special communication

Dynamic BTPS correction factors for spirometric data

JOHN L. HANKINSON AND JOSEPH O. VIOLA
Division of Respiratory Disease Studies, National Institute for Occupational Safety and Health, Morgantown, West Virginia 26505

HANKINSON, JOHN L., AND JOSEPH O. VIOLA. *Dynamic BTPS correction factors for spirometric data.* J. Appl. Physiol.: Respirat. Environ. Exercise Physiol. 55(4): 1354–1360, 1983.—Because it is often difficult to completely control ambient temperature, a study was conducted to investigate dynamic body temperature pressure saturated (BTPS) correction factors for spirometric data. A forced expiratory simulator system was heated to 37°C and loaded with air saturated with water vapor. This air was then forced from the simulator into a dry rolling-seal spirometer maintained at various ambient temperatures from 3 to 32°C. Errors in forced expiratory volume in 1 s (FEV_1) and peak flow from assuming a constant BTPS correction ranged from 7.7 and 14.1% at 3°C to 2.1 and 4.6% at 23°C. Differences between errors observed when saturated and dry air were forced into the spirometer indicate that water vapor condensation introduces an added heat load to the spirometer, adding approximately one percent to the error in FEV_1 at lower temperatures. By use of a model to estimate the dynamic BTPS correction factor, errors in FEV_1 at all temperatures between 3 and 32°C were reduced to less than 1.5%.

pulmonary function tests; spirometry; lung volume measurements; temperature correction

ALL COMMON SPIROMETRIC PARAMETERS (e.g., forced vital capacity, forced expiratory volume in 1 s) are reported at body temperature pressure saturated (BTPS). To convert values obtained at ambient temperature pressure saturated (ATPS), particularly for volume-measuring spirometers, it is necessary to multiply each observed value by a BTPS correction factor. This correction factor is a function of ambient temperature and to a lesser extent ambient pressure. A constant BTPS correction factor is applied with the assumption that the subject's exhaled air (~37°C) cools instantly upon entry into a spirometer. This assumption is not correct, and in a previous study of spirometers (1) at 22°C, the error introduced to the measurement of forced expiratory volume in 1 s (FEV_1) was found to be about 2%.

In field studies it is often difficult to completely control ambient temperature. As ambient temperature decreases, there is a corresponding increase in error due to the faulty assumption of a constant BTPS correction factor. When spirometer temperature during the early stages of expired breath has not reached equilibrium with ambient temperature, the BTPS correction factor is falsely elevated; and correspondingly, the corrected FEV_1 is falsely elevated. The forced vital capacity (FVC) is usually not in error since sufficient time usually has elapsed for thermal equilibrium to occur.

The error introduced due to low ambient temperature is a particular problem in epidemiologic studies because it introduces a constant bias into the data. If ambient temperature is different during two studies, then statistically significant differences in FEV_1 could be observed between the studies due to the ambient temperature differences alone. For example, during a recent study at a cotton-processing facility, the temperature was 10°C during the preshift examinations. After 6 h of exposure, the spirometric examinations were repeated on the same subjects. However, the ambient temperature after the work shift was approximately 25 or 15°C higher.

Upon analysis of these data, an average decrease in FEV_1 of approximately 4% over the work shift was observed. Not only was a decrease observed for the exposed workers but also for the technicians who were conducting the examinations. This decrease was thought to be explained by the increase in ambient temperature over the work shift. With low temperatures, the BTPS correction factor was falsely elevated, resulting in falsely elevated FEV_1's. After the work shift, the FEV_1's were less in error because of a higher temperature, and therefore statistically significant drops over the work shift were observed. The cotton dust standard defines a worker as a possible "reactor" if he has a 5% or greater drop in FEV_1 over the work shift.

The present study was conducted to obtain additional information concerning the effects of ambient temperature on spirometric results.

METHODS

To investigate the effects of ambient or spirometer temperature on spirometric data, a forced expiratory volume stimulator was heated to 37°C, and this heated air was forced into a spirometer maintained at various temperatures from 3 to 32°C. The forced expiratory simulator is a servo-controlled hydraulic pump capable of delivering any input waveform within the physiological range of a human subject. The mechanical pump was placed in a chamber heated to 37 ± 1°C. The exact instantaneous displacement, and therefore output volume of the pump, was measured by a linear velocity-displacement transducer (LVDT) mounted on the pump. However, to obtain the instantaneous volume of gas delivered to the spirometer, the volume lost to gas compression within the pump (Vcomp) must be subtracted from the pump displacement

$$\mathrm{Vcomp} = \mathrm{PcompVpump}/(\mathrm{Patm} - \mathrm{P_{H_2O}})$$

where Pcomp is the pump pressure increase with gas compression; Vpump is the instantaneous total volume within pump, Patm is the barometric pressure; $\mathrm{P_{H_2O}}$ is the water vapor pressure; and

$$\mathrm{Vp} = 6.0 - \mathrm{Vpump} - \mathrm{Vcomp}$$

where Vp is the corrected pump volume output and maximum pump volume = 6.0 liters.

