Spirometry with a Fleisch pneumotachograph: upstream heat exchanger replaces heating requirement

MARTIN R. MILLER,[1] OLE F. PEDERSEN,[2] AND TORBEN SIGSGAARD[2]
[1]*Department of Medicine, University of Birmingham, University Hospital Trust, Birmingham B29 6JD, United Kingdom; and* [2]*Department of Environmental and Occupational Medicine, University of Aarhus, Aarhus DK-8000, Denmark*

Miller, Martin R., Ole F. Pedersen, and Torben Sigsgaard. Spirometry with a Fleisch pneumotachograph: upstream heat exchanger replaces heating requirement. *J. Appl. Physiol.* 82(4): 1053–1057, 1997.—The exact temperature of the head of an unheated Fleisch pneumotachograph (PT) during recording is not known, and variation in its temperature may lead to errors in measuring spirometric indexes. We measured PT head temperature during blows from five normal subjects, recorded by using a PT with and without an upstream heat exchanger to condition the air to the ambient temperature that was set in a climate chamber. Group mean (±SD) temperature of a thermocouple (TC) placed inside the PT head was 11.8 ± 1.9°C with 7°C ambient, 25.4 ± 1.3°C at 23°C, and was 37.2 ± 0.3°C at 37°C. The between-subject range of temperature for this TC was 7.5° at 7°C, 5.5° at 23°C, and 1.1° at 37°C. The mean within-subject within-blow variation of temperature for this TC was 10.0° and 3.3°C for ambient of 7° and 23°C, respectively. At the usual ambient temperature in a laboratory, these differences in temperature lead to a 3.6% between-subject bias in recording, and the within-subject differences lead to 2.6% underreading of peak expiratory flow and a 0.5% overreading later in the blow, which makes ATPS-to-BTPS correction erroneous or difficult to perform. With the use of an upstream heat exchanger, the group mean temperature was 8.7 ± 0.4°, 23.2 ± 0.2°, and 37.1 ± 0.2°C at the three ambient temperatures, respectively, and the within-subject within-blow variation was reduced to <1°C. A heat exchanger placed upstream of the PT satisfactorily conditioned expired air to the ambient temperature and removed the error.

lung function; flow measurement; Fleisch pneumotachometer; expired air temperature; thermocouples

THE RECORDING of the maximal forced expiratory maneuver (MFEM) is a routine and common clinical test that can be undertaken with the use of a volume-measuring device or flow-measuring device such as a pneumotachograph (PT). Strict requirements have been stipulated for the accuracy needed for this form of measurement (1, 8), and any errors inherent in the method used may become important and affect the clinical value of the recorded index of lung function. The problem with measuring volume and differentiating it with respect to time to obtain flow is that this enhances any noise on the signal; furthermore, if they are not adequately heated, volume-measuring devices are susceptible to cooling effects (4).

PT are also sensitive to temperature, and Fleisch-type PT are often heated to prevent condensation. Thermal stability of the PT head is essential for accurate recordings, but many heating arrangements are unlikely to achieve acceptable thermal stability, and even with optimal heating, the PT-head temperature was found to vary during a blow (4). Some PT devices are used in an unheated form, because the errors resulting from using them in this way may be smaller than when heating the PT in a suboptimal way (6). If a PT is not thermally stable during an MFEM, then the temperature of the gas at the moment of recording is not known and may change during the blow.

This uncertainty about PT temperature could mean that there are important measurement errors when recording the lung function of patients. Therefore, we undertook experiments by using an unheated standard Fleisch-type PT in a climate-controlled chamber to determine the extent of the temperature change in the PT head and the relation of the change to ambient conditions. We then estimated the magnitude of the likely errors in recording lung function due to this temperature change, and we propose a method to reduce these errors by stabilizing the temperature of the PT head.

METHODS

Measurements and procedures. A Vitalograph Fleisch PT assembly was used that comprised a PT head of 60-mm ID with a white, plastic, upstream geometry that is 180-mm long, tapering at the mouth end to accept standard 28-mm-ID cardboard mouthpieces. Three fast-response 5-µm type K thermocouples (TC; RS Components, UK) were placed into this assembly. The time constant of response quoted by the manufacturer was <10 ms. We have previously (2) shown that the time constant of response on immersion in cold water is 7 ms, and when placed in a stream of air at known flow passing through a mouthpiece, the time constant of these TC in milliseconds is given by

