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TECHNICAL NOTE

Expired air temperature at the mouth during a maximal forced expiratory manoeuvre

I. Madan, P. Bright, M.R. Miller

Expired air temperature at the mouth during a maximal forced expiratory manoeuvre. I. Madan, P. Bright, M.R. Miller. ©ERS Journals Ltd 1993.
ABSTRACT: We have studied the temperature of expired air during a maximal forced expiratory manoeuvre, because this has not previously been fully investigated and it will influence how flow and volume recording devices should be calibrated and used.

Temperature was recorded with a fine thermocouple, the response time of which was determined at various gas velocities and for which a correction was made. Recordings during maximal forced expiratory manoeuvres were made on 12 normal subjects and 12 subjects with chronic airflow limitation. The thermocouple was placed in the mouthpiece, so that it was at the level of the lips during a blow. In the normal subjects, the effect of differing inhalation protocols was also determined.

In the normal subjects, the mean temperature was 33.6°C at peak expiratory flow (PEF), and 34.4°C at 75% forced vital capacity (FVC), but fell to 33.4°C at FVC. In the subjects with chronic airflow limitation, the temperature was constant at 35.0°C from PEF up to 50% FVC, being significantly higher than in the normals, and fell to 33.5°C at FVC. Expired air temperature up to 50% FVC was significantly negatively correlated with absolute PEF, forced expiratory volume in one second (FEV_1) and FVC. In the normals, a slow inhalation through the nose raised the expired temperature by almost 1°C throughout the blow, whereas inhaling air at 6°C did not affect expired air temperature.

The expired air temperature can vary by up to 3°C between individual subjects, and it is influenced by the route of inhalation and the inspired volume. For performing a maximal forced expiratory manoeuvre the least temperature variation between subjects would be obtained following a slow inhalation through the mouth.
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Dept of Medicine, University of Birmingham, Good Hope Hospital, Sutton Coldfield, West Midlands, UK.

Correspondence: M.R. Miller
Dept of Medicine
University of Birmingham
Good Hope Hospital
Sutton Coldfield
West Midlands B75 7RR
UK

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When recording the maximal forced expiratory manoeuvre, consideration must be given to the choice of which instrument is best to meet the demands of the test. Spirometers are often employed because they are simple to use, their calibration does not vary a great deal, and they are robust for the clinical setting. However, spirometers are subject to temperature dependent errors [1]. For accurate recording of flow a pneumotachograph may be preferred, since the frequency response of spirometers may not be ideal for the measurement of flow, and differentiating volume with respect to time to obtain flow will accentuate any noise on the signal. When using a pneumotachograph, one must give due consideration to its calibration and temperature control [2], because the response of a pneumotachograph is sensitive to the temperature of the gas, due to both Charles's law and the effect temperature has on gas viscosity. Therefore, irrespective of the type of recording device being used, it is essential to know the temperature of the gas being exhaled during a maximal forced expiratory manoeuvre. It has been assumed in the past that mouth gas temperature was close to 37°C but more recent work has suggested that this temperature is about 33°C [3–6].

We have therefore undertaken a study to record the temperature of expired gas during a maximal forced expiratory manoeuvre, and to determine whether it changes significantly during the course of the manoeuvre or is altered by the presence of airflow limitation.

Method

Flow volume curves were recorded using a Fleisch pneumotachograph (60 mm internal diameter I.D.) with a differential capacitance transducer (Furness Controls Ltd, Bexley, UK), the analogue signal of which was sampled every 4 ms using a digital computer with a 12 bit A/D converter. The upstream geometry of the pneumotachograph was a fibreglass cone 300 mm long, being 28 mm diameter at the mouthpiece end and 60 mm diameter to accommodate the Fleisch head [2]. The pneumotachograph was calibrated with air at 34°C saturated with water vapour that was discharged from a heated brass water sealed spirometer of 4.5 *l* volume which fell under gravity. Its drop was retarded by counter balance weights and a dash-pot damper, so that the flow profile varied to give a range of flows up to 8 $l \cdot s^{-1}$. Expired air temperature was measured with a 5 µm Type K thermocouple (RS Components Ltd, UK), placed in the flow stream 1 cm from the mouth end of a standard 28 mm internal diameter (I.D.) cardboard mouthpiece used by the subject. This meant that the thermocouple was effectively at the level of the lips during a blow. The thermocouple was calibrated by immersion in water, at 37°C, which was continuously stirred and allowed to cool. The water temperature was measured with a mercury thermometer and at 1 degree intervals the thermocouple analogue output was A/D converted and stored in a computer. Its response was perfectly linear and calibration factor was derived by linear regression.

