

TECHNICAL NOTE

Prevention of thermal and condensation errors in pneumotachographic recordings of the maximal forced expiratory manoeuvre

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ABSTRACT: When recording respiratory manoeuvres using a pneumotachograph (PT), it is customary to heat the pneumotachograph head to avoid condensation errors. It is technically demanding to heat the PT correctly, and this increases the complexity of the equipment. We have studied whether a simpler method can eradicate condensation errors and preserve thermal stability of the PT.

We tested the accuracy of a PT by recording the discharge of 1,000 ml of air through the PT before and after a subject had blown through it, thus causing both condensation within the PT and a rise in its temperature. We then determined whether the thermal and condensation errors could be avoided by placing the PT, between blows, on a fan that was blowing air at a constant 1.65 l.s^{-1} .

With ambient temperature at 20°C , a single blow through the PT was found to cause a subsequent 4% over-reading in volume, due to condensation and temperature changes in the PT. After five consecutive blows the error was 7%. Placing the PT on the fan for 15 s after a single blow abolished these errors, whereas a wait of 15 s did not. At an ambient temperature of 14°C there was a 5% over-reading of volume after a single blow, and an over-reading of 9% after five blows. At an ambient temperature of 26°C these errors were 3 and 5%, respectively. All of these errors were abolished by placing the PT on the fan for 15 s and 30 s, respectively. These errors were significantly greater for a Fleisch as compared to a mesh screen type of pneumotachograph.

Placing a pneumotachograph, in between blows, in the flow stream of a fan blowing ambient air for 15 s minimizes errors due to condensation effects and temperature change in the pneumotachograph head.

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Pneumotachographs (PTs) are widely used in lung function laboratories for recording maximal forced expiratory manoeuvres (MFEM). The stability and linearity of modern transducers, amplifiers, and analogue-to-digital graphic recording in recent years. However, PTs are susceptible to: 1) changes in temperature, which alter correction factors and the prevailing gas viscosity; 2) changes in viscous resistance to gas flow as a consequence of condensation in the PT head; and 3) changes in the gas constituents.

The problems of temperature and condensation effects have in the past been addressed by heating the PT. There has been little guidance in the literature on how this heating should be performed or monitored, and there are many commercially available PTs that are not heated. One publication [1] has suggested that optimal conditions for recording MFEM with a PT are obtained by controlling the PT head to a temperature of 30°C , using a thermocouple

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placed in a peripheral capillary of the PT head to give feed back control to the heating element. Such heating arrangements add to the technical complexity of using a PT, and would be difficult to achieve in a truly portable device. Furthermore, to heat a PT in a suboptimal way may lead to greater errors than would be obtained by not heating the PT at all [1].

We have undertaken experiments to determine the magnitude of the error from thermal and condensation effects when using an unheated PT, and we have determined whether placing the PT on a fan between blows can minimize these errors.

Method

We have studied a widely-used and commercially available unheated pneumotachograph (Vitalograph, Buckingham, UK), together with its 200 mm long plastic

upstream assembly, which accepts standard 28 mm internal diameter cardboard mouthpieces, and have compared this mesh screen type of PT (type F300L, Mercury Electronics Ltd, Glasgow, Scotland). The pressure drop across the PTs was measured by a differential capacitance transducer (FC040, Furness Controls, Bexley, UK) the signal of which was sampled every 4 ms (250 Hz) via a 12 bit analogue-to-digital converter and then stored in a computer. Flow was numerically integrated with respect to time, to give volume. The PTs were calibrated using a 1 l syringe, discharging ambient air through the PT with a peak flow of about 3 l·s⁻¹. The integrated volume in the computer was then equated to the known discharged volume to derive a calibration factor.

The effect of temperature and condensation was determined by repeating the discharge of 1 l of ambient air from the syringe, as for the calibration procedure, but under different test conditions as summarized in figure 1. The recorded discharged volume was determined using the baseline calibration factor, and any variance from the expected 1 l indicated an effect due to either condensation within the PT head or a change in its temperature. The effect of placing each PT head in the outlet flow stream of a small fan producing a flow of 1.65 l·s⁻¹ through the PT was then determined, to see if this prevented these temperature and condensation effects. Experiments were carried out in a climatically controlled room-sized chamber, at two selected temperatures on consecutive days, and further studies were at the uncontrolled ambient temperature. In between each experiment the PT was allowed to return to ambient conditions. One series of experiments was conducted using a 3 l syringe to determine if the magnitude of the errors changed.