An Ohio Medical Products model 840 rolling-seal spirometer was placed in an environmental chamber and maintained at temperatures from 3 to 32 ± 1°C. The analog volume signals from both the mechanical pump and spirometer were acquired by a digital computer (LSI-11) using a 12-bit analog-to-digital converter and a 10-ms sampling interval (100 samples/s). These data were stored on digital cassettes for later analysis. Selected tests were also conducted on a Stead-Wells water-sealed spirometer (Warren Collins, Braintree, MA).

Before analysis of the temperature effects could be conducted, it was necessary to account for the dynamic characteristics of the spirometer and gas compression within the spirometer. Therefore, the waveforms were forced into the spirometer with the spirometer and the pump at the same temperature and humidity. In this manner, the spirometer output as a function of the input waveform with no temperature effect could be determined for later reference. This particular procedure was conducted three times, and the average of the three trials was used. All trials conducted at other temperatures were then referenced to these values, thereby removing the effects of any static or dynamic deficiencies of the spirometer as well as correcting the spirometer volume for gas compression. For example, at high flow rates, the spirometer lagged behind the pump displacement during the high flow portion of the maneuver, due in part to gas compression within the spirometer. Since we are using relatively small volume differences to measure the effects of temperature, even small errors can be significant.

Calibration was performed with each waveform by correcting the final or steady-state spirometer volume (corrected using pump and spirometer temperatures) to agree with the final pump displacement as measured by the LVDT. At the end of each maneuver, the pump was held at the final displacement for an additional 10 s, and volume data were collected every 100 ms to ensure that thermal equilibrium had been reached for determination of FVC. Pump and spirometer temperatures were measured with a thermocouple having an accuracy of ±0.5°C.

When investigating the dynamic BTPS factor, water vapor present in exhaled air (saturated air) must also be considered. Two different humidity conditions were used to load the simulator: *1*) vapor pressure = 10 Torr and *2*) vapor pressure = 47 Torr. The first condition was obtained by loading the simulator with room air at approximately 35% relative humidity. The second condition was obtained by loading the simulator with air from an enclosure heated to 37°C and saturated with water vapor by a vaporizer. The relative humidity in the enclosure was measured and maintained to within 3% of 100% relative humidity or saturated. The BTPS factor can be obtained from the gas laws by

$$\mathrm{PpVp/Tp} = \mathrm{PsVs/Ts}$$

where Pp is the pump pressure, Vp is the corrected pump volume decrease; Ps is the spirometer pressure; Vs is the corrected spirometer volume increase; Tp is the pump temperature; and Ts is the spirometer temperature.

Therefore

$$(\mathrm{Patm} - \mathrm{P_{H_2O(37)}})\mathrm{Vp}/310 = (\mathrm{Patm} - \mathrm{P_{H_2O(T)}})\mathrm{Vs}/(\mathrm{Ts} + 273)$$

where Patm is the barometric pressure or 740 Torr; $\mathrm{P_{H_2O(37)}}$ is the water vapor pressure at 37°C (47 Torr); and $\mathrm{P_{H_2O(T)}}$ is the water vapor in Torr at a particular temperature (at 3°C, saturated air, $\mathrm{P_{H_2O(3)}} = 6$ Torr).

When the simulator is loaded using room air at 20°C and approximately 35% relative humidity, the vapor pressure at 37°C is approximately the same as at the lowest temperature (3°C or 6 Torr). Since the water vapor pressure is the same for both temperatures and since corrections for gas compression have been applied, pressure can be neglected and the equation can be simplified to

$$\mathrm{Vp}/310 = \mathrm{Vs}/(\mathrm{Ts} + 273)$$

and

$$\mathrm{Ts} = (310\mathrm{Vs} - 273\mathrm{Vp})/\mathrm{Vp}$$

Therefore, it is possible to calculate the effective temperature of the spirometer as a function of time, since Vs and Vp are both measurable. Notice that for very small Vp, Ts is indeterminable; therefore, all data were analyzed after *time 0*, as determined by backextrapolation of the volume-time curve, and very small Vp's were avoided. Again, since Ts is known as a function of time, the water vapor pressure ($\mathrm{P_{H_2O(T)}}$) as a function of time (or temperature) can also be calculated and used to calculate a simulated dynamic BTPS correction factor

$$\mathrm{Vp}(t) = \mathrm{BTPS}(t) \times \mathrm{Vs}(t)$$

where

$$\mathrm{BTPS}(t) = [310(\mathrm{Patm} - \mathrm{P_{H_2O(T)}})]/[(\mathrm{Ts}(t) + 273)(\mathrm{Patm} - \mathrm{P_{H_2O(37)}})]$$

Since we are loading the simulator with a low water vapor pressure, there is little or no change in vapor pressure as the air is cooled to the lowest temperature used in the study. This test condition is similar to using dry air, and for the purposes of this report, we will refer to this test condition as dry air.