The relationship between time constant of response of the thermocouple and gas velocity through a 28 mm I.D. mouthpiece was determined by heating the thermocouple to 36°C between the jaws of a mechanical clamp, which isolated the thermocouple from the airstream. This clamp could be operated from the computer to open at a predetermined moment. The clamp was placed above a servo-controlled pump, which could produce a precise gas flow of up to 15 $l \cdot s^{1}$ [1, 2]. Different flows were generated and, once these were established, the jaws of the clamp were opened and the fall in temperature registered by the thermocouple was sampled every 10 ms. From these data the relationship between gas velocity (flow in the 28 mm I.D. tube) and time constant was derived and used to correct the instantaneous temperature in the following way. For each instantaneous flow recorded during a blow, the corresponding temperature was not taken as the coincident temperature but that recorded after a delay corresponding to the 90% rise time in response of the thermocouple for that flow, *i.e.* 2.3026 times the pertinent time constant. At the end of each blow where flow is very low, this correction for time constant of response could not be fully applied because this would project beyond the end of the blow. However, since temperature does not change very rapidly at this point of the blow, little error should be incurred by not being able to effect a full correction.

Two groups of subjects had maximal forced expiratory manoeuvres recorded with simultaneous measurement of the gas temperature at the mouth. Group 1 comprised 12 patients with chronic airflow limitation, who were having routine lung function tests performed for other reasons. Group 2 was made up of 12 normal healthy volunteers from amongst laboratory and medical staff. The demographic and lung function data for the subjects in each group are shown in table 1, with mean±SD for each group shown. For group 2 the peak expiratory flow (PEF) was on average 0.60 standardized residuals (SR) [7] above predicted, whereas for Group 1 the PEF was on average 2.34 SR below predicted, *i.e.* below the lower 98% confidence limit. Each subject was asked to inhale rapidly to total lung capacity (TLC) through the mouth and then immediately place the mouthpiece in their mouth and deliver a maximal forced expiratory manoeuvre (MFEM). None of the subjects were febrile. Group 2 subjects also recorded MFEM, using the following additional inhalation protocols: 1) slow inhalation through the mouth and immediate exhalation; 2) slow inhalation through the nose and immediate exhalation; and 3) nine of these subjects performed a rapid inhalation of air at 6°C through the mouth, followed by immediate exhalation. Five subjects from Group 2 also performed a rapid inhalation followed by a 30 s breathhold before exhalation. The effect of mouth temperature was further explored, by five subjects from Group 2 rinsing their mouths for 15 s with either cold (6°C) or hot water (50°C), and spitting this out immediately prior to rapid inhalation of ambient air through the mouth followed by immediate exhalation. All the subjects from Group 2 who undertook these additional protocols rehearsed these manoeuvres before they were recorded.

Table 1. – Demographic and lung function data for the subjects with chronic airflow limitation (Group 1) and the normal healthy volunteers (Group 2)

	Group 1 n=12	Group 2 n=12	p
Age yrs	60±13.3	24±3.6	<0.0001
Sex M:F	5:7	9:3	
PEF $l \cdot s^{-1}$	4.0±1.6	10.1±2.0	<0.0001
FEV_1 l	1.3±0.6	3.8±0.6	<0.0001
FEV_1%	64±16.3	80±6.4	<0.005
FVC l	1.9±0.6	4.8±1.0	<0.0001
PEFvol l	0.27±0.85	0.42±0.15	<0.05

Data are presented as mean±SD. PEF: peak expiratory flow; FEV_1: force expiratory volume in one second; FEV_1%: FEV_1 expressed as a percentage of FVC; FVC: forced vital capacity; PEFvol: volume exhaled by the time PEF was achieved.