The following basic protocol (shown schematically in figure 1) was followed. The PT system was calibrated by five discharges of 1 l of ambient air. A subject who had a forced vital capacity (FVC) 5.5 l, peak expiratory

flow (PEF) 10 l·s⁻¹, forced expiratory time 5 s performed one or five MFEM through the PT and then 1 l of ambient air was again discharged through the PT either straight away, after a timed delay, or after a timed period on the fan. The apparent volume registered using the original calibration factor was recorded. All the results are the mean±SD for five repetitions of each experiment. We also tested both pneumotachographs using a computer-controlled pump [2, 3], which delivered American Thoracic Society (ATS) waveform PW24 [4] scaled to give known FVC, forced expiratory volume in one second (FEV₁) and PEF repeatedly to the devices, before and after five blows were delivered through the PT. The scaled waveforms, No. 4 and No. 6, were chosen so that their respective PEF (200 and 300 l·min⁻¹, approximately) were within the limits of linearity for both pneumotachographs. Statistical analysis was performed using Minitab Version 7 on a microcomputer, with comparisons between means being tested by a two sample Student's t-test, unless otherwise stated. A probability of less than 5% was accepted as significant.

Results

With the climate chamber set to an ambient temperature of 20°C (relative humidity 25%, barometric pressure 102.3 kPa) 1,000 ml was discharged through the PT immediately after the subject's blow, and then again after a 15 s wait. The baseline recorded volume (mean±SD) was 1,000±2.1 ml, which rose significantly to 1,042±2.0 ml ($p<0.0001$) immediately post-blow, and fell slightly to 1,034±4.2 ml following a further 15 s wait. This experiment was repeated with the 15 s wait following immediately after the subject's blow, that is before any testing was done, and the recorded volume was still significantly higher at 1,037±2.8 ml after the wait ($p<0.0001$) when compared to the baseline of 1,000±1.5 ml. When this wait was extended to 60 s the recorded volume of 1,034±5.3 ml was not significantly different from the recorded volume after a wait of 15 s.

The experiment was then repeated with a subject blowing through the PT, followed immediately by the 1,000 ml being discharged through the PT, then the PT was placed for 15 s on the fan, followed by a further 1,000 ml being discharged through the PT. The baseline volume was 1,000±2.4 ml, rising to 1,040±3.1 after the blow, and was subsequently 997±3.3 ml after the 15 s on the fan. Although this volume recorded after the time on the fan was slightly below 1,000 ml, it was not significantly different from the baseline volume ($p=0.2$). When this experiment was repeated with five consecutive blows at 30 s intervals, before discharging the 1,000 ml through the PT, the recorded volume rose from a baseline of 1,000±2.8 ml to 1,073±3.1, and 15 s on the fan reduced it to 998±1.0 ml.

These experiments were repeated with the climate chamber set to a temperature of 14°C (relative humidity 27%, barometric pressure 102.7 kPa). When 1,000 ml was discharged through the PT immediately after the subject's blow, the volume rose from a baseline of

