Technical Communication

Demonstration of a problem in estimating sensible heat loss from the respiratory tract by thermometry

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We have investigated sensible respiratory loss, which is usually taken as the product of expired volume and the temperature difference between inspired and expired air ($\dot{V}_E \times \Delta T$). Air temperature was measured with a 0.122 mm copper-constantan thermocouple mounted in the mouthpiece of a T-piece breathing system, and expired volume with a pneumotachograph. Changing air temperature (ΔT) at the mouth and expired air volume (V_E) were recorded simultaneously while the subject voluntarily breathed at different tidal volumes and rates. Inspired temperatures were controlled at 12.05°C, 21.80°C and 25.74°C at a low dewpoint temperature of 4–5°C.

Temperature volume "loops" were constructed using an x-y plotter. The areas of each "loop" and enclosing rectangle ($V_E \times \Delta T$) were measured. The difference was divided by the weight of the rectangle to give the percentage of overestimation of sensible heat loss, which ranged from 5.5 to 17.2 per cent. The error increased significantly with decreasing tidal volume and increasing respiratory rate.

Key words
MEASUREMENT TECHNIQUES: respiratory heat loss.

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Conventionally, respiratory heat loss is calculated by the sum of the convective (sensible) and evaporative (insensible) heat loss from the respiratory tract.[1,2] The equation used is as follows:

$$RHL = \{\dot{V}_E \cdot \rho \cdot C_p \cdot (T_{ex} - T_{in})\} + \dot{V}_E \cdot 580 \cdot (\Delta pH_2O/760) \cdot \{273/(273 + T_a) \cdot 0.80\}$$

This paper deals only with the first part of the above equation. In this first part sensible heat loss is expressed as the product of minute volume ($\dot{V}_E$) in $L\,min^{-1}$ at standard temperature and pressure, density of air (ρ) at standard temperature and pressure in $g \cdot L^{-1}$, specific heat of air (C_p) at standard temperature and pressure in $J \cdot g^{-1} \cdot {}^\circ C^{-1}$ and the difference between the expired (T_{ex}) and inspired (T_{in}) temperatures (ΔT) in °C.

This assumes that all the expired air is at the same temperature, thus describing a square wave. In practice, this is not so, as the initial portion of the temperature wave form of expired air describes a curve.[2,3] It would be more correct to let T_{ex} represent the temperature of the mixed expired air, denoted as $\bar{T}_{ex}$. Formally respiratory sensible heat loss must be expressed as

$$f \cdot \rho \cdot C_p \cdot \int_0^{V_E} (T_{ex} - T_{in}) dV,$$

where T_{ex} represents the instantaneous temperature when a volume V of air has been expired.

The purpose of the study was to estimate the magnitude of overestimation when end expiratory temperature is taken as T_{ex} by solving the above