Statistical comparisons between sets of data were made by Mann-Whitney test, using Minitab release 6.1., with a probability of 5% or less being accepted as significant.

Results

The time constant (TC) of response for the thermocouple was determined for gas flows from 0.16 $l \cdot s^{-1}$ to 10.24 $l \cdot s^{-1}$ through a 28 mm I.D. mouthpiece, and the results for three different flows are shown in figure 1. All such curves could be fitted by a single exponential, the TC of which was recorded. Table 2 shows the TCs for the full range of flows. The relationship between TC and the natural logarithm of flow is shown in figure 2 with the regression line also plotted. For comparison, the sudden immersion of the thermocouple into cold water gave a TC for its response of 7 ms. The TC measured in ms within the range of airflows used was given by:

$$TC = 210.5 - \log_e(\text{flow in } l \cdot s^{-1}) \cdot 65.95$$

The effect of correcting for the time constant of response can be seen in figure 3, which shows the flow-volume curves with simultaneous and corrected temperature profiles for one subject from each of the two groups. All results presented below have been corrected for the time constant of the thermocouple.

Figure 4 presents the mean±SEM for the gas temperatures recorded at peak flow, and at 25, 50, 75 and 100%, until FVC, for the subjects with chronic airflow limitation (Group 1) and the normals (Group 2). The temperatures at peak flow, 25 and 50% of FVC were significantly higher in the patients compared with the normals ($p<0.006$). Gas temperature increased by 0.9°C from PEF to 75% of FVC in

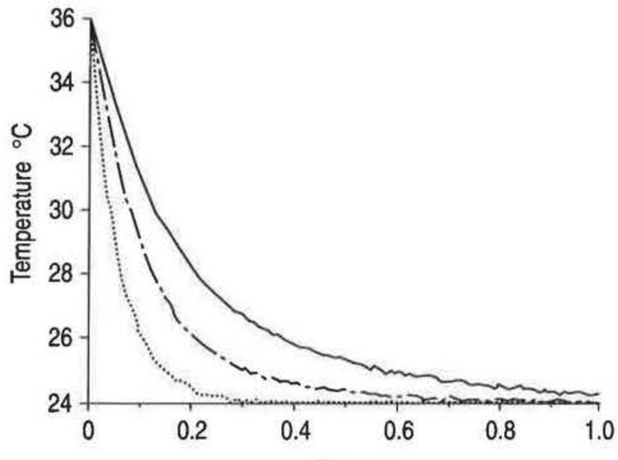

Fig. 1. – Plots of thermocouple response at various gas flows through a 28 mm I.D. mouth piece. —— : 0.64 $l \cdot s^{-1}$; – – — : 2.56 $l \cdot s^{-1}$; ········ : 10.24 $l \cdot s^{-1}$.

Table 2. – Time constant (TC) for response of thermocouple in ms at different airflows through a 28 mm internal diameter mouth piece

Flow $l \cdot s^{-1}$	TC ms
0.32	293
0.64	234
1.28	192
2.56	144
5.12	105
10.24	60

Group 2, and then fell by 1°C to 33.4°C at FVC. Whereas, in the Group 1 subjects with chronic airflow limitation the temperature was relatively constant from PEF to 75% FVC, and then fell by 1.5°C to 33.5°C at FVC. The maximum between-subject difference in temperature during the blow was 3.1 °C. With both groups considered together, the Pearson correlation coefficients for the relationship between expired temperatures and absolute FVC, forced expiratory volume in one second (FEV_1) and PEF are shown in Table 3.