The above condition assumes that temperature conditions in the spirometer will behave similarly with or without air saturated with water vapor as long as water vapor is included in the calculations. The advantages of using dry air (low humidity) are the simplicity of the testing conditions and the capability of calculating temperature as a function of time. We know of no method of dynamically measuring humidity or the vapor pressure of the air in the spirometer, and therefore dynamic temperature could not be derived with saturated air.

Since the conversion of water vapor to a liquid releases heat which must be transferred from the spirometer, tests using saturated air (37°C) were also conducted to investigate the effects of water vapor. Water vapor pressure of 47 Torr at 37°C can in theory make a considerable contribution to the amount of heat that must be transferred from the spirometer. For example, the heat of vaporization for water is approximately 539 cal/g of water. When air saturated with water vapor (37°C) is cooled to 3°C, the partial pressure of water vapor pressure drops from 47 to 5.8 Torr, and approximately 250 mg of water will condense out of 6 liters of air. Therefore, approximately 135 cal of heat are released which must be transferred from the spirometer. In comparison, if 6 liters of dry air are cooled from 37 to 3°C (specific heat of air is 0.241 cal/g of air), approximately 60 cal of heat must be transferred from the spirometer. So the amount of heat to be transferred is much greater if water vapor is present, and a difference in the rate at which heat is transferred from the spirometer with dry and saturated air would be predicted.

The percent error with saturated air was calculated from the corrected pump displacement (Vp) and corrected spirometer volume (Vs) by

$$P_e = 100F_e = [100(Vp - Vs)]/Vs$$

where P_e is the percent error and F_e is the fractional error. Also notice that BTPS = $1 + F_e$, since Vp = BTPS = $1 + F_e$, since Vp = BTPS × Vs, Vp = $[1.0 + F_e]$Vs, Vp = Vs + F_e × Vs, and F_e = (Vp − Vs)/Vs.

Notice that for any very small Vs, F_e is indeterminable; therefore, all data were analyzed after *time 0* (as determined by backextrapolation of the volume-time curve), so that very small Vs's were avoided.

To completely characterize the temperature effects, the spirometer was driven with a variety of different types of waveforms. Linear ramp waveforms were chosen to simplify the analysis of the temperature effects. For the ramp waveforms, flow rates of 0.6, 3, 6, and 9 l/s and volumes of 1, 2, 3, 4, 5, and 6 liters were used to determine whether the temperature effects were flow or volume dependent with dry air. Exponential waveforms were used because they presented a simple mathematical approximation of the type of waveform that a patient produces. Exponential waveforms with time constants of 0.4, 0.8, and 2 s and FVC's of 1.5, 3.5, 5, and 6 liters were used. In addition to these waveforms, waveforms from 12 patients were used to provide a final test of any model that might be developed. A description of these waveforms has been previously published (1–3).

RESULTS

Figure 1 shows a plot (using a filtered exponential waveform and with the spirometer at 3°C) of the percent error in volume introduced by assuming a constant BTPS factor (see equations) for dry air and air saturated with water vapor. For example, at 1 s, the BTPS correction factor should be approximately 1.126 instead of 1.19, and a 6.4% error is made by assuming a constant BTPS correction factor. Notice that a significant difference exists between the results when dry air is used and when saturated air is used. Only the initial 5 s of the curves are shown in the figures as the percent errors approach zero by the end of the maneuver. The differences between these curves are most likely due to the increased heat load caused by condensation of water vapor. Table 1 shows the mean percent error introduced by incorrectly assuming a constant BTPS correction factor for calculating the FEV_1 when dry air is loaded into the simulator and water vapor pressure is estimated from the dynamic temperature. Similar dry-air test results were obtained for the Stead-Wells spirometer (4.4% error in FEV_1 at 10°C). Table 1 also shows the mean percent error introduced by incorrectly assuming a constant BTPS correction factor for calculating the FEV_1 when saturated air is loaded into the simulator. Notice in Table 1 (saturated air) that at 23°C the percent error in FEV_1 introduced by assuming instantaneous equilibrium with ambient temperatures (constant BTPS correction factor) is about 2%, as found in a previous study (1). However, at lower temperatures (3°C saturated air), the percent error becomes much more significant, as much as 12.8% for one waveform, with an average of 7.7% for all the patient waveforms used in this study.

