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BTPS Correction for Ceramic Flow Sensor*

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Several commercially available spirometers use unheated ceramic elements as flow sensors to determine flow and calculate volume of air. The usual method of correcting the resulting flow and volume values to body temperature pressure saturated (BTPS) is to apply a constant factor approximately equal to 30 percent of the full BTPS correction factor. To evaluate the usual BTPS correction factor technique, we tested several sensors with a mechanical pump using both room air and air heated to 37°C and saturated with water vapor. The volume signals used to test the sensors were volume ramps (constant flow) and the first four American Thoracic Society (ATS) standard waveforms. The percent difference in FEV_1 obtained using room vs heated-humidified air (proportional to the magnitude of the BTPS correction factor needed) ranged from 0.3 percent to 6.2 percent and varied with the number of maneuvers previously performed, the time interval between maneuvers, the volume of the current and previous maneuvers, and the starting temperature of the sensor. The temperature of the air leaving the sensor (exit temperature) showed a steady rise with each successive maneuver using heated air. When six subjects performed repeated tests over several days (each test consisting of at least three maneuvers), a maneuver order effect was observed similar to the results using the mechanical pump. These results suggest that a dynamic, rather than static, BTPS correction factor is needed for accurate estimations of forced expiratory volumes and to reduce erroneous variability between successive maneuvers. Use of exit air temperature provides a means of estimating a dynamic BTPS correction factor, and this technique may be sufficient to provide an FEV_1 accuracy of less than ±3 percent for exit air temperatures from 5° to 28° C. *(Chest 1994; 105:1481-86)*

ATS=American Thoracic Society; BTPS=body temperature pressure saturated

There are essentially two types of spirometers: those measuring volume directly and those measuring and integrating flow to determine volume of air. The flow type spirometer, because of its small size, is particularly well suited in situations where portability is important. An unheated ceramic flow sensor, one type of flow sensor frequently used to determine flow and calculate expiratory volume, is particularly well suited for use in battery-operated spirometers. These ceramic flow sensors do not need to be heated-a process that consumes considerable battery power. As they become available, these portable devices will likely have wide clinical application in the assessment of asthma, providing much useful information in addition to peak expiratory flow (*eg*, flow-volume curves and FEV_1s).

With any flow or volume measurement, it is usually necessary to correct values to body temperature pressure saturated (BTPS).[1] Most methods of correcting volumes to BTPS assume that expired air immediately cools to ambient temperature. The BTPS correction factor is based on ambient temperature, and to a lesser extent, barometric pressure. Although some cooling of the air occurs as the air passes through most ceramic flow sensors, cooling is usually not complete, and a BTPS correction factor somewhat less than the factor based on ambient temperature is required. The BTPS correction technique most frequently recommended by ceramic flow sensor manufacturers is to apply a static factor, based on room temperature, approximately equal to 30 percent of the full BTPS correction factor[2]—assuming only partial cooling of the air.

While using a constant BTPS correction factor may be adequate in some situations, we have observed that FVC and FEV_1 values from the first maneuver are usually lower than those for subsequent maneuvers (Fig 1). This trend was first suspected when an inordinate proportion of tested subjects, using a ceramic sensor, had difficulty satisfying the American Thoracic Society (ATS) FVC and FEV_1 reproducibility criteria (5 percent), primarily because of differences between the first and second maneuvers. Since one possible explanation for this observation was inappropriate BTPS correction, we investigated BTPS correction factor techniques in unheated ceramic flow sensors, using a mechanical lung simulator filled with either room air or air heated to 37°C and saturated with water vapor.

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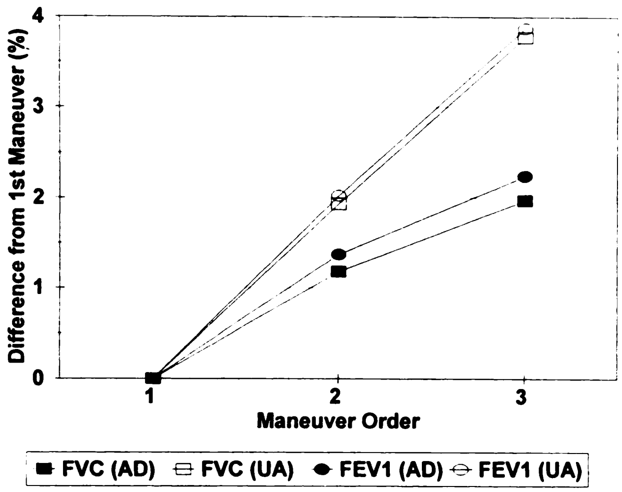

FIGURE 1. Average difference between first maneuver's FVC and FEV_1 values vs subsequent maneuvers for six subjects. Open symbols (UA) represent values obtained with constant BTPS correction factor and filled symbols (AD) represent results using dynamic BTPS correction factor.