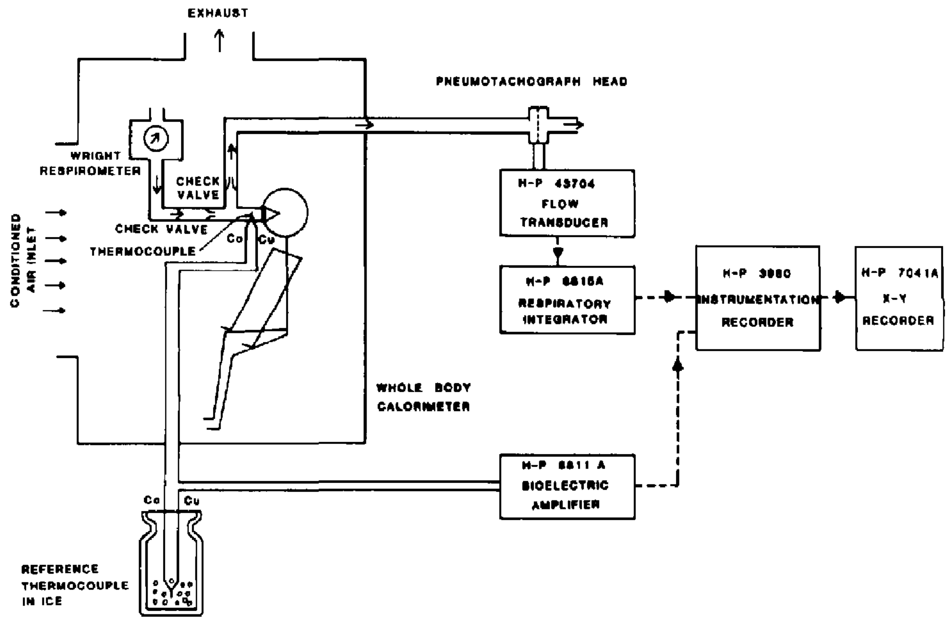

FIGURE 1 Schematic diagram to illustrate the equipment used to record expired temperature and expired volume per breath. (Co): constantan; (Cu): copper.

equation with a graphical method, and to make a preliminary investigation of factors influencing it.

Methods

The temperature of the inspired and expired air was continuously measured using a 0.122 mm spot welded copper-constantan thermocouple (electrically insulated by dipping it in Insl-x®), mounted in the mouthpiece of a T-piece breathing system, equipped with one-way valves. The response time of the insulated thermocouple was measured by suddenly exposing it to 37° C air saturated with water vapour and recording its response with the apparatus described below. To make the response time of the pen recorder negligible, the result was first recorded on magnetic tape at a high speed and then written out on an x-y recorder (described below) at a slow speed. The thermocouple voltage was amplified by a HP bioelectric amplifier model HP 8811A and calibrated against a HP quartz thermometer model 2804A using a quartz probe model 1811A with a resolution of 0.001° C; the output on the recorder was found to be linear with temperature: $y = 0.298 \cdot x + 8.656$; $s_{xy} = 0.112°C$; where y = temperature in ° C and x = scale divisions (0–100). The amplifier gain and the sensitivity of the recorder were unchanged throughout the experiments. Further, the response time was checked using a Tektronix oscilloscope and Polaroid camera. Both methods showed that the 60 per cent response time of the insulated thermocouple to moist 37° C air was 40 msec.

A healthy, young adult male subject seated at rest in a human whole-body calorimeter[4] at known temperature and humidity (Figure 1), voluntarily controlled his rate and depth of respiration while inspiring through a Wright's respirometer.[5] Expired volumes were recorded using a Hewlett Packard flow transducer model 47304A with a Type 2 pneumotachograph head and a Hewlett Packard respiratory integrator model 8815A. The volume recordings were calibrated prior to each session with a series of different volumes using a calibrated air syringe (Medscience Electronics Co., Cal Stat™ model 1000). The time between the onset of temperature deflection and the onset of volume

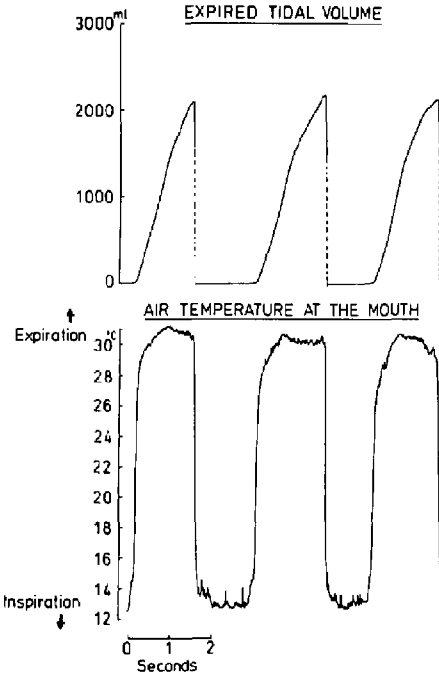

FIGURE 2 Single channel recordings of expired volume per breath and air temperature at the mouth, as displayed on the H-P x-y plotter.