$$TC = 210.5 - \log_e(\text{flow in liters/s}) \times 65.95$$

One TC was placed 0.5-cm upstream of the Fleisch capillaries (TC1); the second TC (TC2) was placed 0.5 cm inside the distal end of one of the peripheral capillaries; the third TC (TC3) was placed 0.5-cm downstream from the end of the PT head (see Fig. 1). Flow measurements made from the PT were recorded by using a differential pressure transducer (type FC040; Furness Controls, Bexhill, UK) the signal of which was filtered by a 6-pole Butterworth low-pass 100-Hz filter and was sampled at 250 Hz by using a 12-bit analog-to-digital (A/D) converter. These data were numerically integrated with respect to time by using the trapezoid rule to give expired volume. Instantaneous flow, expired volume, and elapsed time were stored, together with the three TC readings, whenever the volume increment exceeded 20 ml or elapsed time exceeded 50 ms, whichever occurred first.

All the equipment was placed within the climate chamber at Aarhus University and was allowed to equilibrate to the

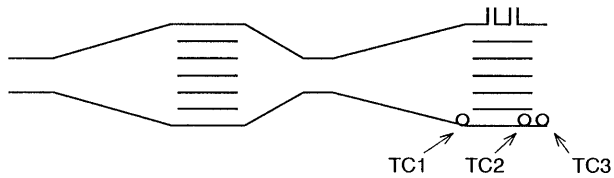

Fig. 1. Schematic drawing of double pneumotachograph (PT) assembly with position of proximal thermocouple (TC1), distal thermocouple (TC3), and thermocouple placed 0.5 cm inside end of PT capillaries (TC2).

prevailing temperature overnight. The chamber was set at 7, 23, and 37°C on different days. Details of the ambient conditions are shown in Table 1.

The TC were calibrated by equilibration of the TC, the computer, and amplifiers to three different temperatures. The response of each TC was perfectly linear across the working range ($r^2 = 0.998$) with a residual SD from the calibrating regression line of 0.3°C. The PT was calibrated for each ambient temperature by using a 3-liter syringe filled with ambient air. The syringe was discharged through the PT, and the summed bit value from the A/D converter was equated to the 3-liter volume discharged to give a calibration factor (12). This procedure was repeated up to eight times, covering a range of flows; the average of these calibration factors was used for the set of experiments at each temperature.

On each day, subjects recorded three MFEM through the PT assembly and then also through the PT system when an additional identical PT was placed upstream (Fig. 1). The order of blowing through the two assemblies was randomized. Preliminary experiments had shown that expired air having passed through a single PT was close to ambient temperature, as can be seen in Fig. 2, which shows the temperature of each TC during a subject's blow. Thus the double-PT arrangement might precondition the expired air before recording the flow. Between blows, the PT assemblies were placed on a fan blowing air to return the temperature of the PT head to ambient temperature and to remove any condensation (2). For analysis, the temperatures of the TC at the point of peak expiratory flow (PEF) and at 25, 50, 75, and 100% of forced vital capacity (FVC) were used.

Two devices were constructed to determine the most effective way of conditioning the expired air before passing though the PT, other than using a second PT upstream of the first. One consisted of four coil elements placed inside an aluminum holder (100-mm long, 48-mm ID), with each coil made by rolling up two strips of stainless steel shim, each 25-mm wide. One of these was 0.05-mm thick and had corrugations made in it with a pitch of 2.5-mm and a peak-to-valley depth of 1.3 mm. This strip was then coiled up together with a flat strip 0.038-mm thick to give a coil of 48-mm diameter to fit into the aluminum holder. Each coil weighed 20 g and was similar to a small Fleisch-type PT head. The other device comprised two plastic holders in series that are usually used to house 80-mm diameter bacterial filters (Vitalograph, UK) but were packed with 45 g of copper shavings. Preliminary experiments had shown that simple bacterial filters did not have any thermal-

Table 1. *Details of ambient conditions for each experiment*

Temp.	Relative Humidity, %	PB, kPa
7°C	64	100.8
23°C	35	100.8
37°C	16	102.9

Temp., temperature; PB, barometric pressure.

