Original Articles

Office spirometry: temperature conversion of volumes measured by the Vitalograph-R bellows spirometer is not necessary

F. MADSEN*, L. FRØLUND*, C. S. ULRIK† AND A. DIRKSEN‡

*Department of Internal Medicine B, University of Copenhagen at Frederiksberg, Denmark
†The RHIMA-centre, Department of Respiratory Medicine, The Rigshospital, University of Copenhagen, Tagensvej 20, DK 2200 Copenhagen N., Denmark

The aim of the present study was to investigate the relevance of BTPS (gas at body temperature, atmospheric pressure and saturated with water vapour) conversion of volumes measured with the Vitalograph bellows spirometer. The Vitalograph bellows were tested against a MicroMedical turbine spirometer in extreme temperatures (0-37°C) using a biological control to deliver expired gas at BTPS. Before testing, it was shown that the accuracy of the DairyCard turbine was stable in the relevant temperature range. In a clinical trial six patients with emphysema performed home spirometry b.i.d for 1 month using both the Vitalograph and the turbine. Both the DairyCard and the Vitalograph showed stable accuracy at extreme temperatures when results were reported without any BTPS conversion. These findings were supported by the clinical trial but the conclusions from the clinical setting were weakened by the surprising fact that domiciliary temperatures showed almost no variation. We conclude that the Vitalograph bellows, during dynamic spirometry, measures expired volume at conditions closer to BTPS (than to ATPS) gas at ambient temperature, atmospheric pressure and saturated with water vapour. The use of the BTPS correction based on ambient temperature seems unjustified at office temperatures close to 23°C and at extreme temperatures the conversion of volume will introduce significant over or underestimation.

Introduction

Expired volume measured using the Vitalograph bellows spirometer is today reported with a BTPS\textsubscript{pseudo} conversion of the measured volume, which is the volume within the bellows (BTPS, gas at body temperature, atmospheric pressure and saturated with water vapour). The BTPS\textsubscript{pseudo} conversion introduced by Vitalograph Ltd. implies multiplication of the bellows volume by a constant (1.085), assuming the gas, in the bellows, to be at ATPS (gas at ambient temperature, atmospheric pressure and saturated with water vapour), and a bellows temperature of 23°C. This constant is incorporated into the recording paper scaling. 'Correct' conversion of gas volumes (Table 1) assumes true information on gas conditions and therefore that the temperature of most volume recording spirometers should be measured inside the spirometer (1,2). When these data are obtained, the BTPS\textsubscript{correct} conversion is straightforward (3).

It has been recommended (BTPS\textsubscript{recommended}) (2) to use the ambient temperature as an estimate of bellows temperature in cases where internal measurement of temperature is not feasible, but this method has not been validated using the Vitalograph bellows. Two laboratory studies indicate that BTPS\textsubscript{recommended} conversion of volumes recorded with the Vitalograph-bellows spirometer can distort results (4,5). Even though the Vitalograph bellows has no internal thermometer we found it worthwhile to question the relevance of the 'pseudo' and 'recommended' BTPS conversion, because the Vitalograph bellows is one of the most popular spirometers in Western Europe. Since 1964 more than 100 000 have been sold. The purpose of the present investigation was therefore to examine the effect of different BTPS conversion factors on the accuracy of the Vitalograph bellows spirometer.
TABLE 1. In spirometric practise the factors in the table can be applied for volume conversion. The factors are derived from the formula, 
\[ V_{BTPS} = V_{ATPS} \left( \frac{B - P_{H2O \cdot \cdot \cdot}}{B - P_{H2O \cdot \cdot \cdot}} \right) \left( \frac{(273 + 37)}{273 + t} \right) \], where \( B \) is the barometric pressure, \( P_{H2O \cdot \cdot \cdot} \) is the pressure of water vapour at \( t \)°C, and \( t \) the temperature of the measured gas. The factor in parenthesis is the ATPS to BTPS conversion factor

<table>
<thead>
<tr>
<th>Term for conversion factor</th>
<th>Factor</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>BTPS_Correct</td>
<td>See equation</td>
<td>In the spirometer bellows</td>
</tr>
<tr>
<td>BTPS_Recommended</td>
<td>See equation</td>
<td>Ambient</td>
</tr>
<tr>
<td>BTPS_Pseudo</td>
<td>1.085</td>
<td>23°C</td>
</tr>
<tr>
<td>BTPS_Uncorrected</td>
<td>1.000</td>
<td>37°C</td>
</tr>
<tr>
<td>BTPS_TRUE</td>
<td>True BTPS-volume/volume measured with turbine DiaryCard</td>
<td></td>
</tr>
</tbody>
</table>