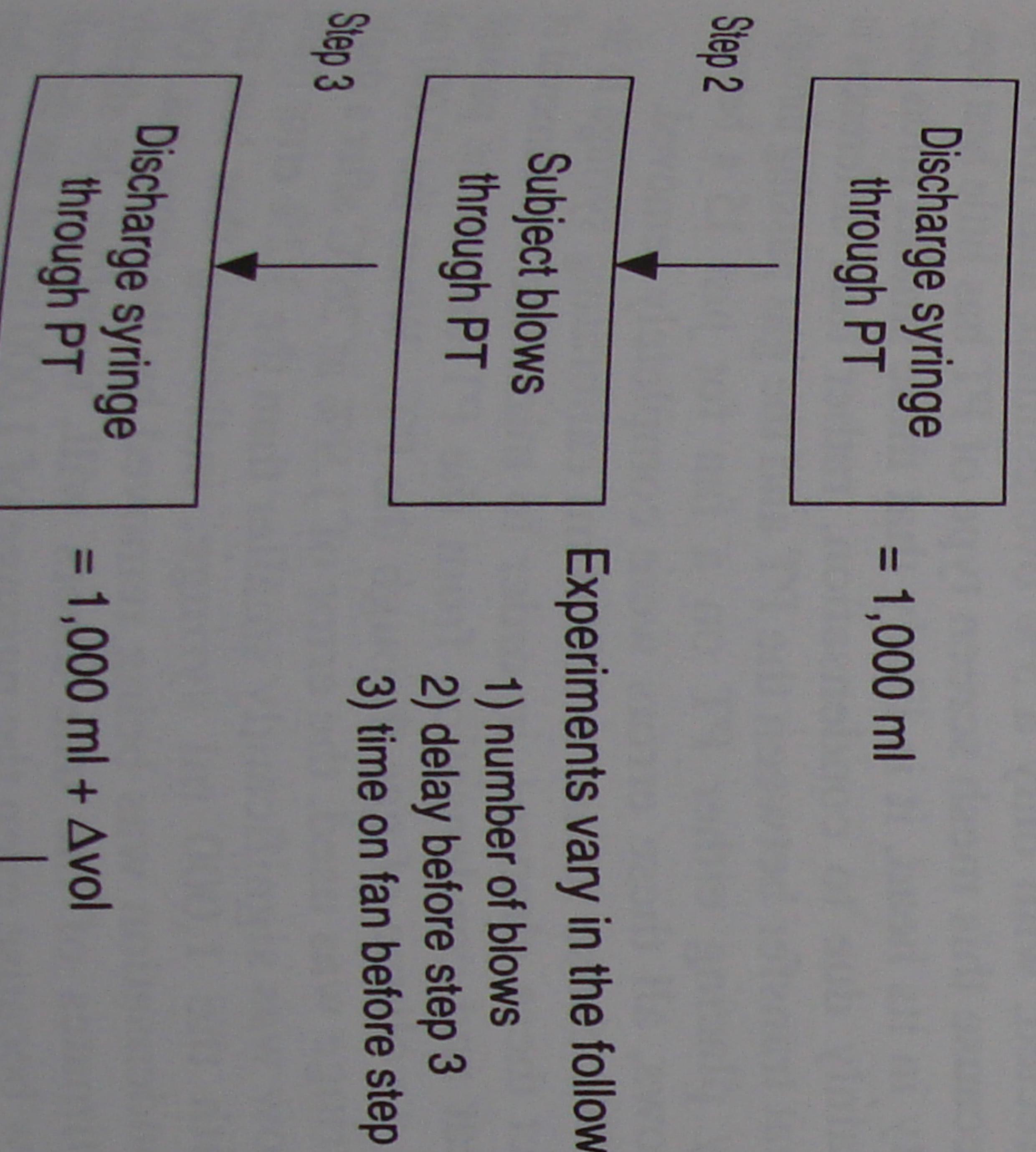


Fig. 1. – Schematic representation of the experimental protocol. PT: pneumotachograph.

Table 1. – Results of FVC, FEV₁ and PEF from the two ATS PW24 profiles recorded by the mesh screen pneumotachograph before and after five blows

| | Start PW24 No. 4 | After 5 blows | %Δ | Start PW24 No. 6 | After 5 blows | %Δ |
|-------------------------|---------------------|------------------|------|---------------------|------------------|------|
| FVC ml | 2013±1 | 2040±3 | 1.34 | 2861±2 | 2895±3 | 1.19 |
| FEV ₁ ml | 1509±1 | 1531±2 | 1.46 | 2163±2 | 2183±3 | 0.92 |
| PEF l·min ⁻¹ | 217±0.5 | 220±0.7 | 1.38 | 303±0.1 | 307±0.1 | 1.32 |

Data are presented±SD. FVC: forced vital capacity; FEV₁: forced expiratory volume in one second; PEF: peak expiratory flow; ATS: American Thoracic Society.

Table 2. – Results of FVC, FEV₁ and PEF from the two ATS PW24 profiles recorded by the Fleisch pneumotachograph before and after five blows

| | Start PW24 No. 4 | After 5 blows | %Δ | Start PW24 No. 6 | After 5 blows | %Δ |
|-------------------------|---------------------|------------------|------|---------------------|------------------|------|
| FVC ml | 2001±1 | 2130±2 | 6.45 | 3010±2 | 3151±4 | 4.68 |
| FEV ₁ ml | 1495±1 | 1594±1 | 6.62 | 2239±1 | 2351±3 | 5.00 |
| PEF l·min ⁻¹ | 209±0.3 | 222±0.9 | 6.22 | 305±1.2 | 322±1.8 | 5.57 |

Data are presented as ±SD. For abbreviations see legend to table 1.

1,000±2.1 ml to 1,048±2.9 ml, and 15 s on the fan reduced this to 1,001±2.9 ml, which was not significantly different from the baseline reading. If the subject blew five times consecutively through the PT with 30 s between each blow, the recorded volume rose from 1,000±2.0 ml to 1,094±2.9 ml, and 30 s on the fan corrected this to 1,004±1.7 ml, which was not significantly different from the baseline value.

With the ambient temperature uncontrolled at 26°C (relative humidity 25%, barometric pressure 99.1 kPa) a single blow through the PT raised the recorded volume from 1,000±1.6 to 1,032±2.7 ml, and after five blows at 30 s intervals this was 1,049±5.5 ml. When the PT was placed on a fan for 15 s, after a single blow the reading of the PT was 1,001±2.3, and this was not significantly different from baseline reading ($p=0.13$). After five blows followed by 30 s on the fan, the reading was 1,003±2.8, which was not significantly different from baseline ($p=0.11$). A 3,000 ml calibrating syringe was then used, giving a baseline reading of 3,000±14.2 ml rising to 3,056±10.0 ml after a single blow, and 15 s on the fan reduced this to 2,995±7.7 ml. The error found using the 3,000 ml syringe after a single blow of 1.9% was significantly smaller ($p<0.005$) than the 3.2% error found when using the 1,000 ml syringe.