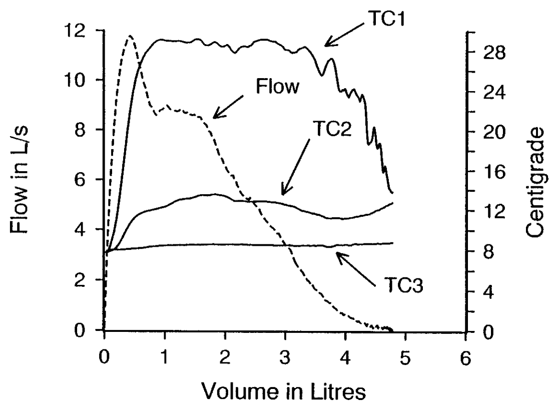

Fig. 2. Plot of expired flow against volume (broken line) recorded with a single-PT assembly at 7°C, together with temperatures of TC plotted with ordinate scale (*right*).

conditioning effect. Each subject performed an MFEM with one of these conditioners upstream of the PT, and during the blow, the temperature of the TC1, just upstream of the PT, was recorded. This protocol was repeated with the ambient temperature set at 7°C and then repeated at 23°C.

The linearity of response and resistance of the various configurations of the PT system were measured by using a servocontrolled pump system (7) to generate known constant flows. The upstream pressure was measured with a differential pressure transducer (type 60239C; Honeywell), sampled at 250 Hz, and filtered with a 100-Hz low-pass 6-pole Butterworth filter.

Statistics. One-way analysis of variance was used to determine whether TC temperature was related to *1*) the point during the blow when was sampled, *2*) the subject, or *3*) the use of upstream conditioning elements. Bonferroni correction for repeated measures was applied. All calculations were done by using SPSS for Windows, version 6.0. The standard spirometric indexes from the subjects tested were related to their predicted values using the method of standardized residuals (5), which are similar to *z*-scores, and are given by

$$\text{standardized residual} = (\text{recorded} - \text{predicted})/\text{RSD}$$

where RSD is the residual SD of the predicting regression equation used (8). This method removes age, height, and gender bias, with a standardized residual equal to zero, indicating that the index is exactly as predicted, and one equal to −1.645, indicating that the index is at the lower 90th percentile confidence limit.

RESULTS

Five normal subjects (3 men), age range 27–54 yr [mean 38.2 ± 11.0 (SD) yr], took part in the experiments. The PEF was 8.6 ± 2.1 l/s, FVC was 4.7 ± 0.8 liters, and forced expiratory volume in 1 s (FEV_1) was 3.5 ± 0.5 liters. When these data were related to predicted values and expressed as standardized residuals, the indexes in these subjects were 0.01 ± 1.4, 0.61 ± 1.5, and −0.4 ± 1.6 for PEF, FVC, and FEV_1, respectively, indicating a reasonable spread of spirometric data within the normal range.

Figure 3 shows the mean with SE bars for the temperature of each TC at PEF and at points through the MFEM to FVC for the five subjects using the single- and double-PT assembly at 7°C. With the double-PT

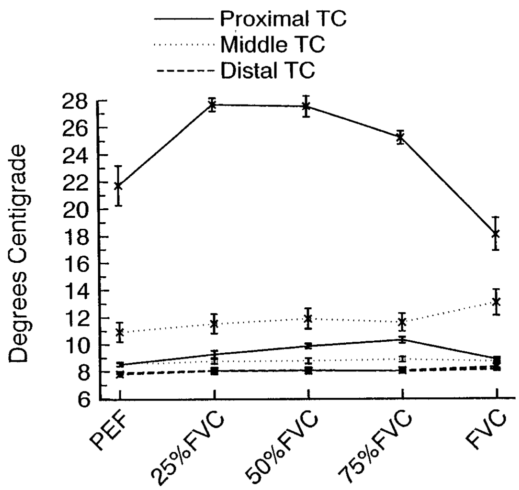

Fig. 3. Plot of group mean temperature of 3 TC with SE bars at points through blow, using single- and double-PT assembly with ambient temperature at 7°C. x, Results for single PT. PEF, peak expiratory flow; FVC, forced vital capacity.

assembly, the proximal TC temperature was much closer to the PT head temperature than with the single PT. Figure 4 shows the same plot for ambient of 23°C. For the ambient of 37°C, the TC temperatures were all within 1°C of one another and within 1°C of ambient both with and without the second PT assembly.

With the single-PT assembly, the temperature of the TC placed within the PT head varied considerably during the blows. The second TC placed within the capillaries of the PT head is that most likely to be close to the temperature of the gas as it is being measured (4). Table 2 shows the group mean ± SD, minimum, maximum, and range of temperatures for TC2 during blows through the single- and double-PT assembly for each ambient temperature. The results are derived from the five recorded instantaneous temperatures (at PEF, 25%, 50%, 75%, and 100% of FVC) taken from one blow from each of the subjects.