METHODS

To investigate BTPS correction, five different experiments were conducted. Both the flow sensors and associated electronics were purchased (Tamarac Systems, Denver) and used with data acquisition software written specifically for our particular experiments. To calibrate the ceramic spirometry system, five runs of 30 different constant flows (6 L of volume injected at a constant flow) from 0.4 to 12 L/s were injected through each of the flow sensors (150 flow tests for each sensor). The resulting flows were measured and a calibration equation for flow was determined by using a quadratic function least squares fit to the 30 flow values. Volume was determined by integrating the calibrated flow signal.

Because of the inherent variability of spirometric parameters in human subjects, we decided to use a mechanical pump to simulate subjects performing an FVC maneuver.[3,4] In experiments 1, 2, 3, and 4, we tested several ceramic sensors, filling the mechanical pump with either room air or air heated to 37°C and saturated with water vapor. The dead space between the pump and the ceramic flow sensor was equal approximately to that of the mouthpiece used when testing subjects. The temperature inside the pump was measured before each test (thermocouple temperature probe, Doric model 412A) and was maintained between approximately 35° and 38°C. The temperature of the air as it left the flow sensor (exit temperature) was measured with a temperature sensor (National Semiconductor model LM34DZ) mounted to measure the downstream air temperature as shown in Figure 2. The percent difference between results using room air vs heated-humidified air was calculated using equation 1:

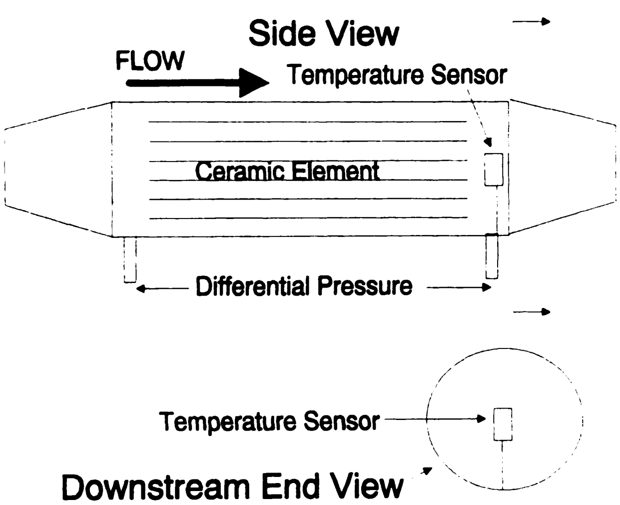

FIGURE 2. Diagram of ceramic flow sensor showing placement of air temperature sensor used to measure exit air temperature.

$$\text{(1)} \quad \text{Difference (\%)} = 100 \times \frac{\text{FEV}^1\ \text{heated} - \text{FEV}^1\ \text{room air}}{\text{FEV}^1\ \text{room air}}$$

Since a difference is being calculated, the uncorrected (no flow calibration or BTPS correction) values from the flow sensor were used in equation 1. The pump injected the identical volume or waveform but under two different conditions: (1) room air and (2) heated-humidified air. Therefore, any differences in results should be due to differences in the condition of the air passing through the sensor. The room air tests were conducted first, with the pump unheated for several days before the testing. Three repeated injections through the flow sensor, using room air, were conducted and the results were averaged for each of the waveforms to provide the FEV_1 room air results used in equation 1, for experiments 1 through 4.

In experiment 1, the first four ATS standard waveforms[1] (FVC=6.00, 5.00, 3.50, and 1.50 L, representing a range of expiratory volumes) were forced through the flow sensor. Each waveform was repeatedly forced through the flow sensor (ten times) as quickly as the simulator could be filled with heated-humidified air (less than 2 min between maneuvers). This experiment was conducted to simulate a subject performing ten consecutive FVC maneuvers within 2 min of each other.