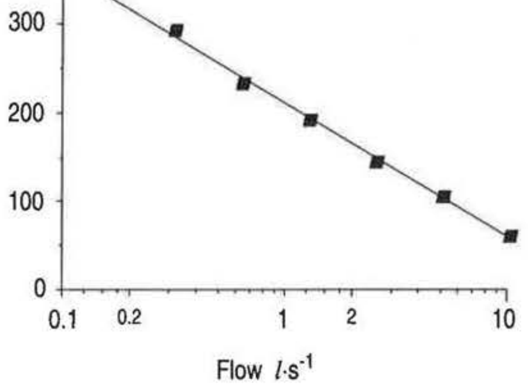

Fig. 2. – A semi-log plot of the relationship between gas flow and the thermocouple time constant of response, with the regression line drawn. The standard deviation from the regression was 6 ms and correlation was 1.0.

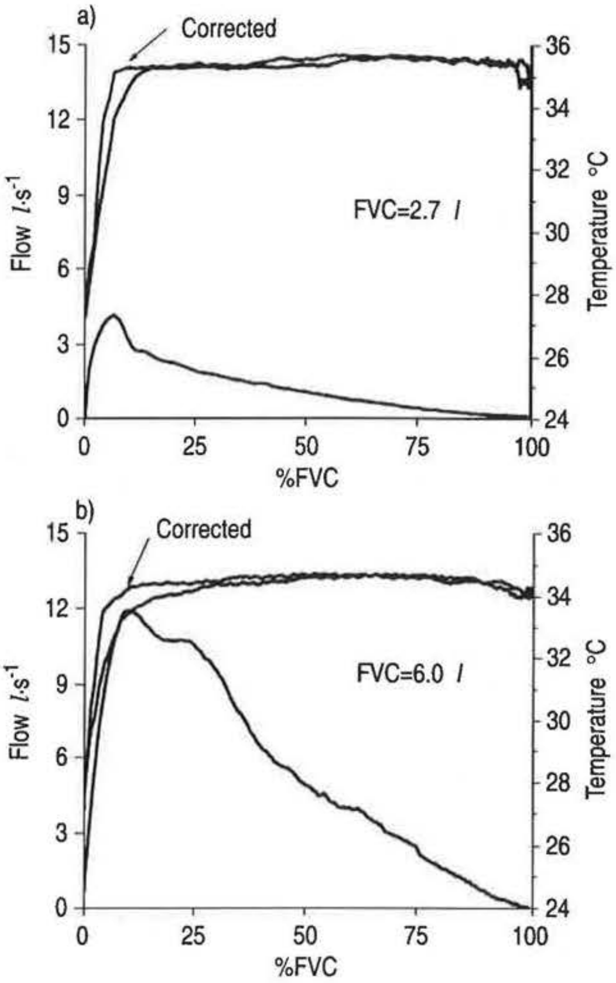

Fig. 3. – Flow volume curves with both the raw and corrected expired air temperature for: a) a subjects with chronic airflow limitation (Group 1); and b) a normal subject (Group 2). FVC: forced vital capacity.

In the Group 2 subjects, the effect of changing the mode of inhalation is seen in figure 5, with a fast inhalation through the mouth compared with a slow inhalation through the nose and a slow inhalation through the mouth. At PEF, 25% of FVC and 50% of FVC the temperature was significantly higher after slow inhalation through the nose when compared to fast through the mouth ($p<0.01$). All other comparisons between the three inhalation methods were not significantly different from zero.

Figure 6 shows the results for nine subjects from Group 2 who inhaled cold air (6°C) rapidly through the mouth and then immediately exhaled, and five of these subjects who also performed a prolonged breathhold of 30 s after inhaling ambient air before exhaling. Also shown for comparison are the Group 2 results for a normal fast inhalation of ambient air followed by immediate exhalation. The results for cold air inhalation were not significantly different from the normal values with ambient air. However, after the prolonged breathhold the air temperatures were significantly higher at all points other than FVC ($p<0.001$), by between 1.3 – 1.8°C. The expired air temperature did not approach