For the single PT with an ambient of 7°C, the mean within-person range of temperature for TC2 was 2.3°C, compared with the group range of 7.5°C. For an ambient of 23°C, the mean within-person range was 3.3°C, compared with the group range of 5.5°C. With the double-PT assembly at 7°C, the mean within-person range of temperature was 0.3°C, compared with the group range of 1.3°C. For the other two ambient temperatures, the mean within- and between-person ranges were <0.5°C. With the single PT for 23°C ambient temperature, the lowest within-subject variation in TC2 temperature was 2.6°C and the largest was 4.6°C. These data indicate that the temperatures within the PT varied considerably between and within subjects at temperatures likely to be encountered when recording in a laboratory. The mean ± SD difference between the temperature of the proximal TC and the distal one for a single PT was 16.0 ± 4.3°C at an ambient temperature of 7°C, 7.5 ± 2.4°C at 23°C, and −0.4 ± 0.5°C at 37°C. With the twin-PT assembly, the difference of temperature across the PT head (proximal TC temperature minus distal TC temperature) during a MFEM was 1.3 ± 0.7°C at an ambient of 7°C, 1.0 ± 0.4°C at 23°C, and 0.3 ± 0.3°C at 37°C.

Table 2. *Group results for temperature of middle thermocouple with single- and double-PT assembly*

Ambient Temp.	PT Assembly	Mean ± SD	Minimum	Maximum	Range
7°C	Single PT	11.8 ± 1.9	9.0	16.5	7.5
7°C	Double PT	8.7 ± 0.4	8.2	9.5	1.3
23°C	Single PT	25.4 ± 1.3	22.8	28.3	5.5
23°C	Double PT	23.2 ± 0.2	23.0	23.4	0.4
37°C	Single PT	37.2 ± 0.3	36.8	37.9	1.1
37°C	Double PT	37.1 ± 0.2	36.8	37.2	0.4

PT, pneumotachograph.

A one-way analysis of variance on the data for the single PT at 7°C showed that only for the temperature of the proximal TC was the temperature related to the point through the blow at which the temperature was recorded ($P < 0.001$), and only for TC2 and TC3 was the temperature significantly related to the subject doing the blow ($P < 0.001$). At 23°C, the temperatures of TC1 and TC2 were significantly related to the point through the blow of the recording ($P < 0.001$), but only for TC3 was the temperature related to the subject ($P < 0.01$). There were too few subjects to look for meaningful individual correlation between spirometric indexes and the TC temperatures.

Figure 5 shows the mean proximal TC temperature with ambient at 7 and 23°C with different upstream conditions, namely either under normal operating conditions (that is no upstream heat exchanger), with the empty assembly to hold the metal coils (no coils), with one and up to four coils in the upstream assembly. Use of two bacterial filters, each filled with copper shavings and placed upstream of the PT, changed the upstream temperature to 11°C for an ambient temperature of 7°C. This configuration did not work quite as well as using the coils and so was not tested at 23°C. A one-way analysis of variance showed that at 7°C the temperature of TC1 with three or four coils upstream was significantly cooler ($P < 0.001$) than with fewer coils, with no difference between three or four coils. At 23°C, the temperature of TC1 with two or more coils was significantly cooler ($P < 0.001$) than with fewer coils, but with no difference found between two or more coils.

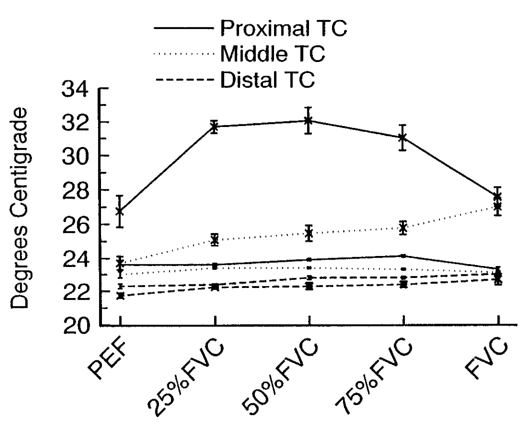

Fig. 4. Plot of group mean temperature of 3 TC with SE bars at points through the blow, using single- and double-PT assembly with ambient temperature at 23°C. x, Results for single PT.