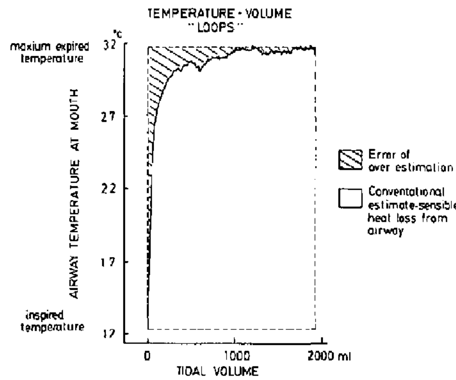

FIGURE 3 Construction of the temperature–volume "loop," plotting expired air temperature on the ordinate versus expired volume on the abscissa.

deflection was 273 ± 15 msec. The 60 per cent response time of the pneumotachograph was estimated to be less than 10 msec.

Continuous readings of airway temperature at the mouth and expired volume were simultaneously recorded on separate channels of a HP instrumentation tape recorder model 3960, at the highest tape speed (15 ft·min^{-1}). These recordings were first played back one by one at the slowest tape speed (15/16 ft·min^{-1}) and written out on a HP 7041A x-y recorder set at one constant x-axis time sweep, yielding temperature and volume tracings against time (Figure 2). Then temperature volume "loops" were constructed with expired volume on the abscissa and temperature on the ordinate (Figure 3). Again, the precaution was taken of playing back the tapes at slow speed, to minimize the effect of the x-y recorder's response time. "Loops" were made at expired volumes of about 500, 1000, 1500 and 2000 ml at different respiratory rates, at three different inspired temperatures of 12.05° C, 21.80° C, and 25.74° C, and a dewpoint temperature of 4–5° C.

Using the maximum expired temperature and known inspired temperature ΔT was determined. A rectangle of ΔT as ordinate and V_E as abscissa was constructed around each corresponding temperature-volume "loop" (Figure 3) which was plotted on Omniscribe™ graph paper (chart type ECP-100). The precaution was taken to store all sheets of paper in the air-conditioned laboratory and all cutting and weighing were done on the same day, although it was not expected that small differences in moisture content of the sheets would affect the ratio of the weights of two parts of the same sheet of paper. The shaded area (Figure 3) was cut out and weighed to the nearest 10 μg on an analytical balance (Mettler model 64), and expressed as a percentage of the total weight of the rectangle. A total of 62 "loops" were collected in this way. Attempts to construct "loops" at an inspired temperature of 30 and 35° C had to be abandoned because ΔT was too small. At an inspired temperature of 35° C there was hardly any temperature fluctuation observable.

Data were analyzed on a Hewlett Packard 9810A table top calculator with a 9862A plotter. The programs for two variable linear regression, three variable linear regression, and analysis of covariance, mentioned in the section on results, were written and verified by one of us with numerical examples from text books. The indication to use a particular test will be mentioned where necessary, in the next section. The teminology used is in accordance with the textbook on statistics[6] listed in the references.

Results

The percentage error of overestimation of sensible heat loss ranged from 5.5 to 17.2 per cent. The 5.5 per cent error was at a large expired volume (1958 ml) and a slow respiratory rate (3 breaths·min^{-1}), the 17.2 per cent error was at a small expired volume (450 ml) and a high respiratory rate (36 breaths·min^{-1}).

The three groups of observations at the three inspired air temperatures were divided each into two categories, one at low respiratory rates (<12) and one at higher respiratory rates (>14) because simple inspection of the list showed higher percentages of error in the latter category.

The percentage errors (y) of the high respiratory rate category were plotted against their pertinent expired volumes in ml (x). They showed linear relationships for each temperature which could be expressed in regression equations (Table I).