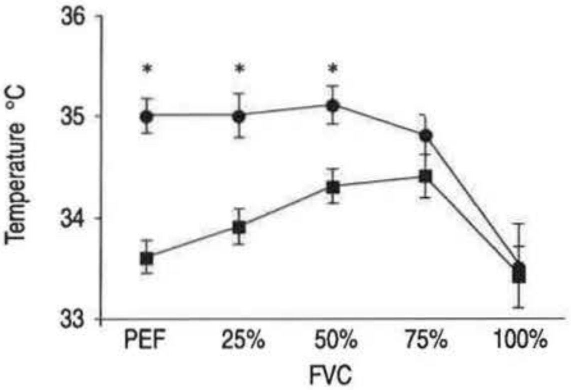

Fig. 4. – Mean expired air temperatures for subjects with chronic airflow limitation (Group 1) (●) and normal subjects (Group 2) (■) at various points during a maximal forced expiratory manoeuvre, with standard error bars shown. *: denotes that the results for Group 1 are significantly different from those for Group 2 ($p<0.006$) Mann-Whitney test. PEF: peak expiratory flow; FVC: forced vital capacity.

Table 3. – Pearson correlation coefficients (r values) for the relationship between the expired air temperature at PEF, 25, 50, 75 and 100% of FVC and the actual FVC, FEV_1 and PEF for Group 1 (subjects with chronic airflow limitation) and Group 2 (normal subjects) taken together (n=24)

	Expired air temperature						
	PEF	25% FVC	50% FVC	75% FVC	100% FVC	PEF	FEV_1
FVC	-0.69	-0.48	-0.40	-0.15	-0.10	0.95	0.94
FEV_1	-0.79	-0.60	-0.51	-0.25	-0.04	0.92	-
PEF	-0.65	-0.46	-0.40	-0.19	-0.15	-	-

Absolute r values greater than 0.21 are significantly different from zero ($p<0.05$). For abbreviations see legend to table 1.

37°C, but was significantly higher than that found in Group 1 subjects after a rapid inhalation without breathhold.

Five normal subjects recorded blows immediately after rinsing their mouths with water, at either 6° or 50°C, for 15 s and then spitting it out. The results are shown in figure 7, and even after rinsing with hot water in this way the average expired air temperature at the mouth only reached 36°C.

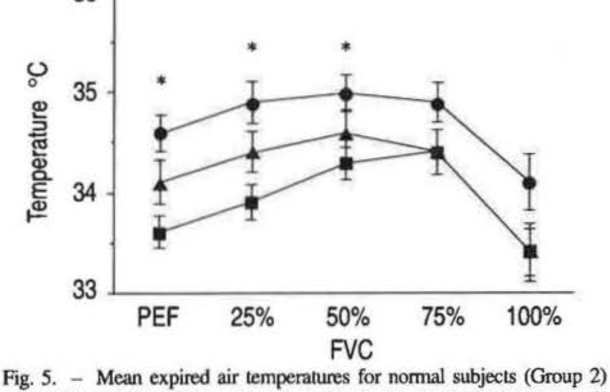

Fig. 5. – Mean expired air temperatures for normal subjects (Group 2) using different inhalation protocols, with standard error bars shown. *: denotes that the results for slow nose inhalation were signficiantly different from those for a fast mouth inhalation ($p<0.01$) Mann-Whitney test. ●: slow nose inhalation; ▲: slow mouth inhalation; ■ Fast mouth inhalation. PEF: peak expiratory flow; FVC: forced vital capacity.

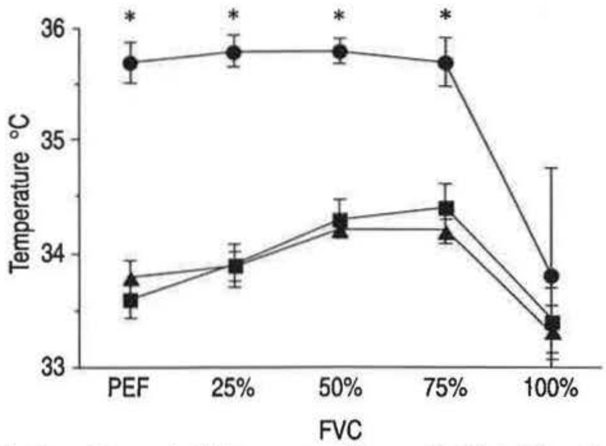

Fig. 6. – Mean expired air temperatures for normal subjects (Group 2) using different inhalation protocols, with standard error bars shown. *: denotes that the results for the breathhold were signficantly different from those for the other two protocols ($p<0.001$) Mann-Whitney test. ●: breathhold of 30 s (n=5); ■: rapid mouth inhalation (n=12); ▲: cold air inhalation (n=9). PEF: peak expiratory flow; FVC: forced vital capacity.