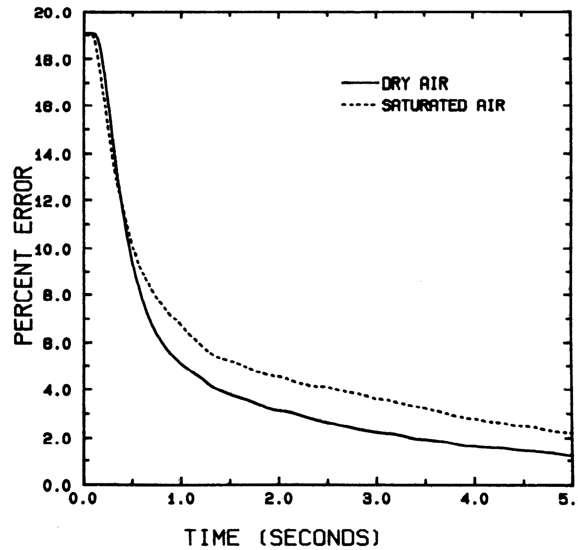

FIG. 1. Plot of percent error introduced by assuming a constant BTPS correction factor for dry air and air saturated with water vapor as a function of time for a filtered exponential waveform at 3°C (waveform 1, time constant = 0.8 s, FVC = 6.00, FEV_1/FVC% = 70.7, PF = 7.17). See text for abbreviations.

Figure 2 shows the percent error in volume introduced by assuming a constant BTPS correction factor for a filtered exponential waveform at 11 different temperatures using saturated air. The results at 7 and 9°C were excluded as a small leak was suspected on the day these tests were conducted and could not be confirmed until the data were analyzed.

An attempt was also made to determine a dynamic correction factor for flow rates. Table 2 shows the percent

TABLE 1. *Percent difference for 12 waveforms between actual and corrected FEV_1 using a constant BTPS correction factor*

Spirometer Temperature, °C												
3	5	7	9	11	13	15	17	20	23	26	29	32
Simulator loaded with dry air at 37°C												
6.4 ±2.0	6.0 ±2.0	5.3 ±1.7	6.2 ±1.9	4.0 ±0.8	3.6 ±1.0	3.7 ±1.4	3.3 ±1.0	2.9 ±1.1	2.9 ±1.1	2.9 ±1.6	1.6 ±0.9	1.3 ±1.0
Simulator loaded with saturated air at 37°C												
7.7 ±1.9	6.6 ±1.8			5.1 ±1.3	4.5 ±0.9	4.8 ±1.3	4.1 ±0.9	3.1 ±0.9	2.1 ±0.7	1.5 ±0.7	0.8 ±0.4	0.0 ±0.3

Values are means ± SD. FEV_1, forced expiratory volume in 1 s; BTPS, body temperature pressure saturated.

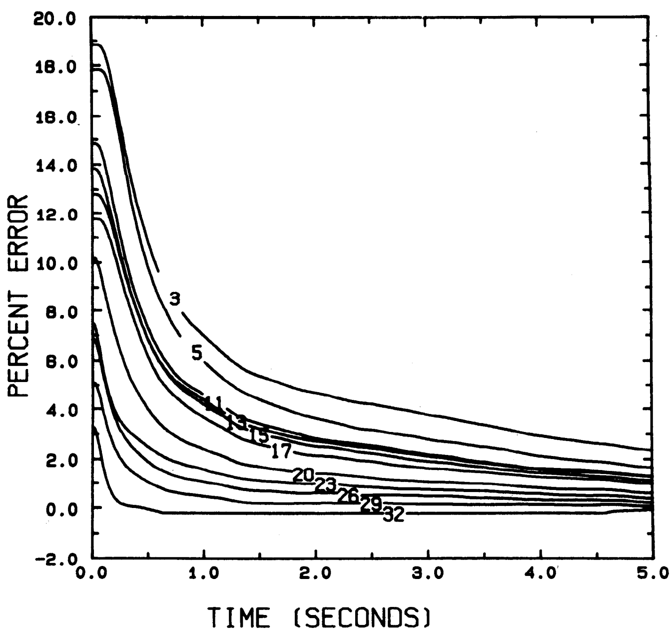

FIG. 2. Plot of percent error introduced by assuming a constant BTPS correction factor for air saturated with water vapor as a function of time for a filtered exponential waveform (waveform 1) at 11 different temperatures (3, 5, 11, 13, 15, 17, 20, 23, 26, 29, 32°C).