In experiment 2, the time between successive maneuvers was varied (<1 min, 2 min, 5 min, 10 min, 15 min, and 20 min). The first ATS standard waveform was forced through the sensors, but five consecutive repeats, instead of ten (as in experiment 1), were conducted. This experiment was repeated on four different flow sensors and results were averaged for the four sensors. In both experiments 1 and 2, the flow sensors were flushed with room air and allowed to cool to ambient temperature before repeating the ten (five) consecutive maneuvers.

In experiment 3, to obtain a range of flow sensor (ceramic element) temperatures and a larger range of flows and volumes, 11 different ATS standard waveforms (1, 2, 3, 4, 12, 15, 17, 18, 21, 23, and 24) were forced through the sensor with less than a 2-min wait between consecutive simulated FVC maneuvers. The flow sensor was then flushed with room air and allowed to cool before the 11-waveform sequence was repeated (5 replicates).

In experiment 4, one flow sensor was cooled overnight to approximately 0°C and then tested in a fashion similar to experiment 3. These tests were conducted almost immeidately after the flow sensor had been removed from the cool environment, before the room environmental temperature (20°C) could significantly increase the temperature inside the ceramic element. The same 11-waveform sequence (1→24) was performed once and then the 11 waveforms were immediately repeated in reverse order (24→1). These tests provided lower exit air temperatures for our regression of percent difference in FEV_1 (equation 1) vs 1-s exit air temperature. For the regression analysis, all of the data from experiments 1 through 4 were used. Linear regression analysis consisted of a linear least squares fit to these data using a software package (MATLAB, The MathWorks, Inc; Natick, Mass).

In experiment 5, six subjects performed five coached FVC maneuvers on a dry rolling seal spirometer and, after a brief rest period, three additional FVC maneuvers on the flow spirometer using a ceramic flow sensor.[5] Subsequently, repeated FVC maneuvers were self-administered by the subjects on a portable flow spirometer every 2 h while awake for up to 12 days. The subjects were instructed to perform at least three FVC maneuvers at each test session. These subjects were part of an indoor air quality investigation and were performing repeated spirometry to assess changes in pulmonary function over the day and week—both at and away from work. To reduce fatigue and obtain better subject compliance with the testing protocol, the subjects were told they could terminate forced exhalation when the instrument beeped at 6 *s* after the onset of flow. Although the flow spirometer continued to collect data for up to 9 *s*, the resulting FVCs are actually the result of the subjects terminating their maneuvers after approximately 6 *s* of exhalation. To compare results using the volume spirometer with those using the flow spirometer, only the first three FVC maneuvers obtained on the volume spirometer were used. In addition, some comparisons were made using the FEV_6, since the exhalation times were limited to 6 to 9 *s* when using the flow spirometer. A dynamic BTPS correction factor previously described[4,6] was used to correct the FEV_1, FEV_6, and FVC obtained from the flow spirometer, the dynamic BTPS correction factor developed in this study was used.

Besides beeping at 6 *s*, the instrument provided feedback to the subject concerning the adequacy of his effort. This feedback consisted of either a blinking red (insufficient effort) or green light (good effort), depending on the reproducibility of peak flow.

For each subject, averages over all test sessions were calculated for FVC and FEV_1 by maneuver order. Sessions were excluded from the average if the session had less than three maneuvers. That is, the mean was calculated for all results from the first maneuvers at all sessions for a subject, both for FVC and FEV_1. Means were similarly calculated for all second and all third maneuvers. The percent difference of the second and third maneuvers compared with the first maneuver was then calculated for each subject and averaged to provide the results shown in Figure 1. To prevent an unsatisfactory maneuver from unduly influencing the results, any maneuver set (three maneuvers), which had an individual FVC or FEV_1 value that differed from other maneuvers in the set by more than ± 20 percent, was eliminated from this analysis. Five of 273 sets were eliminated. Two different BTPS correction factors were used for experiment 5. The first method used a factor that was 30 percent of the BTPS correction factor calculated using room temperature. The second method estimated a dynamic BTPS correction factor based on the regression analysis results obtained from experiments 1 through 4. The independent variable used to estimate the dynamic BTPS correction factor was exit air temperature.