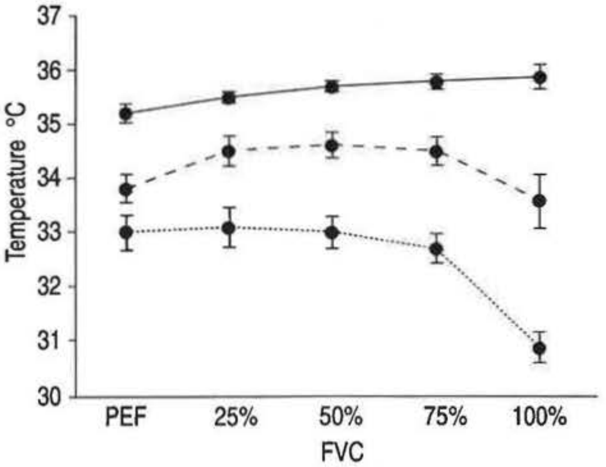

Fig. 7. – Mean expired air temperatures, with standard error bars, for five normal subjects (Group 2) following a 15 s mouth rinse of water that was either at 6 or 50°C.——— : 50°C rinse; – – – : normal; ……… : 6°C rinse. PEF: peak expiratory flow; FVC: forced vital capacity.

Discussion

We have presented the first data on expired air temperature measured at the level of the lips during a maximal forced expiratory manoeuvre in humans. We have shown a difference in expired air temperature between normal subjects and those with chronic airflow limitation, and have also demonstrated that the mode of inhalation can affect the temperature.

Before further discussing our findings it is pertinent to consider the factors governing the heat exchange between the lungs and air during breathing. Heat is transferred by conduction and convection between the walls of the airways and the air. On inspiration, there is loss of heat from the airways to the air by conduction and convection, and there is the additional heat loss from the airway walls consequent from the latent heat of evaporation required to humidify the inspired air. On expiration, the air leaving the alveoli will be warmer than the conducting airways, which were cooled on inspiration, so that heat is transferred back to the airways. As the gas cools, water vapour will condense back on to the airway walls, since a cooler gas when saturated holds less water vapour. These mechanisms help to prevent the excessive loss to the environment of heat and water from air-breathing animals. Changes in ambient air temperature and humidity will influence events, with humidity being predominant. Zawadaski *et al.* [8] showed that inhaling warm (40°C) but dry air, in fact, led to a loss of heat from the airways, due to the magnitude of the latent heat of evaporation required being twice the thermal energy available in the inspired gas. Inhaling cold air leads to even greater thermal demands on the airways, because a cold gas can carry less water vapour and, as it is heated, greater amounts of water vapour must evaporate from the airways to saturate it.

The dimensions of the airways have an effect, as shown from measurements made in animals with differing airway structure [9]. These studies on the dynamics of heat transfer in airways showed that the heat exchange depended on three factors; 1) the total surface area available for conduction and convection; 2) the velocity of the airstream; and 3) the distance of the centre of the airstream from the airway wall. Increasing the surface area, lowering the gas velocity, and reducing the diameter of the airways, all enhance the transfer of heat between the air and the airways.