Patients and methods

As a part of a randomized clinical trial, six patients (Table 2) with emphysema performed domiciliary spirometry for 1 month using both a Vitalograph-R bellows and the direct BTPS recording spirometer (DiaryCard, Micromedical, Rochester, U.K.) (6). All patients had proved that they could perform high quality PASS (patient-administered serial spirometry) for at least 1 year and our spirometric methods and blinding procedures have previously been described in detail (7). In addition, one test subject with known repeatability of FEV₁ (7) was used as a biological control (SD of 10 FEV₁ measurements = 2.1%).

The DiaryCard turbine measures flow by electronic counting of the revolutions of the vane which is placed 11.3 cm from the distal end of the cardboard mouthpiece. Theoretically the DiaryCard is a direct BTPS recording instrument, therefore in an experimental setting it was tested in extreme temperatures to secure its recording validity.

The Vitalographs and DiaryCards were subsequently placed in a freezer and a heating chamber until the temperature, which was measured in 1 l of water, had been stable for at least 30 min. In an additional experiment thermocouples (Ni Cr-Ni Greisinger GTH 1200, Germany) were placed inside the bellows and spirometer respectively and the spirometer transferred from an ambient temperature of 15-6°C to 5-0°C, in order to detect differences between bellows and spirometer temperature during cooling.

Initially the complete DiaryCard with turbine was cooled but after malfunction of the electronics was observed at low temperatures only the turbine was cooled. The complete testing sequence, including removing the turbine from the freezer and the three rapid strokes with the syringe, was performed within 30 s. The turbines were not re-cooled between the strokes and therefore the turbine temperature would increase slightly between the first and last syringe stroke, which were within an interval of 25 s. No systematic effect on readings of heating or cooling between the first and third measurement was observed, even during a separate test with 10 min of heating. Calibration syringes, patient thermometers and thermocouples were calibrated and traceable to ISO. The BTPS_Recommended conversion was based on the ambient temperature measured by the patients themselves (Table 2) and the atmospheric pressure which varied between 997 and 1033 hPa (Danish

TABLE 2. Comparison of the effect of application of different BTPS conversion factors on volume recorded with the Vitalograph bellows. The domestic temperatures were relatively equal in the six homes (mean) and also constant (sp). No effect on the precision of FEV₁ was observed (confidence interval for the mean difference), but the accuracy of FEV₁ was best with the pseudo conversion of volume, due to the initial calibration of the Vitalograph

<table>
<thead>
<tr>
<th>Patients</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years) &amp; sex</td>
<td>40 F</td>
<td>50 M</td>
<td>62 M</td>
<td>64 F</td>
<td>49 F</td>
<td>30 F</td>
</tr>
<tr>
<td>FEV₁ (l)</td>
<td>1.64</td>
<td>2.30</td>
<td>1.48</td>
<td>1.37</td>
<td>1.73</td>
<td>0.99</td>
</tr>
<tr>
<td>Domiciliary temperature (mean °C)</td>
<td>23</td>
<td>24</td>
<td>23</td>
<td>23</td>
<td>21</td>
<td>22</td>
</tr>
<tr>
<td>SD temperature (°C)</td>
<td>0.73</td>
<td>1.42</td>
<td>1.39</td>
<td>1.51</td>
<td>2.61</td>
<td>1.04</td>
</tr>
<tr>
<td>Measurements (n)</td>
<td>46</td>
<td>55</td>
<td>70</td>
<td>103</td>
<td>69</td>
<td>54</td>
</tr>
<tr>
<td>Difference between FEV₁ reported with and without BTPS conversion</td>
<td>Mean (ml)</td>
<td>95% confidence interval (ml)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DairyCard - Vitalograph uncorrected</td>
<td>-113</td>
<td>-126.1</td>
<td>-100.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DairyCard - Vitalograph recommended</td>
<td>-112</td>
<td>-124.9</td>
<td>-98.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DairyCard - Vitalograph pseudo</td>
<td>13</td>
<td>0.1</td>
<td>26.3</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Meteorological Institute) (8). Full saturation of the gas in the bellows with water vapour was assumed.