The pairs of data of these three regression lines were then subjected to an analysis of co-variance[6] which is the method of choice to decide (a) whether the slope of the lines differ (if so, the analysis ends, if not, a common slope for all lines can be calculated), (b) whether the slope of the lines differ significantly from zero (if they do not, a straightforward analysis of variance is indicated) and (c) whether the y intercepts differ significantly from each other (if they do not, the lines do not differ significantly from each other). The test statistic used is the F ratio which must be higher than the calculated value at the two degrees of freedom (ν) and the selected probability level (e.g., 1–0.05 = 0.95) in order to show statistical significance.

The analysis of co-variance revealed that the slope of the lines (b co-efficients), did not differ significantly: ($F = 0.7190; \nu_1 = 2, \nu_2 = 19; F_{0.95} = 3.52$). The hypothesis that the b co-efficient might be zero could also be rejected: ($F = -0.024; \nu_1 = 1, \nu_2 = 19; F_{0.95} = 4.38$). The y-intercepts of the three regressions with a common b co-efficient (−0.00391) did not differ either: ($F = 0.1243; \nu_1 = 2, \nu_2 = 19; F_{0.95} = 3.52$). Similar results were found for the low respiratory rate category, which yielded the regression equations shown in Table II.

It was therefore concluded that there was no effect of inspired temperature on the percentage error. The data in each category could therefore be pooled together, yielding two linear regression equations given in Table III. Co-variance analysis revealed again that the slopes did not differ significantly: ($F = 0.2287; \nu_1 = 1, \nu_2 = 58; F_{0.95} = 4.00$), but that the y-intercepts of the two lines with a common slope (−0.00243) differed highly significantly: ($F = 13.3401; \nu_1 = 1, \nu_2 = 58; F_{0.995} = 8.49$). Thus, it was established that the percentage error was not dependent on inspired air temperature, but negatively dependent on expired volume and moreover on rate. Next the residual percentage error, corrected for the effect of expired volume ($y = -0.00234\ V_E$), was plotted against rate (x) using all data. Again a linear relationship was found (Figure 4): $y = 0.145 \cdot x + 6.28$; N = 62; $s_{yx} = 2.98$.

TABLE I Data – high rate

$T_{insp.}$	*N*	*Regression equation*	s_{yx}
12.05	10	$\hat{y} = 15.95 - 0.00338 \cdot x$	1.32
21.80	9	$\hat{y} = 17.90 - 0.00551 \cdot x$	1.07
25.74	6	$\hat{y} = 15.74 - 0.00314 \cdot x$	1.02

Percentage error (y), expressed as a function of expired volume (x), at three inspired air temperatures; category of high respiratory rates (>14); S_{yx} is standard error of estimate.

TABLE II Data – low rate

$T_{insp.}$	*N*	*Regression equation*	s_{yx}
12.05	12	$\hat{y} = 13.233 - 0.00348 \cdot x$	1.32
21.80	14	$\hat{y} = 10.841 - 0.00135 \cdot x$	0.66
25.74	11	$\hat{y} = 14.397 - 0.00118 \cdot x$	2.80

Percentage error (y), expressed as a function of expired volume (x), at three inspired air temperatures; category of low respiratory rates (<12); S_{yx} is standard error of estimate.

TABLE III Data – combined groups

	N	*Regression equation*	s_{yx}
Low rate	37	$\hat{y} = 12.46 - 0.00186 \cdot x$	2.52
High rate	25	$\hat{y} = 16.50 - 0.00383 \cdot x$	1.16

Percentage error (y), expressed as a function of expired volume (x), pooled from Tables I and II, but given for the categories of low and high breathing rates. S_{yx} is standard error of estimate.