We have demonstrated that this recovery of heat (and consequently of water) from the expired gas can vary with the mode of inhalation, and with the presence of airflow limitation. Separating the inspiratory route and expiratory route by inhaling through the nose leads to less efficient heat recovery from the expirate, and a consequently higher expired temperature. Under these circumstances, the expired gas is not cooled so much on exhalation because the mouth temperature has not been cooled during inspiration. Cooling or heating the mouth by a cold or hot water rinse dramatically enhanced this effect. McFadden *et al.* [10] have shown that increasing the heat transfer load by increasing the minute ventilation leads to cooling of the airways to a deeper level in the lungs. By inhaling through the nose, which is a more efficient heater and humidifier of air because of its larger surface area and smaller diameter, means that the trachea and lower airways will be cooled less. All these factors contribute to the poorer recovery of heat from the expirate during a maximal forced expiratory manoeuvre after inhaling through the nose.

Our patients with chronic airflow limitation showed a higher expired temperature than that found in the normal subjects, and this was true even when the normal subjects had inhaled *via* the nose. Our patients had a lower inspired volume and lower inspiratory and expiratory flows than our normals. The velocity of gas in the airways has two effects: 1) more heat can be removed from airways by increasing the velocity of gas within the airways; but 2) a given volume of gas will be less well-heated by the consequent shorter residence time. The human respiratory system is such that with higher gas flows in the airways a greater part of the conducting airway path becomes involved in the heating process. Solway *et al* [11] showed that the influence of residence time outweighed that due to velocity, in that a higher expired temperature was returned from a higher expiratory flow when their subjects had undergone a constant preconditioning regimen breathing cold air. How-ever, they could not demonstrate any such change due to expiratory flow when their subjects were preconditioned by breathing in ambient air. In our subjects, the preconditioning of the airways during inhalation was not constant, since the patients in Group 1 had a smaller inspired volume. Solway *et al.* [11] had also shown that quiet breathing gave a higher expired temperature than found with hyperpnoea, indicating that inspired volume was important. The work of McFadden *et al.* [6] showed that by increasing the minute ventilation the air temperature at the carina and deeper in the lungs was lowered. One can infer from this that with a larger and faster single inhalation the expired temperature would be lower, and this would fit with our data.

A possible explanation for our observed differences between patients and normal subjects is that the thermal load of cold air inspired was different for the two groups and, therefore, in the patients the airways were cooled less on inspiration and during expiration incomplete heat return led to higher expired temperature. In the normal subjects, the larger inspired volume cooled the airways more and thus cooler air was returned on expiration due to the greater, but still incomplete, heat transfer back to the airways. In our subjects, there was a significant negative correlation between expired air temperature up to 50% of FVC and the FVC, FEV_1 and PEF. This supports the finding of Solway *et al.* [11], that the magnitude of the inspiratory volume also contributed to the determination of expired temperature, with a larger inspired volume leading to a lower expired temperature. Expired air temperature close to the end of the manoeuvre does not correlate with the expired (and hence inspired) volume, because the low flows in the tail of the manoeuvre lead to a substantial influence from cooling to the surroundings through the pneumotachograph assembly and the mouthpiece. Therefore, at the end of the manoeuvre, the temperature at the lips cannot be taken to be representative of the temperature in the mouth or the airways.

Our finding that after a prolonged breathhold the expired temperature was still not at 37°C, could be due to inadequate mixing within the airways, or due to a poor blood supply, and hence heat supply, to the airway walls. A review of the data concerning the effect of airway heat and water losses on the flow in the tracheobronchial circulation indicates that there is no consensus on this subject [12]. We have shown that oral temperature has a profound effect on expired temperature, and under normal circumstances surface oral temperature is close to core temperature, indicating adequate blood supply. It is most likely that, during a held inspiration, layering of the air against the walls of the airways leads to incomplete transfer of heat to the air in the centre of the airway. Cardiogenic oscillation of airway walls may help mixing to a small extent, but may be insufficient to break a layering effect.