Results

Figure 3 shows the results for experiment 1 or the percent difference between room air and air heated-humidified for FEV_1 vs the order in which the maneuvers were performed. The ten consecutive FVC maneuvers for each ATS waveform are connected by a line. For each successive FVC maneuver, the percent difference between room and heated air decreases, particularly for waveforms with larger volumes (ATS waveforms 1 and 2). Lower percent differences between room and heated air correspond to a smaller BTPS correction factor being required for BTPS correction. Note that for wave-

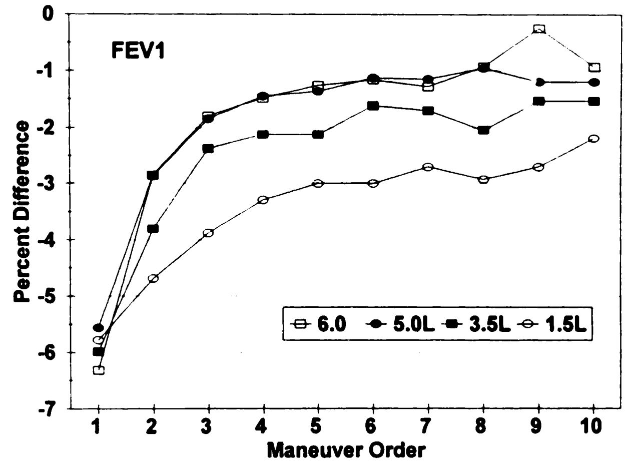

FIGURE 3. Percent difference in FEV_1 obtained using room air and heated-humidified air vs the order in which the maneuver was performed, using the first four ATS standard waveforms. Symbols represent different waveforms with different FVCs.

form 4 (FVC=1.5L), the magnitude of the percent difference remains greater than approximately 2 percent even after ten consecutive maneuvers have been performed.

Exit air temperature (placement of temperature sensor shown in Fig 2) at the end of each simulated FVC maneuver was measured and found to increase with each successive maneuver in a manner essentially the same as shown in Figure 3 for the percent difference in FEV_1. This increase in exit air temperature is most likely due to warming of the flow sensor's ceramic element with each successive maneuver. With the warming of the ceramic element, there is a corresponding decrease in the amount of heat removed from the air as it passes through the flow sensor.

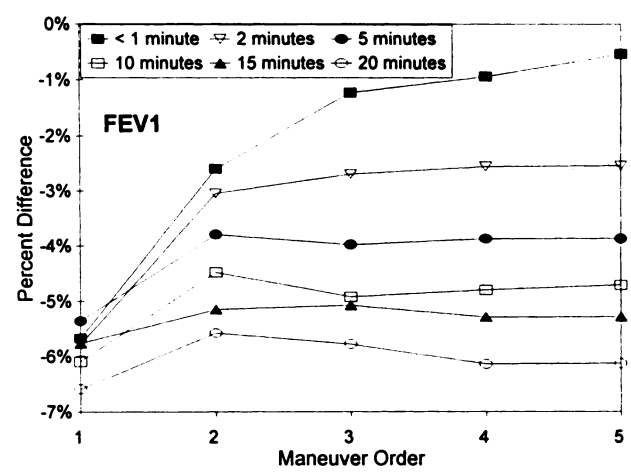

FIGURE 4. Percent difference in FEV_1 obtained using room air and heated-humidified air vs the maneuver number for six different time intervals between successive maneuvers (<1 min, 2 min, 5 min, 10 min, 15 min, and 20 min) using ATS standard waveform number 1. Sensor flushed with room air and allowed to cool between each time-interval series (connected points).

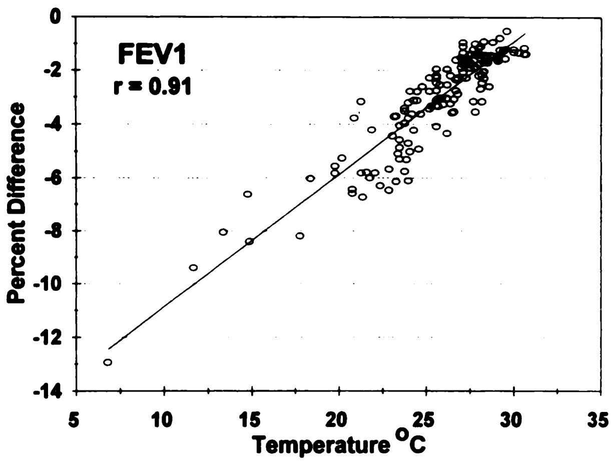

FIGURE 5. Percent difference in FEV_1 between room air and heated-humidified air vs exit temperature at 1 *s* after the start of exhalation.