The correction of gas volumes to conditions with different temperature and pressure is based on the gas law, $PV = nRT$, where $P$ is pressure, $V$ is volume, $T$ is temperature (degrees Kelvin), $R$ is the gas constant and $n$ the number of moles. According to this equation the gas volume at BTPS conditions can be calculated according to the formula

$$V_{\text{BTPS}} = V_{\text{ATPS}} \frac{(B - P_{\text{H2O-37}})}{(B - P_{\text{H2O-20}})} \times \frac{(273 + 37)}{(273 + t)}$$

where $B$ is the barometric pressure, $P_{\text{H2O-37}}$ is the pressure of water vapour at $37^\circ\text{C}$ and $t$ the temperature of the gas. The factor in parentheses is the ATPS to BTPS conversion factor. Changes in atmospheric pressure will only have a minor influence. The conversion factors used in practice in spirometry are given in Table 1.

STATISTICS

The correlations of forced expiratory volume in 1 s (FEV$_1$) measurements obtained with the turbine (BTPS$_{\text{TRUE}}$) and the FEV$_1$ obtained with the Vitalograph (BTPS$_{\text{UNCORRECTED}}$, BTPS$_{\text{RECOMMENDED}}$, BTPS$_{\text{RECOMMENDED}}$) were estimated by calculation of the 95% confidence interval (CI) for the mean differences (paired Student's t-test) (9). Comparison of the rate of change of bellows temperature and spirometer temperature during cooling was performed by linear regression.

Results

The assumption that the DiaryCard spirometer measurements were independent of ambient temperature was shown to be correct (Fig. 1). The accuracy and precision of the turbines were also independent of temperature in the range 0-35°C (Fig. 1), but when the DiaryCard electronics were cooled to below 0°C, malfunction of all DiaryCards occurred. The effects of the 'BTPS' conversion of volumes measured with the Vitalograph are given in Fig. 1 and Table 2. During cooling of the Vitalograph from 15.7 to 5.0°C, the rate of change during the first 9 min of cooling was $t_{\text{bellows}} = 0.078 - 0.016 \ln(t)$ and $t_{\text{spirometer}} = 0.071 - 0.030 \ln(t)$ (temperature in °C and time in min).

Discussion

In the laboratory part of the study we showed that the accuracy of the turbines was stable over a wide range of temperatures (Fig. 1). We therefore used DiaryCard turbines as our gold-standard.

The Vitalograph bellows showed stable accuracy at temperatures from 0 to 37°C when no temperature conversion was applied (Fig. 1). In contrast a severe temperature-dependent change in accuracy was found when the 'recommended' conversion of volume was applied, resulting in an overestimation of volumes at low temperatures (Fig. 1).

When the Vitalograph 'uncorrected' volume was applied an underestimation of volume of approx 0.5 was observed. This may simply be a matter of adjustment of the Vitalograph or related to the measurement with different meters (example: higher resistance of the Vitalograph will, in cases of negative effort dependence, increase FEV$_1$ (Fig. 1).

The experimental findings were confirmed in the study of emphysema patients, although the conclusion has to be restricted to a very narrow temperature range. Unexpectedly, all patients had very stable domiciliary temperatures. However, in a clinically-relevant range and under these conditions it seems safe to conclude that the BTPS$_{\text{RECOMMENDED}}$ or BTPS$_{\text{RECOMMENDED}}$ conversion of dynamic Vitalograph recordings did not improve accuracy. As shown in Table 2, the FEV$_1$ has the same degree of agreement with the true value (95% CI = approx. 25 ml) when volume is reported using BTPS$_{\text{UNCORRECTED}}$, BTPS$_{\text{RECOMMENDED}}$ or BTPS$_{\text{RECOMMENDED}}$. 
The explanation for these findings may be the relatively low heat conductivity of the Vitalograph plastic bellows, which may lead to a difference between temperature in the bellows and ambient or spirometer temperature during rapid changes in ambient or bellows temperature.

In conclusion, the Vitalograph measures FEV₁ closer to BTPS<sub>TRUE</sub> than ATPS and the measurements can be used without conversion of volumes.

Acknowledgements

We thank the Danish Lung Association, The Danish National Board of Health and ASTRA Denmark for financial support.

References