We have demonstrated that expired air temperature is higher in subjects with airflow limitation, and this may be significant with respect to current ideas regarding exercise-induced asthma and changes in both bronchial temperature and the bronchial circulation [13, 14]. It is thought that either the cooling of the airways from the above challenges [13], or an osmotic surface effect [14], leads to an increase in bronchial circulation, and it is this that causes the bronchoconstriction [15, 16]. The subsequent rewarming of the airways seems to relate to increased bronchial blood flow [17] from the bronchial and not the pulmonary circulation. This increase in blood flow occurs much more rapidly in asthmatics than in normal subjects [18], and it is known that asthmatics have a more vascular airway submucosa than do normal subjects [19, 20]. Under stable conditions, our subjects with airflow limitation had a higher expired air temperature than normals. A possible explanation for this is that there was an increased resting bronchial blood flow in the subjects with intrapulmonary airflow limitation, and so the recovery of their bronchial airway temperature immediately following an inspiration, but before expiration, was faster. Thus, on expiration, less heat was needed to be returned to the airways from the expirate. Greater heat transfer does occur in the presence of bronchial narrowing and lower gas velocity [9], but this effect on heat transfer is true for both inspiration and expiration. This might account for a change in the depth of airway cooling (with regard to the generation of airway affected) in asthmatics, but because of the counter-current nature of the transfer of heat in the airways, it does not readily explain the observed higher expired air temperature. Therefore, our data lend support to the idea that bronchial blood supply is increased and more responsive in the presence of diseases that cause intrapulmonary airflow limitation, such as asthma and chronic bronchitis.

The temperature of expired gas has, in the past, been assumed to reach ambient temperature for the purposes of recording all volumes and flows, with a body temperature and pressure, saturated (BTPS) correction being applied to determine what volumes and flows would have been recorded if the gas had not been allowed to cool and lose water vapour. We have previously shown that cooling within spirometers is not instantaneous, and so full BTPS correction may be incorrect [1]. We have now presented data showing that the true temperature of gas at the mouth is less than 37°C, in agreement with the work of others [3–6], and it is altered by the mode and volume of inhalation. These results will influence the calibration and recording procedures for certain flow measuring devices, and may also affect the choice of BTPS correction factor. For example, if a pneumotachograph is being heated to prevent condensation and to maintain thermal stability of the device, then the temperature of the expired air stream is important in determining what the correct temperature for the pneumotachograph head should be. Hence, the way in which subjects inhale prior to performing a maximal forced expiratory manoeuvre should be standardized, and we suggest that a slow inhalation through the mouth to TLC is likely to lead to the least bias between subjects. If recording devices could perfectly heat or cool expired air to a desired temperature then there would not be a problem and true expired air temperature would be irrelevant. However, even sophisticated temperature controllers with proportional feedback for maintaining pneumotachograph temperature cannot heat expired gas perfectly [2], and the same would probably be true for heating or cooling jackets around the pneumotachograph or spirometer assembly. Many pneumotachographs are used unheated and the relevant temperature at which the measurements are made is always that of the pneumotachograph head. This will vary according to the ambient temperature and the nature of the upstream geometry, as well as the patient and inspiratory characteristics that we have demonstrated.

When making BTPS corrections to the data recorded for spirometry the pertinent temperature is that within the device at the instant that the recording is being made. This will depend on the input temperature and the cooling characteristics of the recording device. This study has presented data with regard to the former and has indicated how this may be standardized to minimize differences between subjects. The maximal difference of 3°C that we have observed between subjects could cause up to a 2% error in temperature correction of expired volumes. We have previously indicated that the cooling characteristics of the recording device and the effective time constant of the blow have a substantial influence on what the correct BTPS correction should be [1]. We found an error of 5–6% having made a conventional BTPS correction when using a rolling seal or water sealed spirometer. The cooling characteristics of these devices can be kept roughly constant or can be largely eliminated by heating the spirometer or the pneumotachograph to maintain a constant temperature, and our present study helps determine what the appropriate temperature might be. An alternative approach has been to calculate a dynamic BTPS correction factor [21] for the recording device, and this method was shown to reduce the observed errors of 2–4% due to cooling in a rolling seal spirometer at an ambient temperature of 23°C to errors of less than 1.5%. This approach requires a complex analysis for each spirometer to determine its cooling characteristics, which must then be kept constant. A dynamic correction is then applied throughout each manoeuvre to adjust the data. This is likely to prove more cumbersome than minimizing the cooling effect by better design of the equipment.

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