Figure 4 shows the results for experiment 2 or the percent difference between room air and air heated-humidified for FEV_1 vs the order in which the maneuvers were performed using waveform 1 (FVC=6 L). The lines in this figure connect identical waiting times between successive maneuvers. Six different waiting times were used in this experiment. In addition to the effect of maneuver order shown in Figure 3, Figure 4 shows the percent difference was related to the time interval between successive maneuvers.

Figure 5 shows the relationship of the percent difference in FEV_1 between room air and heated-humidified air vs the exit air temperature at 1 *s* using data from experiments 1 through 4. A least squares linear fit to these data is shown in the figure and the correlation coefficient was 0.91. Since there were only a few data points at the lowest temperatures, a second linear fit was made using only data with temperatures greater than 20°C. The correlation coefficient in this analysis was only reduced to 0.89. If the relationship shown in Figure 5 is used to derive a dynamic BTPS correction factor, then the

Table 2—*Number of Repeated Examinations for Six Different Subjects*

Subject	1	2	3	4	5	6	Total
N	90	43	31	54	35	15	268

equivalent FEV_1 accuracy would be within ±2 percent when a dynamic BTPS correction factor is used. Similar results were obtained for $FEV_{0.5}$.

The results for experiment 5 (six subjects) are shown in Table 1 and Figure 1. Table 1 shows the FVC, FEV_1, and FEV_6 values obtained using a dry rolling sealed spirometer with the corresponding values using the flow sensor or flow spirometer. The FEV_6 measurements from the dry rolling seal spirometer were used in comparisons with the flow sensor FEV_6. Since the FVC maneuver was terminated after approximately 6 *s* of exhalation, the flow sensor FVC was approximately an FEV_6. The tests using the flow sensor were conducted after those using the volume spirometer with only a brief (<15 min) rest period. Table 2 shows the number of test sessions (at least three self-administered FVC maneuvers) for each of the six subjects. These repeated tests were used to derive the results shown in Figure 1. One flow spirometer malfunctioned and only 15 test sessions were obtained for subject 6.

As can be seen in Table 1, the volume and flow spirometer values of FEV_1 and FEV_6 are not statistically different ($p>0.14$), with mean differences of 0.10 and 0.13 L, respectively. The two subjects with the largest FVCs (cases 2 and 3) appear to contribute the most to these differences.

Figure 1 shows the average FVCs and FEV_1s for repeated testing sessions vs maneuver order. The FVC and FEV_1 values obtained (unfilled symbols) clearly show a maneuver order effect: the second and third maneuvers provide significantly larger values than the first maneuver when a constant BTPS correction factor is used. When an adjustment to the BTPS correction factor is made, based

Table 1—*FVC, FEV_1, and FEV_6 Results Using Both a Dry Rolling Seal Spirometer (VS) and a Flow Spirometer (FS) in Six Subjects**

Subject	FVC (VS), L	FEV_6 (VS), L	FEV_6 (FS), L	Δ FEV_6, L	FEV_1 (VS), L	FEV_1 (FS), L	Δ FEV_1, L
1	3.72	3.67	3.64	0.03	2.89	2.86	0.03
2	4.26	4.03	3.58	0.45	3.37	3.02	0.35
3	5.09	5.01	4.75	0.26	4.41	4.19	0.26
4	3.41	3.17	3.08	0.09	2.53	2.49	0.04
5	2.71	2.50	2.46	0.04	1.06	1.91	0.03
6	2.54	2.31	2.39	0.08	1.24	1.31	−0.07
			Mean	0.13†		Mean	0.10†
			SD	0.17		SD	0.14

*Examinations using the flow sensor were conducted after those using the volume spirometer with only a brief (<15 min) rest period.
†Not significant.

on the exit air temperature (filled symbols), the maneuver order effect is still present but is reduced and the resulting values are within ±3 percent. The standard errors of the mean or standard deviations are not shown in Figure 1 because they were extremely small, due to the large number of repeated examinations (N=268).