TABLE 2. *Percent difference for 12 waveforms between actual peak flow and corrected, actual peak flow and uncorrected peak flow, using a constant BTPS correction factor*

Spirometer Temperature, °C										
3	5	11	13	15	17	20	23	26	29	32
Corrected										
14.1 ±4.6	12.0 ±4.4	8.9 ±3.5	8.9 ±5.0	9.0 ±3.5	8.5 ±5.2	7.4 ±4.2	4.6 ±3.1	3.6 ±2.8	2.0 ±1.1	0.2 ±0.5
Uncorrected										
−4.9 ±4.6	−6.0 ±4.4	−6.1 ±3.5	−5.1 ±5.0	−4.0 ±3.5	−3.4 ±5.2	−2.9 ±4.2	−4.0 ±3.1	−3.3 ±2.8	−3.2 ±1.1	−3.1 ±0.5

Values are means ± SD. Simulator was loaded with saturated air at 37°C. BTPS, body temperature pressure saturated.

errors for peak flow when a constant BTPS correction factor is used and when no BTPS correction is used. Notice in Table 2 that the true peak flow is closer to the uncorrected than to the corrected values. When considering flow-volume curves, the problem becomes much more complex. Since flow is plotted as a function of volume, both volume and flow must be dynamically corrected.

Table 3 shows the percent error introduced for forced expiratory flow at 50 and 75% of vital capacity ($FEF_{50\%}$ and $FEF_{75\%}$, respectively) when a constant BTPS correction factor is applied to both volume and flow. For both $FEF_{50\%}$ and $FEF_{75\%}$, the percent error is highly variable between patient waveforms and can be significant with respect to the American Thoracic Society (ATS) accuracy requirement of 5% for flow. Because of the inherent noise in flow measurements and the variability between the waveforms for the different patients, a model that would consistently correct flow-volume curves to true BTPS is difficult to develop. Notice in Table 4 that the $FEF_{50\%}$ and $FEF_{75\%}$ are closer to the actual values with no BTPS correction than when a constant BTPS correction factor is used (Table 3). Volume in Tables 3 and 4 was corrected using a constant BTPS correction factor.

The intersubject variability in FEV_1, $FEF_{50\%}$, and $FEF_{75\%}$ errors was expected. The flow profile used to obtain a particular volume has a significant effect on the instantaneous average temperature within the spirometer and therefore on the instantaneous dynamic BTPS correction factor. Since no two patients have exactly the same volume-time curve, the percent error in FEV_1 (assuming a constant BTPS factor) should be different.

TABLE 3. *Percent difference for 12 waveforms between actual $FEF_{50\%}$ and corrected $FEF_{50\%}$, actual $FEF_{75\%}$ and corrected $FEF_{75\%}$, using a constant BTPS correction factor*

Spirometer Temperature, °C										
3	5	11	13	15	17	20	23	26	29	32
$FEF_{50\%}$										
15.7 ±18.9	13.4 ±16.7	9.8 ±13.2	8.5 ±13.5	9.4 ±13.2	8.3 ±10.5	6.1 ±10.5	3.9 ±5.3	3.6 ±3.8	2.1 ±3.2	0.2 ±1.2
$FEF_{75\%}$										
25.9 ±15.0	25.6 ±12.4	21.8 ±14.7	21.7 ±12.7	21.7 ±13.8	20.2 ±12.5	15.7 ±11.8	9.4 ±7.4	6.2 ±6.5	2.8 ±5.2	−0.4 ±2.4

Values are means ± SD. Simulator was loaded with saturated air at 37°C. $FEF_{50\%}$ and $FEF_{75\%}$, forced expiratory flow at 50 and 75% vital capacity, respectively; BTPS, body temperature pressure saturated.

TABLE 4. *Percent difference for 12 waveforms between actual $FEF_{50\%}$ and uncorrected $FEF_{50\%}$, actual $FEF_{75\%}$ and uncorrected $FEF_{75\%}$*

Spirometer Temperature, °C										
3	5	11	13	15	17	20	23	26	29	32
$FEF_{50\%}$										
−3.3 ±18.9	−4.6 ±16.7	−5.2 ±13.2	−5.5 ±13.5	−3.6 ±13.2	−3.6 ±10.5	−4.2 ±10.5	−4.7 ±5.3	−3.3 ±3.8	−3.1 ±3.2	−3.1 ±1.2
$FEF_{75\%}$										
6.9 ±15.0	7.6 ±12.4	6.8 ±14.7	7.7 ±12.7	8.8 ±13.8	8.3 ±12.5	5.3 ±11.8	0.7 ±7.4	−0.7 ±6.5	−2.4 ±5.2	−3.7 ±2.4

Values are means ± SD. Simulator was loaded with saturated air at 37°C. $FEF_{50\%}$ and $FEF_{75\%}$, forced expiratory flow at 50 and 75% vital capacity, respectively.

