td>246</td>
<td>-0.18</td>
<td>0.75</td>
<td>7.6</td>
</tr>
<tr>
<td></td>
<td>369</td>
<td>-0.23</td>
<td>0.83</td>
<td>6.4</td>
</tr>
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<td></td>
<td>491</td>
<td>-0.28</td>
<td>0.90</td>
<td>5.8</td>
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<td></td>
<td>702</td>
<td>-0.34</td>
<td>0.83</td>
<td>4.9</td>
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<tr>
<td>Vitalograph (low)</td>
<td>123</td>
<td>-0.07</td>
<td>0.88</td>
<td>6.3</td>
</tr>
<tr>
<td>Standard Wright</td>
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<td>-0.13</td>
<td>0.87</td>
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<td>Spira</td>
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<td>-0.10</td>
<td>0.96</td>
<td>8.4</td>
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<td>0.97</td>
<td>8.1</td>
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<td>0.99</td>
<td>6.1</td>
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<td></td>
<td>491</td>
<td>-0.26</td>
<td>0.99</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>702</td>
<td>-0.35</td>
<td>0.99</td>
<td>5.0</td>
</tr>
<tr>
<td>Assess</td>
<td>123</td>
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</tr>
<tr>
<td></td>
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<td>-0.20</td>
<td>0.99</td>
<td>8.3</td>
</tr>
<tr>
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<td>-0.26</td>
<td>0.99</td>
<td>7.1</td>
</tr>
<tr>
<td></td>
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<td>0.99</td>
<td>6.7</td>
</tr>
<tr>
<td></td>
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<td>6.0</td>
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<tr>
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<tr>
<td></td>
<td>246</td>
<td>0.0007</td>
<td>0.53</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>369</td>
<td>0.0105</td>
<td>0.91</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>491</td>
<td>0.0055</td>
<td>0.69</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>702</td>
<td>-0.0040</td>
<td>-0.13</td>
<td>0.06</td>
</tr>
</tbody>
</table>

*Slope is the rate of change in liters per minute per mm Hg that the PFMs alter their readings. The slope coefficients were multiplied by 100 mm Hg and divided by the target flow to calculate the percent change per 100 mm Hg at each target flow.

(>0.3 mm Hg at all simulated altitudes. Relative humidity and temperature were 59.2±2.4% (mean±SD) and 26.0±0.58°C.

Measured peak flows for the spirometer at 100 m altitude are listed in Table 2. Across the simulated altitudes, measured peak flows differed from target values on average by -0.06 L/min or 0.34%. For the spirometer, no significant differences were observed in the measured peak flows at any altitude or any target (Table 4). Average FVC and FEV₁ were within 0.36% and 0.41% of their target values, respectively, and deviated no more than ±30 mL absolute from any target at any altitude.

Average peak flows ± SD for all PFMs at each target flow for the near sea level altitude (100 m) are shown in Table 2. There was good agreement between target and the overall average measured peak flow up to 469 L/min. At the highest target flow (702 L/min), the average measured peak flow (631 L/min) was significantly below the target by 70 L/min.

In the forward stepwise regression analysis, no squared or cubic terms were added at the p<0.05 level. All stepwise regressions stopped after adding barometric pressure. We conclude that over the pressure range in this study (751.8 to 526.6 mm Hg), the meter readings showed a linear decrease with decreasing barometric pressure.

Peak flow readings fell with increasing altitude (p<0.05). A typical plot of measured peak flow against barometric pressure is shown for 1 m in Figure 1. Over all meters, at a target flow of 123 L/min, the absolute change in PEF reading with barometric pressure (Pb) ranged from -0.0749 to -0.1520 L/min/mm Hg; at a target flow of 702 L/min, PEF readings changed from -0.307 to -0.378 L/min/mm Hg. The slopes of measured PEF against altitude are least steep at the smallest target flow and steepest at the maximum target flow (Fig 1, Table 4).

Analysis of covariance using target peak flow as a covariate to the regression of measured peak flow on altitude again showed a significant effect of altitude on peak flow after compensating for the target flow (p<0.001). Peak flow is significantly more affected by altitude at higher peak flow rates.

There were small differences between different model PFMs in the magnitude by which they underestimated peak flow at the 3,000-m altitude. For example, the Ferraris low-range meter measured 81.70% of its sea level value, whereas, the standard Wright measured 87.65% of its sea level value, a difference of approximately 6% between the two meters.

