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MEASUREMENT OF RESPIRATORY AIR TEMPERATURES AND CALCULATION OF RESPIRATORY HEAT LOSS WHEN WORKING AT VARIOUS AMBIENT TEMPERATURES

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DEFENCE RESEARCH ESTABLISHMENT OTTAWA
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Environmental Protection Section
Protective Sciences Division

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ABSTRACT

The purpose of this investigation was to establish the temperature and humidity of the expired air of subjects working at various metabolic rates at ambient temperatures between -40°C and 20°C in order to calculate the heat loss from the body due to respiration. Measurements of the respired air temperature and water vapour content were made for five subjects while they either stood or walked on a treadmill. The results indicated that the maximum respired air temperature varied slightly with the ambient air temperature but changes in metabolic rate, respiration rate and breathing frequency had no apparent effect on the expired air temperature under the conditions studied. The relative humidity of the respired air was found to be close to saturation in the extreme-cold environments. Heat loss due to respiration was calculated and the influence of various physiological and environmental variables on the respiratory heat loss is discussed.

RÉSUMÉ

Le but de cette étude était d'établir la température et l'humidité de l'air expiré par des sujets travaillant à des taux métaboliques variables et à des températures ambiantes s'échelonnant de -40°C à 20°C afin de calculer la perte de chaleur due à la respiration. Des mesures de la température et de la quantité de vapeur d'eau contenue dans l'air expiré furent effectuées sur les cinq sujets pendant qu'ils étaient debout immobile ou qu'ils marchaient sur un tapis roulant. Les résultats indiquent que la température maximum de l'air expiré variait légèrement avec la température ambiante mais que des variations de taux métabolique, de la vitesse de respiration et de la fréquence de respiration n'avaient pas d'effet apparent sur la température de l'air expiré pour les conditions étudiees. Dans les environnements de froid intense l'humidité relative de l'air respiré approchait le point de saturation. On a calculé la perte de chaleur de à la respiration. L'influence de différents facteurs physiologiques et des conditions environmentales sur la perte de chaleur respiratoire est aussi discuté.

EXECUTIVE SUMMARY

Heat loss due to respiration can represent a sizable portion of the body's total heat loss. The temperature and humidity of expired air are important in determining the respiratory heat loss since this heat loss depends upon, among other things, the difference between the inspired and expired air temperatures and the change in the absolute humidity of the respired air.

The temperature of expired air has been reported to be as low as approximately 20°C and as high as 37°C. Reports on the humidity of the expired air have also varied, from approximately 80% relative humidity to fully saturated. Since these variations in both temperature and humidity may have been due to the slow response times of the sensors used, this investigation was undertaken using a fast response temperature sensor in an attempt to obtain a better estimate of the correct values.

In this study, the temperature of the respired air was measured while subjects worked at four different rates and at four different ambient air temperatures. During tests at very cold temperatures, the water content of the expired air was also measured. With this information and with measured respiratory ventilation rates, the respiratory heat loss was calculated for various metabolic rates and ambient temperatures.

It was found that the temperature of expired air of individuals working normally depends mainly on the ambient air temperature but that even at very cold ambient temperatures, the expired air temperature is approximately 28°C. The expired air was found to be saturated, or very close to saturation, for all conditions studied. The respiratory heat loss was found to be between 25 and 30% of the resting metabolic rate but was between 15 and 20% of the working metabolic rate.

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1.0 INTRODUCTION

This study was initiated to determine the state of the expired air of subjects working normally at various ambient temperatures in order to calculate the heat loss due to respiration. Heat loss due to respiration can represent a sizable portion of the body's total heat loss (Burton, 1955). The temperature and humidity of expired air are important in determining the respiratory heat loss since this heat loss depends upon, among other things, the difference between the inspired and expired air temperatures and the change in the absolute humidity of the respired air.

Investigations of the temperature of the expired air have found values as low as approximately 20°C (Webb, 1951; McFadden et al., 1985) and as high as body core temperature (37°C) (Newburgh, 1968; Höppe, 1981). Reports on the humidity of the expired air also varied, from approximately 80% relative humidity (Ferrus et al., 1984; McCutchan and Taylor, 1951; Mitchell et al., 1972) to fully saturated (Belding et al., 1945; Newburgh, 1968). As some of the methods and measuring techniques of these investigations would not have produced an accurate value of the expired air temperature, this investigation was undertaken in an attempt to obtain a better estimate of the correct values.

In this study, the temperature of the respired air was measured while subjects worked at four different rates and at four different ambient air temperatures. During tests at very cold temperatures, the water content of the expired air was also measured. With this information and with measured respiratory ventilation rates, the respiratory heat loss was calculated for various metabolic rates and ambient temperatures.

A summary of the work which is described in detail in this report has been submitted for publication in the open literature.

2.0 Experimental Procedure

Five male volunteers gave their informed consent to participate in the experiments. The average and standard deviation of age, height and weight of the subjects were 28 ± 5 years, 171 ± 7 cm and 74 ± 12 kg respectively. The experiments were conducted in an environmental chamber at each of four ambient temperatures: -40, -20, 0 and 20°C. The subjects dressed in appropriate clothing so that they were comfortable at each of these temperatures. Experiments consisted of a series of four tests at each ambient temperature. Tests were conducted at four different work rates, those being standing quietly and walking on a treadmill at: 3 $km \cdot h^{-1}$ on a 0% grade; 3 $km \cdot h^{-1}$ on a 5% grade; and 5 $km \cdot h^{-1}$ on a 5% grade. Each of the four tests in an experiment lasted approximately 22 minutes and the duration of each experiment was approximately 90 minutes.