DESCRIPTION OF DYNAMIC BTPS MODEL

The dynamic BTPS correction factor model consists of a piecewise fit to the curve as shown in the Fig. 3 at 3°C temperature. The first component of the piecewise fit is a linear fit and the second component is a fit of two exponential functions. The first step in implementing the model is to estimate the time required for the dynamic BTPS correction factor to reach $Y_{1/2}$, one-half of the difference between 1.0 and the steady-state correction factor. The best estimate for this time parameter (T_{off}) is 3.0 s divided by the observed peak flow, with the resulting time being limited to less than 1 s. For extremely low peak flows, it is necessary to limit the offset time (T_{off}) to 1 s. A linear approximation from *time 0* to (T_{off}, $y_{1/2}$) is used to estimate the dynamic correction factor during the initial phase of the FVC maneuver.

The remaining component of the piecewise fit is only used after T_{off} has occurred or $Y_{1/2}$ has been achieved and consists of the sum of two exponential functions. The first exponential is related to the rate at which the air cools while air is entering the spirometer or the turbulent heat transfer rate. The time constant during this phase is approximately 0.25 s for dry air and 0.33 s for air saturated at 37°C. The second exponential is related to the rate at which the air cools when no air is entering the spirometer or the nonturbulent heat transfer rate. The time constant during this phase is approximately 3.3 s for dry air and 5.0 s for air saturated at 37°C. For $0 < T_n < T_{\mathrm{off}}$

$$\mathrm{BTPS}(T_n) = 1 + Y_{1/2} \times T_n/T_{\mathrm{off}}$$

For $T_n > T_{\mathrm{off}}$

$$\mathrm{BTPS}(T_n) = 1 + T_{\mathrm{off}} + (Y_{1/2}/V_n) \sum_{i=1}^{n} \{2 - \exp \cdot [(T_i - T_n)/T_s] - \exp[(T_i - T_n)/T_f]\} dV_i$$

where $T_{\mathrm{off}} = 3/\mathrm{PF}$ (PF is the peak flow in l/s); $Y_{1/2} = (\mathrm{BTPS_s} - 1)/2$ ($\mathrm{BTPS_s}$ is the static BTPS factor); V_n is the volume at n sample point; $T_n = n/R$ (n is the number of sample points from start of exhalation to V_n and R is the number of samples/s); $T_i = i/R$ (i = 1 to n, i.e., number of sample points from start of exhalation to V_i); $T_s = 3.3$ s for dry air and $T_s = 5.0$ s for saturated air; $T_f = 0.25$ s for dry air and $T_f = 0.33$ s for saturated air; and dV_i is the change in volume from V_{i-1} to V_i.

The model was first derived from the dry-air volume ramp waveforms by estimating the two time constants for the exponential (curve-stripping method) and then further refined by trial and error using air saturated with water vapor. Figure 3 shows the model fit for 3°C and air saturated with water vapor for a filtered exponential waveform. By use of the model, at each temperature the average error in FEV_1 is reduced to less than 1.5% and typically less than 1%.

When flow-time curves or flow-volume curves (Fig. 4) are examined, it is obvious that the simplest model for correcting peak flow is to use the uncorrected flow values. Some additional accuracy is obtained if a correction factor of 30% of static BTPS correction is used for peak flow, or

$$\mathrm{BTPS}_{\text{for peak flow}} = 1 + 0.3(\mathrm{BTPS_s} - 1.0)$$

where $\mathrm{BTPS_s}$ is the static BTPS correction factor.

Peak flow usually occurs early in the FVC maneuver when the volume in the spirometer is small and the heated air, rapidly entering the spirometer, has not had sufficient time to cool. For all flow rates, the dynamic correction factor is dependent on the dynamic BTPS correction factor and the rate at which the dynamic correction factor is changing with time or

$$\mathrm{flow}(t) = d[\mathrm{BTPS}(t)V(t)]/dt$$

Since $\mathrm{BTPS}(t)$ is a function of time, then

$$\mathrm{flow}(t) = [dV(t)/dt]\mathrm{BTPS}(t) + [d\mathrm{BTPS}(t)/dt]V(t)$$

where $d\mathrm{BTPS}(t)/dt = [\mathrm{BTPS}(T_n) - \mathrm{BTPS}(T_{n-1})]/dT$; $\mathrm{BTPS}(T_n)$ is the dynamic BTPS correction at T_n; and dT is the sampling interval.