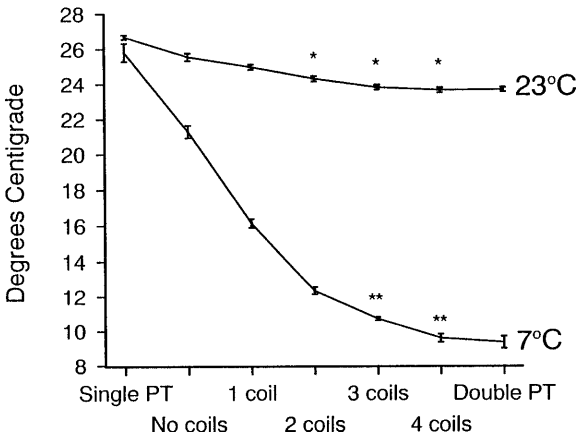

Fig. 5. Plot of group mean proximal TC temperature with SE bars for recordings at 2 ambient temperatures when using single-PT assembly with and without upstream air heat exchanger with up to 4 metal coils and when using double-PT assembly. * Significantly different at ambient temperature of 23°C from those found with fewer coils or with single PT but not significantly different from each other or from temperature with double PT; ** same significance for ambient temperature of 7°C.

Figure 6 shows that the resistance of the PT assembly was more than doubled by the addition of the heat exchanger with four coils to yield a value of 0.079 $kPa \cdot l^{-1} \cdot s^{-1}$, but this was still well below the limit of 0.245 $kPa \cdot l^{-1} \cdot s^{-1}$ set by the American Thoracic Society (1). The flow-calibration factor for the PT was not significantly altered by the addition of the heat exchanger. The mean ± SD calibration factor of eight trials for the PT on its own was 8.5713 ± 0.060 $\cdot ml \cdot s^{-1} \cdot bit^{-1}$. For the PT with the four coils in the heat exchanger, the calibration factor was 8.5997 ± 0.097 $ml \cdot s^{-1} \cdot bit^{-1}$ ($P = 0.09$, paired t-test). The linearity and recording error of the PT system was not significantly altered by the addition of the heat exchanger, as shown in Fig. 7, and its performance was well within the recommendations set by the American Thoracic Society (1).

DISCUSSION

Wedge, rolling seal, or water-sealed spirometers are robust instruments for recording forced expiratory

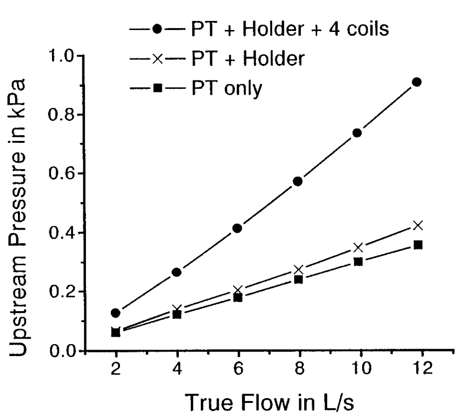

Fig. 6. Plot of pressure upstream to various PT configurations at different known constant flows generated by a servo-controlled pump.

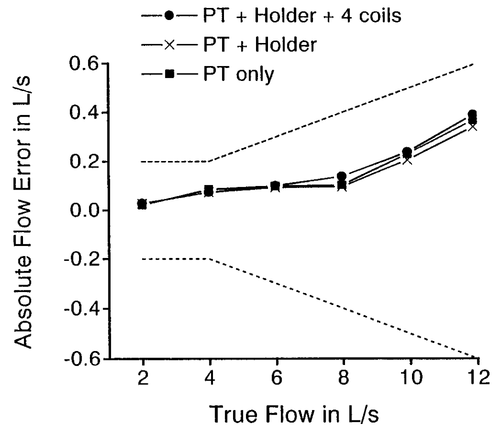

Fig. 7. Plot of absolute error in recorded flow for various PT configurations at different constant flows generated by a servocontrolled pump. Dotted lines, limits for accuracy as recommended by American Thoracic Society.

maneuvers. They do not require repeated careful calibration, but they suffer from the problem of the expired air cooling within them (6). PT are potentially the best means for measuring forced expiratory maneuvers, but they are technically more demanding to use than spirometers and they require careful calibration. It has previously been found that heated PT are not completely free from temperature effects (4), and we now present the first estimates of the temperature variation in an unheated PT.

On first inspection, there may appear to be an anomaly in our data in that the downstream TC with the single PT experiment was at a lower temperature than the upstream TC in the double-PT experiment. However, the temperature of the TC distal to the single PT head was heavily influenced by the ambient temperature, as it was completely exposed to ambient air. With the double-PT assembly the air leaving the first PT was not in open continuity with ambient air, because it was enclosed within the assembly, so the heat within the air could not be dissipated in the way it was with the single PT.