Discussion

The percent difference in FEV_1, obtained using room vs heated-humidified air (proportional to the magnitude of BTPS correction factor needed), ranged from 0.3 percent to 6.2 percent and varied with the number of maneuvers previously performed, the time interval between maneuvers, the volume of the current and previous maneuvers, and the starting temperature of the sensor. Correspondingly, the temperature of the air leaving the sensor (exit) temperature) showed a steady rise with each successive maneuver using heated air. When six subjects performed repeated tests over several days, a maneuver order effect was observed similar to the results obtained using the mechanical pump.

One possible explanation for the larger FEV_1 and FEV_6 values, with subsequent FVC maneuvers, is the buildup of water condensation within the sensor, rather than a warming of the sensor's surface or change in BTPS correction factor. We considered, but rejected, this explanation for several reasons. In experiment 4, we cooled a sensor to below 0°C overnight and the following day injected 20 consecutive FVC maneuvers using heated-humidified air. At the completion of these maneuvers, we detected some water condensation on the aluminum housing but none within the ceramic element of the sensor. Additionally, there is a rise in exit air temperature and a corresponding decrease in the percent difference with each consecutive FVC maneuver, until a plateau is reached. This initial rise and plateau (shown in Fig 3) suggest that the sensor has reached an equilibrium in temperature approximately equal to the air passing through. Water condensation should not be significant since the sensor and air temperatures are approximately equal.

Our results using room air vs heated-humidified air are best explained by a transfer of heat from the air to the ceramic element of the flow sensor as the air passes through the sensor. The amount of heat transferred to the sensor is proportional to the volume of air that passes through the sensor. With FVCs of 5 to 6 L and with an initial sensor temperature of 20°C, the heat transfer after two consecutive trials is sufficient to raise the surface temperature of the sensor to a level at which little additional heat transfer occurs. This heat slowly dissipates with time, with the sensor returning to ambient temperature within approximately 20 min. The fact that the sensor temperature rapidly rises with each successive FVC maneuver probably explains why water condensation has not affected test results.

Our results also suggest that because of this heating of the sensor, a dynamic BTPS correction factor is needed to accurately estimate forced expiratory volumes. The error introduced by using a fixed BTPS correction factor was dependent on the number of maneuvers previously conducted on the sensor, the time interval between the maneuvers, the volume of the current and past maneuvers, and the initial temperature of the sensor. Because of the number of different parameters influencing the effective temperature or BTPS correction factor, some additional measure of sensor temperature other than ambient temperature is needed. Use of exit air temperature may provide a means of estimating a dynamic BTPS correction factor necessary to provide an FEV_1 accuracy of less than ±3 percent for exit air temperatures from 5 to 28°C. However, the results using human subjects suggest that exit air temperature alone may not completely eliminate the difference due to maneuver order (Fig 1). Specifically, exit air temperature may slightly overestimate the sensor temperature for the first maneuver and slightly underestimate sensor temperature for subsequent maneuvers.

Our results using the mechanical simulator assumed that the temperature of the forced exhaled breath is approximately 37°C. However, the temperature of exhaled air may not be 37°C. One study[7] has reported it to be closer to 34°C and we have measured approximately 35.5°C. In addition, the subject's exhaled air contains approximately 5 percent CO_2 that was not present in our experiments using the mechanical simulator, filled with air from the room.

Another possible explanation for the maneuver order effect is the subjects may be exhibiting a learning effect or somehow varying their efforts in this uncoached environment, thereby increasing their values with each successive maneuver. However, feedback based on peak flow was provided to the subject after each maneuver to encourage a maximal effort.

Although the volume spirometer-determined values of FEV_1 and FEV_6 were slightly higher than those obtained on the flow spirometer, these differences were not statistically significant. These differences may be due in part to an absence, with the flow spirometer, of immediate feedback of the FEV_1 and other values as maneuvers are performed. When using the volume spirometer, the FEV_1, FVC, peak flow, and other values are provided to the technician as each maneuver was completed. Regardless, additional studies are necessary to explain the slight differences between results obtained using the mechanical pump vs human subjects.

We believe the best explanation for our results is that the sensor is warming from its initial room temperature with each successive FVC maneuver. Therefore, some measure of sensor temperature other than ambient temperature is warranted and a dynamic, rather than a static, BTPS correction factor should be used. This approach is needed for accurate estimations of forced expiratory volumes and to reduce the erroneous variability in FVC and FEV_1 between successive maneuvers. These results also highlight the need for spirometer testing using heated-humidified air.

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