If flow is expressed as a function of volume, then the dynamic BTPS correction factor from the model should also be used to correct volume in addition to any flow

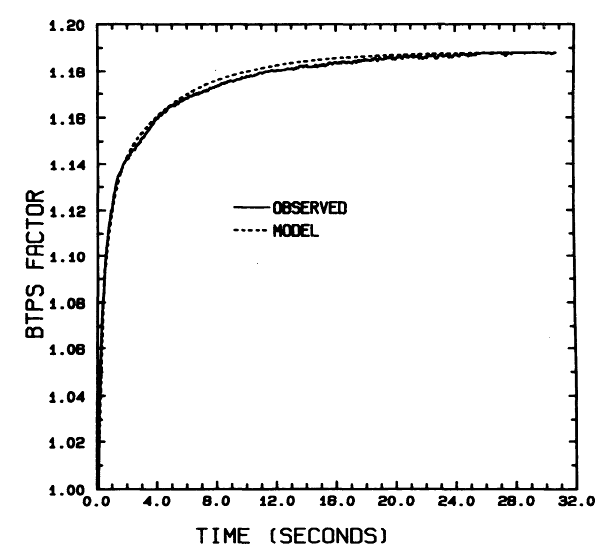

FIG. 3. Plot of dynamic BTPS factor vs. time for a filtered exponential waveform (waveform 1) at a temperature of 3°C; actual dynamic correction factor was calculated from corrected pump displacement and spirometer volume and dynamic BTPS correction factor was obtained from model.

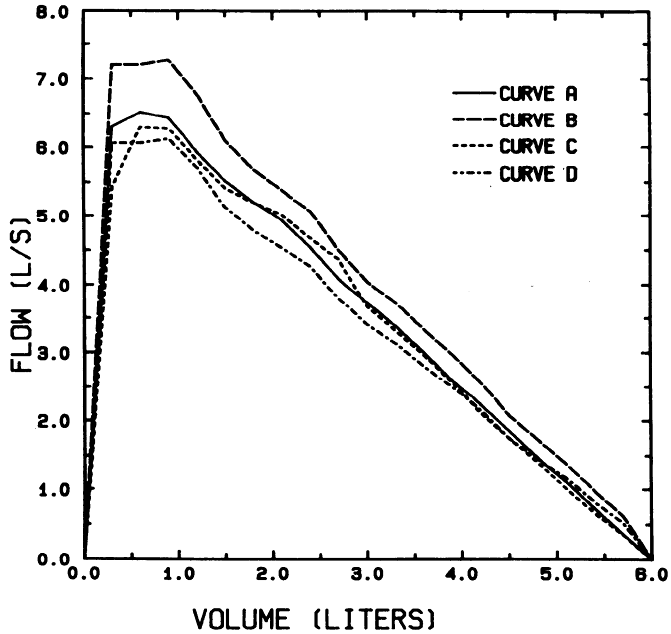

FIG. 4. Plot of flow vs. volume for a filtered exponential waveform (waveform 1) at 3°C. *Curve A*: actual flow-volume curve obtained from corrected pump displacement; *curve B*: obtained using constant BTPS correction factor for both flow and volume; *curve C*: obtained using dynamic BTPS correction factor from model for both flow and volume; *curve D*: obtained using constant BTPS correction factor for volume and no BTPS correction factor for flow.

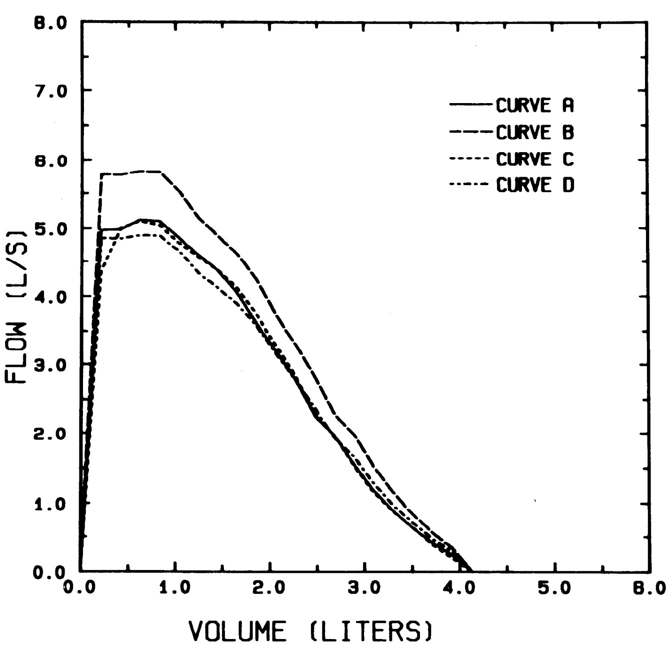

FIG. 5. Plot of flow vs. volume for average of waveforms for 12 patients at 3°C. *Curve A*: actual flow-volume curve obtained from corrected pump displacement; *curve B*: obtained using constant BTPS correction factor for both flow and volume; *curve C*: obtained using dynamic BTPS correction factor from model for both flow and volume; *curve D*: obtained using constant BTPS correction factor for volume and no BTPS correction factor for flow.