Thus it seems safe to assume that percentage error is linearly dependent on tidal volume and on rate. Therefore, a multilinear regression equation was generated,[6] using all available data (N = 62):

$$z = 12.15 + 0.0757 \cdot y - 0.00196 \cdot x; \; s_{zyx} = 2.14$$

where

z = percentage error
y = respiratory rate
x = tidal volume
s_{zyx} = standard error of the estimate

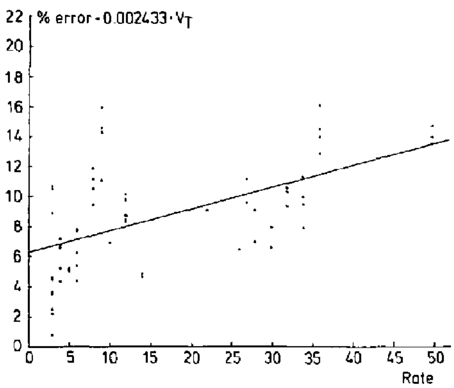

FIGURE 4 Residual percentage error corrected for expired volume plotted against rate and showing a linear regression line.

Discussion

Continuous recording of temperature at the mouth shows the initial portion of the temperature wave form describing a curve and not a square wave. This initial curve should closely reflect the actual expired air temperature at the mouth, since the thermocouple used had a fast response time and precautions were taken to avoid the slow response time of the pen recorder.

Our results show there is an overestimation of sensible heat loss from the airway when using the conventional formula of: $V_E \cdot \rho \cdot C_p \cdot (T_{ex} - T_{in})$. It is clear that the response time of the thermocouple used will tend to exaggerate the effect seen, since it will cause temperature to lag volume. However, any real temperature measuring device must have a finite response time; our thermocouple's 60 per cent response time was 40 msec which could perhaps be improved upon using finer wire and more sophisticated methods of insulation.

On the other hand, the delay time and response time of the expired volume measurement would tend to underestimate the effect since they cause volume measurement to lag behind temperature change. The constraints of the apparatus available to us led to a long delay time (273 ± 15 msec) due, probably, to the time required to open the breathing valves and to gas compressibility. The 60 per cent response time of the pneumotachograph apparatus (10 msec) made a small further contribution. Thus the figures we have arrived at for the percentage error of overestimation of respiratory heat loss by using the conventional equation must be taken to be conservative. More sophisticated techniques should demonstrate a higher percentage of overestimation.

The error of overestimation appears to increase significantly with decreasing expired volume (co-efficient −0.00196) and also with increasing rate of breathing (co-efficient 0.0757). Interestingly, inspired temperature had no significant effect on the percentage error, even though we observed a definite relationship between inspired and maximum expired temperature, as observed by others.[2,3]

If one takes into account the delay time, other factors such as density or specific heat of a gas may also alter this percentage error of sensible heat loss in that it may further change the expired air temperature curve. For example, it may be of practical importance to determine what the error in heat loss estimation is in the hyperbaric helium environment as experienced in diving.

Finally, it should be pointed out that this study attempted to demonstrate the importance of this problem and the prediction equation presented may not have general applicability, as only one subject was studied.

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Résumé

Nous avons étudié les pertes caloriques sensibles de l'arbre trachéobronchique qui sont habituellement obtenues en faisant le produit du volume expiré par la différence de température entre l'air inspiré et l'air expiré ($V_E \times \Delta T$). La température de l'air a été mesurée par un thermocouple cuivre-constantan de 0.122 mm monté sur une pièce buccale placée sur une pièce en T. Le volume expiré était mesuré par un pneumotochographe. La différence de température à la bouche (ΔT) et le volume d'air expiré (V_E) étaient enregistrés simultanément alors que le sujet respirait à différents volumes courants et à différentes fréquences. Les températures inspirées étaient réglées à 12.05°C, 21.80°C, et 25.74°C et la température du point de rosée était maintenue à 4–5°C.

Les courbes température-volume ont été construites en utilisant un axe x-y. Les surfaces de chaque courbe et du rectangle la renfermant ($V_E \times \Delta T$) ont été mesurées. La différence a été divisée par le poids du rectangle pour donner le pourcentage de surestimation des pertes caloriques sensibles, lequel se situait entre 5.5 et 17.2 pour cent. L'erreur augmente de façon significative lorsque le volume courant diminue et que la fréquence respiratoire augmente.