When the Fleisch PT was compared to the mesh screen PT at an ambient temperature of 23°C (relative humidity 26% and barometric pressure of 23°C (relative humidity 1,000±1.0 ml to 1,084±4.0 for the mesh screen PT. The increase for the mesh screen PT was significantly less than that for the Fleisch ($p<0.02$, Mann Whitney). A period of 30 s on the fan brought these volumes back to 1,002±3.2 and 996±2.2 ml, respectively, which were not significantly different from the baseline values. The results from using two scaled versions of ATS profile 24 are presented in tables 1 and 2. For FVC, FEV₁ and PEF there were significant changes

with both PTs after five blows ($p<0.02$, Mann Whitney). For the Fleisch there was on average a 5–6% increase in each reading after five blows, which was significantly larger than the average 1% increase for the mesh screen type of PT ($p<0.02$, Mann Whitney).

Discussion

We have shown that an unheated pneumotachograph is affected by temperature and condensation effects, such that with a Fleisch type PT a second blow may be overestimated by 3–5%. After five blows this overestimate rises to 5–9%. As expected these errors were dependent on the ambient temperature. The results from the mesh screen type of PT showed that this was significantly less affected, with only a 3% overestimate after five blows. Because this mesh screen type of PT has little heat capacity in its head, it is likely that these smaller errors were mainly due to condensation, rather than differences in heat transfer between the PT and the gas passing through. By placing either PT on a fan for just 15 s between blows, all these errors were completely removed.

We chose to use a 1,000 ml calibrating syringe to detect these changes, in order to minimize the removal of heat and condensation from the PT due to the passage of a volume of gas through the PT. When the 3,000 ml syringe was used, the error of 1.9% at 26°C after a single blow was significantly smaller than the 3.2% error found with the 1,000 ml syringe, indicating that heat and condensation was being removed by the extra gas. Our estimates of the true errors will, therefore, be slightly low because even the passage of 1,000 ml of gas through the PT will remove heat and condensation from within that after a single blow the PT will be filled with warm gas, filling the PT's dead space (50 ml). This gas contributed to the volume measured when a subsequent

1,000 ml of ambient air was discharged through the PT, being at a higher temperature would increase the recorded result. The experiments with a prolonged delay after a single blow before testing the PT allowed this dead space gas in the PT to cool, but even a delay of 60 s did not substantially reduce the error. Any dead space effect would be proportionally reduced when the gas was used, and yet a significant error was still obtained. These results suggest that our estimates was still due to the combined effect of condensation of the errors due to the true error, and are of temperature will be close to the true error, and are and problems with the recording method.

There are many unheated PTs in clinical use, and using a fan in the way that we describe can minimize the condensation and temperature errors. An alternative method of avoiding these effects is to heat the PT head. Very little is known about how best to heat a pneumotachograph to prevent thermal and condensation errors, and the mesh screen type of pneumotachograph does not lend itself to being heated. TURNER and BLUMENFELD [5] presented data using dry gas passing through a PT under steady-state conditions. They used an uncontrolled 6 v direct current (DC) applied to the heating coils of a Fleisch PT. In our hands, this produces a PT temperature in excess of 50°C, which is an inappropriate temperature to work with. Furthermore, steady-state temperature conditions are not achieved during a MFEM through a heated PT [1]. A cumbersome arrangement of inspiratory and expiratory heat exchangers has been tried [6] for tidal breathing manoeuvres, and the measured change in temperature of 14.6°C across the unheated PT was reduced to less than 1°C [6]. Our fan method is simple and suitable for single-breath manoeuvres but not for continuous breath-by-breath measurements.

Ideally the expired gas and PT head temperature should be constant during the manoeuvre, and PT calibration

should be with gas under identical circumstances. With heated or unheated PTs these conditions are hard to meet. A previous report on the best method for heating a PT [1] found that, with the upstream geometry they used, a PT temperature of 30°C was optimal for recording expiratory manoeuvres. Even with their sophisticated temperature controller the temperature of the PT head did not stay constant. Heating the PT to a higher temperature led to marked cooling of the PT head, and this might cause a greater error than the rise in temperature during a blow through an unheated PT.

We conclude that when using an unheated pneumotachograph to record maximal forced expiratory manoeuvres, in the airstream of a fan, in order to maintain the thermal stability of the pneumotachograph and to avoid the accumulation of condensation.

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