The temperature variations we have found have two possible effects. The between-subject variation in mean temperature of the PT head will lead to recording errors due to gas viscosity differences and incorrect BTPS corrections that will introduce a between-subject bias. The within-subject variation in temperature will, by the same mechanisms, cause distortions of the recording; therefore, indexes sensitive to the shape of the blow will be affected, as has previously been shown to be the case due to cooling within a volume-measuring spirometer (7). It is important to estimate the magnitude of these possible errors when using an unheated PT to compare it with that found when using a heated PT.

The range of temperature variation for our subjects of the TC within the PT head at an ambient of 23°C was found to be 22.8–28.3°C. With the use of Sutherland's and Wilke's formulas to calculate gas viscosities at various temperatures (9, 13), the viscosity of ambient air used in the calibration at 23°C would be 183.1 micropoises. For the range of PT temperatures we found during blows at this ambient temperature, the viscosity would vary from 178.6 to 180.3 micropoises. This would lead to measurement errors of an underreading of 2.5 and 1.6%, respectively, just due to gas-viscosity differences. The usual assumption is that the recording temperature is at ambient temperature and a full BTPS correction is applied when ambient air has been used to calibrate the PT. Under the circumstances of our experiments, this assumption would lead to a correct BTPS correction at the lower end of the range of PT temperature that we found and to an overcorrection of 2.6% for the subject with the highest temperature for the midplaced TC. This latter error is in the opposite direction to the viscosity error, so the combined error would be an underreading of 2.6% for the subject at the lower temperature and an overreading of 1% for the subject at the higher temperature. Therefore, the between-subject bias because of these errors could be as much as 3.6%.

The mean within-subject within-blow variation in PT temperature at an ambient temperature of 23°C was 3.3°C, with the temperature at PEF being lower than that later in the blow. This difference would mean an underreading at PEF of ~2.6% and an overreading later in the blow of ~0.5%. In the working range of ambient temperatures found in most laboratories, the possible error due to between-subject temperature variation (5.5°C) is ~4%. By using an upstream heat-exchanging element, as we have done, all these errors are removed.

On their own, these errors are within the limits for measuring flow suggested by the American Thoracic Society and by the European Respiratory Society for recording this maneuver (1, 8). However, they will compound with other errors inherent in these measurements, which may then lead to unacceptable errors. To avoid errors due to incorrect BTPS correction, some workers have calibrated the PT with saturated air at a relevant temperature (3). We have shown that by using an upstream heat-exchanging element to render the air to ambient temperature before it enters the PT head, these errors would be made negligible. An alternative is to use a PT heated to a suitable temperature, which has previously been shown to be ~30°C for a usual PT assembly (4). That work also found that the PT head temperature was not perfectly stable during a blow, despite optimized servocontrol of the heating element. The within-blow changes were <0.5°C during expiration and ~1.0°C during inspiration when the PT was heated to 30°C with an ambient temperature of 23°C. This variation would lead to an underreading of ~0.5% due to viscosity and BTPS correction errors if the device were correctly calibrated for the temperature. With a PT heated to a temperature of 37°C, the underreading could be as much as 3%, because the temperature variation within a blow amounts to several degrees (4).

Previous workers (10) have looked at a theoretical treatment of the temperature flux within a heated PT to obtain a correct calibration factor for the device, but they did not consider the unheated situation. Another investigation (11) of the calibration of a heated PT quoted a 10°C difference in the temperature of the PT between a subject's inspiration and expiration, indicating the magnitude of the possible problem when using a heated PT.

To avoid progressive condensation on the PT head, it is necessary to heat a PT if it is being used for continuous breathing maneuvers. The optimal temperature for such heating would depend on the ventilatory circuit being used. However, we conclude that for single expiratory blows, or full or partial flow-volume loop maneuvers, a PT does not need to be heated, and the small errors inherent in this practice will be negligible if an upstream heat-exchanging element is used to condition the air to ambient temperature before recording. The only remaining error is that due to within-blow condensation. This error is likely to be very small, because a total of 12 consecutive blows through a PT at an ambient temperature of 23.5°C has previously been estimated to cause a 1.1% error due to condensation effects (4). Any such progressive effect due to condensation can be eliminated by placing the PT on a fan between blows (6).

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Address for correspondence: M. R. Miller, Dept. of Medicine, Univ. of Birmingham, Univ. Hospital NHS Trust, Selly Oak Hospital, Birmingham B29 6JD, UK (E-mail: m.r.miller@bham.ac.uk).

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