correction. Figure 4 shows the flow-volume curves for a filtered exponential waveform at 3°C. Figure 5 shows the average flow-volume curve for the waveforms for 12 patients. *Curve A* is the actual value obtained from the corrected pump displacement; *curve B* is obtained by applying a constant BTPS correction factor to both flow and volume; *curve C* is the flow-volume curve obtained by applying the model determined dynamic BTPS correction factor to both flow and volume; and *curve D* is the flow-volume curve obtained when no BTPS correction is applied to flow and a constant BTPS factor is applied to the volume. The average percent error of peak flow at each temperature, using the static BTPS correction factor of 30%, is less than 2% and typically 1% or less. If flow-time or volume-time data are available, then the dynamic BTPS correction factor model for flow should be used to correct peak flow. In our data only peak flow is available, and the dynamic correction factor must be estimated (30% of the static BTPS factor).

Notice in Figs. 4 and 5 that both the model and uncorrected values approximate the actual flow-volume curves. However, the model-corrected $FEF_{50\%}$ and $FEF_{75\%}$ errors are highly variable. The inability to consistently correct flow expressed as a percentage of exhaled volume is probably due to the inherent variability of flow and to our inability to accurately estimate the rate at which the dynamic BTPS factor changes with time. When the dynamic BTPS correction factors from the model were used, the average errors at all temperatures for all spirometric parameters were not statistically different from zero.

DISCUSSION

These results suggest that at reasonable ambient temperatures (~23°C or higher), using a constant BTPS factor introduces a relatively small error in FEV_1. As the temperature decreases below 23°C, the error in FEV_1 increases and these errors must be considered. In addition, the ambient temperature differences between two population studies or over a work shift should be less than 3°C if erroneous differences in FEV_1 are to be maintained to less than 1%. These results are slightly less than those reported by Tashkin et al. (4), who found a BTPS factor overcorrection of 5.6% in FEV_1 when comparisons were made between a heated pneumotachograph and rolling-seal spirometers, using a constant BTPS factor of 1.08. They also found an overall thermal time constant of 2.31 s.

Our results for the Stead-Wells water-sealed spirometer were very similar to those observed for the rolling-seal spirometer. Although a dynamic BTPS correction factor model for the Stead-Wells spirometer was not developed, errors in FEV_1, introduced by assuming a constant BTPS correction factor similar to those we observed, should exist in most volume-type spirometers. Spirometers that have relatively low thermal mass or high insulating properties should exhibit even larger errors.

A unique finding of this study is the contribution of water vapor condensation to the heat transfer load of the spirometer. At lower ambient temperatures, the water vapor theoretically increases the amount of heat which must be transferred from the spirometer by a factor of 3. This finding was confirmed by the difference in errors with wet and dry air (Table 1 and Fig. 1). In the model, the fast time constant increased from 0.25 to 0.33 s between dry and wet air and the slow time constant increased from 3 to 5 s. If testing of volume spirometers is to be conducted at lower temperatures, then these tests should be conducted with saturated air at 37°C. Only under these test conditions can extrapolation of test results to patients be made.

It is interesting that in Figs. 4 and 5 the uncorrected flow volume curves (*D*), model-corrected flow-volume curves (*C*), and actual flow-volume curves (*A*) are all approximately the same. In Figs. 4 and 5 (*curve D*) a constant BTPS correction was applied to volume and no BTPS correction was applied to flow. Applying a constant BTPS correction factor to volume results in the volume for any particular flow being falsely elevated; hence the uncorrected flow expressed at an elevated volume is also most likely elevated. Consequently, in an uncorrected flow vs. corrected volume curve, flow appears to be falsely elevated by approximately the amount necessary to give the actual flow. When the model is used to correct volume, the resultant uncorrected flow is lower than the actual flow and flow must also be corrected. The fact that flow should be corrected was confirmed by inspecting the flow-time curves not included in this paper. The need to correct volume can be confirmed by inspecting a flow-volume curve that has a slight flow irregularity. This irregularity was found to occur at a lower volume in the actual and model-corrected curves.

In conclusion, it is clear from these results that ambient temperature does have an effect on spirometric data, and in particular on the FEV_1. The simplest solution to this problem is to maintain the ambient temperature at 23 ± 1.5°C. The error in FEV_1 under these conditions should be less than 2%, and the shift change error in FEV_1 should be acceptable. When it is impossible to control ambient temperature, the model could be used to estimate a dynamic BTPS correction factor for flow, volume, and flow-volume curves. Otherwise, with volume-type spirometers, inaccurate results may be obtained.

Mention of brand names does not constitute endorsement by the Federal Government.

Address for reprint requests: J. L. Hankinson, Div. of Respiratory Disease Studies, National Institute of Occupational Safety and Health, 944 Chestnut Ridge Rd., Morgantown, WV 26505.

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