**DISCUSSION**

This study used a computer-controlled simulator to deliver a standard set of peak flows. The system has been shown to deliver the ATS 24 standard waveforms
accurately and precisely. Volume delivered from the simulator is determined only by the displacement of a piston and does not change with altitude. The dry rolling seal spirometer used in this study has been tested in our laboratory on several occasions and exceeds ATS accuracy criteria. In the present study, at all altitudes, the spirometer measured PEF, FVC, and FEV₁ on average within 0.34%, 0.36%, and 0.41% of target, respectively. The excellent correlation between the simulator target and spirometer values serves as a validation that both the simulator and spirometer are not affected by altitude. The altitude-related changes observed in the peak flow, therefore, are not due to altitude effects on the simulator.

All PEF meter models progressively underread PEF as altitude increased. The altitude effect is expected because the mechanical operation of these PFMs is dependent on air density. We found also that the altitude effect was less pronounced at lower flows in all meters. The underreading of PEF at altitude by these meters is expected because their mechanical operation is dependent on air density. The fall in density with altitude is not linear. Our finding of a linear effect of altitude is only a function of the narrow range of barometric pressures in the study. The effect of altitude should not, therefore, be extrapolated beyond the 3,000-m simulated altitude in this study.

When altitude effect is expressed as a percent of the target value, there is less consistency, but, in general, the pattern is reversed with the largest percent PEF changes occurring with the lowest flows (Table 4). The altitude effect, averaged from all meters, at each target flow ranged from -6.5 to -8.7% (Table 3) per 100 mm Hg decrease in barometric pressure.

The differences reported herein are similar to the average 6.6% per 100 mm Hg change in pressure reported by Thomas et al. In our study, however, the altitude effect is different at each target flow. For simplicity, it seems reasonable to use a 7% decrease in PEF per 100 mm Hg decrease in barometric pressure as a standard altitude effect because this is roughly the average altitude effect of 7.3% in our study (Table 3). However, when different models or technologies are applied to the measurement of peak flow, they should be tested to verify a similar altitude effect.

Since significant changes in peak flow measured by PFMs can be observed at differing altitudes, caution must be used in interpreting data when altitude change becomes an issue. A change of about 7% per 100 mm Hg fall in barometric pressure (approximately 1,400 m above sea level) is roughly twice the within-session variability of 3.6% for peak flow measurements in preshift limestone workers and greater than the 5.7% within-session variability seen in smokers, but less than the 10.4% within-session variability in asthmatics. A change caused by altitude could be greater than the “noise” inherent in making several within-session measures. The National Asthma Education Program (NAEP) defines a significant clinical change of peak flow to be more than 20%, and a 7% change in peak flows per 100 mm Hg fall in barometric pressure may occasionally have significant impact on clinical decisions.

Pneumotachs and mass flow sensors, devices that require calibration before each use, should also be affected by altitude since they rely on physical charac-
teristics of the measured gas for their operation, i.e., density and viscosity. The altitude effect should be eliminated when the devices are calibrated and used at a particular altitude. Calibration compensates for changes in the physical properties of the measured gases due to changes in barometric pressure.

We tested at a constant 60% relative humidity (RH) in contrast to the 100% RH of exhaled breath. Water vapor (PH2O) decreases the density of air at a given temperature by approximately the ratio $\frac{P_{B} - 0.35\times[PH2O]}{P_{B}}$. At sea level, a change in air density with a change from 60 to 100% RH is less than 1%. Further the temperature and RH of exhaled breath are relatively constant. The effect of a change in RH from 60 to 100% on air density is so small we believe our data can be extrapolated to clinical conditions.

Using an identical analysis as Forster and Parker, we found that PEF is approximately proportional to the square root of gas density. This is in contrast to the findings of Forster and Parker that find PEF proportional to the fourth root of gas density. This difference might be due to the wider range of gas densities that were analyzed by Forster and Parker.

If PFM's are used consistently at a single altitude to monitor change, the altitude-related undergrading is unimportant. If, however, flowmeter values are compared with reference values for diagnostic purposes, altitude could affect decisions, especially for group data. In situations in which large altitude changes occur, patients should be cautioned how the PFM readings will change.

Presently, NAEP performance standards for PFM's do not deal with the altitude effect. It is important to include guidelines concerning altitude when defining performance standards for PFM's and PEF reference values. For example, under current guidelines, it is possible for meters to be set up to read accurately at different altitudes. Since most of the population is located near sea level, new performance standards should require calibration at sea level.

References