For each experiment, the subject entered the environmental chamber and stood breathing normally for a period of 10 minutes. The temperature of his respired air was then measured over a two minute period using a thermocouple mounted in a special mouthpiece. The subject then removed the mouthpiece and donned a face mask (Speak-Easy II, Respironics Inc. Monroeville, PA) which was connected to a Beckman Metabolic Measurement Cart in an adjacent laboratory using 47 mm diameter corrugated plastic tubing. The subject's metabolic rate, respiratory frequency and volume of expired air were measured for ten minutes with average values recorded every minute. The subject then walked on the treadmill at the lowest work rate for a ten-minute equilibration period following which the above measurement procedure was repeated with the subject still walking. This procedure was repeated at the next two higher work rates.

The temperature of respired air was measured using a copper-constantan thermocouple (Omega COCO-001). This thermocouple was mounted through the wall of, and the thermocouple junction located at the centre of, a rubber mouthpiece (Vacumed No. 1001) at about the plane of the lips. The mouthpiece was modified to be as short as possible but still held conveniently in place with the teeth and lips. Prior to each test, the mouthpiece was examined to ensure that the thermocouple was properly positioned. It was then left in the environmental chamber to equilibrate to the ambient temperature.

The temperature data was measured and recorded using a Hewlett-Packard data acquisition system (HP 3497A) controlled by a Hewlett-Packard computer (HP 9836). Measurement of both the ambient air temperature and the thermocouple reference temperature were made at the beginning and end of each two minute respiratory air temperature measurement. Only the respired air temperature was monitored during the two minute interval which allowed readings to be recorded every tenth of a second.

The quantity of water in the expired air was measured during experiments at the two coldest ambient temperatures. For these experiments, approximately 3 m of plastic tubing was used to connect the subject's mask to the metabolic cart. The tubing was coiled in the environmental chamber and was used to condense water from the expired breath. The mask and tubing were weighed (Mettler Balance, Model P10N) before and after each experiment in the cold chamber which minimized the errors caused by condensation from the air on the cold outer surfaces. It was assumed that the measured difference in weight during a test was due only to water condensed from the breath.

Having measured the respiratory ventilation rate and the water vapour content of the expired air, the heat loss from the body due to respiration can be calculated from the following equation:

$$Q_r = \rho_a V c_{pa}(T_e - T_i) + \rho_a V(\gamma_e - \gamma_i)h_{fg} + \rho_a V \gamma_i c_{pv}(T_e - T_i) \qquad (1)$$

where

Q_r	respiratory heat loss, W
ρ_a	density of the air, $kg \cdot m^{-3}$
V	respiratory ventilation rate, $m^3 \cdot s^{-1}$
c_{pa}	specific heat of air, $J \cdot kg^{-1} \cdot K^{-1}$
T_e	expired air temperature, $^\circ C$ or K
T_i	inspired air temperature, $^\circ C$ or K
γ_e	absolute humidity of the expired air
γ_i	absolute humidity of the inspired air
h_{fg}	enthalpy of vaporization, $J \cdot kg^{-1} \cdot K^{-1}$
c_{pv}	specific heat of water vapour, $J \cdot kg^{-1} \cdot K^{-1}$

The three terms on the right hand side of equation 1 represent the heat loss associated with warming of the inspired air, humidifying the inspired air and warming the inspired water vapour respectively.

3.0 Results

Figure 1a shows a plot of typical data measured in this investigation for the temperature of respired air. The test begins with the mouthpiece (and thermocouple) at the ambient air temperature. At approximately 17 seconds into the test, the mouthpiece was inserted and measurement of the subject's respired air temperature began. It can be seen that the minimum temperature recorded by the sensor upon inspiration was approximately that of the ambient air temperature (-40°C). The maximum expired air temperature recorded shows some scatter but is approximately constant for each breath. The transition from the minimum to the maximum respiratory temperature was found to take approximately 25% of the total time required for one complete respiratory cycle which is in agreement with other reported values (Webb, 1951).

Figure 1b shows an enlargement of Figure 1a for the first few expired breaths. Several data points are evident at the end of each expiration. The peak temperature is relatively constant although rapid fluctuations are evident indicating that maximum temperatures were recorded.

The expired air temperature and humidity did not vary in any consistent manner for the work rates, metabolic rates, respiration rates or the respiration frequencies encountered in this investigation. The results were therefore averaged over all four work rates and the mean expired air temperatures for various ambient temperatures are plotted in Figure 2. At an ambient temperature of 20°C, the expired air temperature was found to be 34 ± 1°C. The expired air temperature decreased slightly as the ambient air temperature decreased and at -40°C, the expired air temperature was 29 ± 2°C.

The air temperature at the end of the coil of tubing used during measurments of the water vapour content of the expired air was found to be close to the ambient temperature of the environmental chamber. It was therefore assumed that all of the water vapour in the expired air had condensed either in the mask or in the tubing. Drying compounds at the metabolic cart indicated no significant amounts of water in the sampled air, further supporting this assumption.

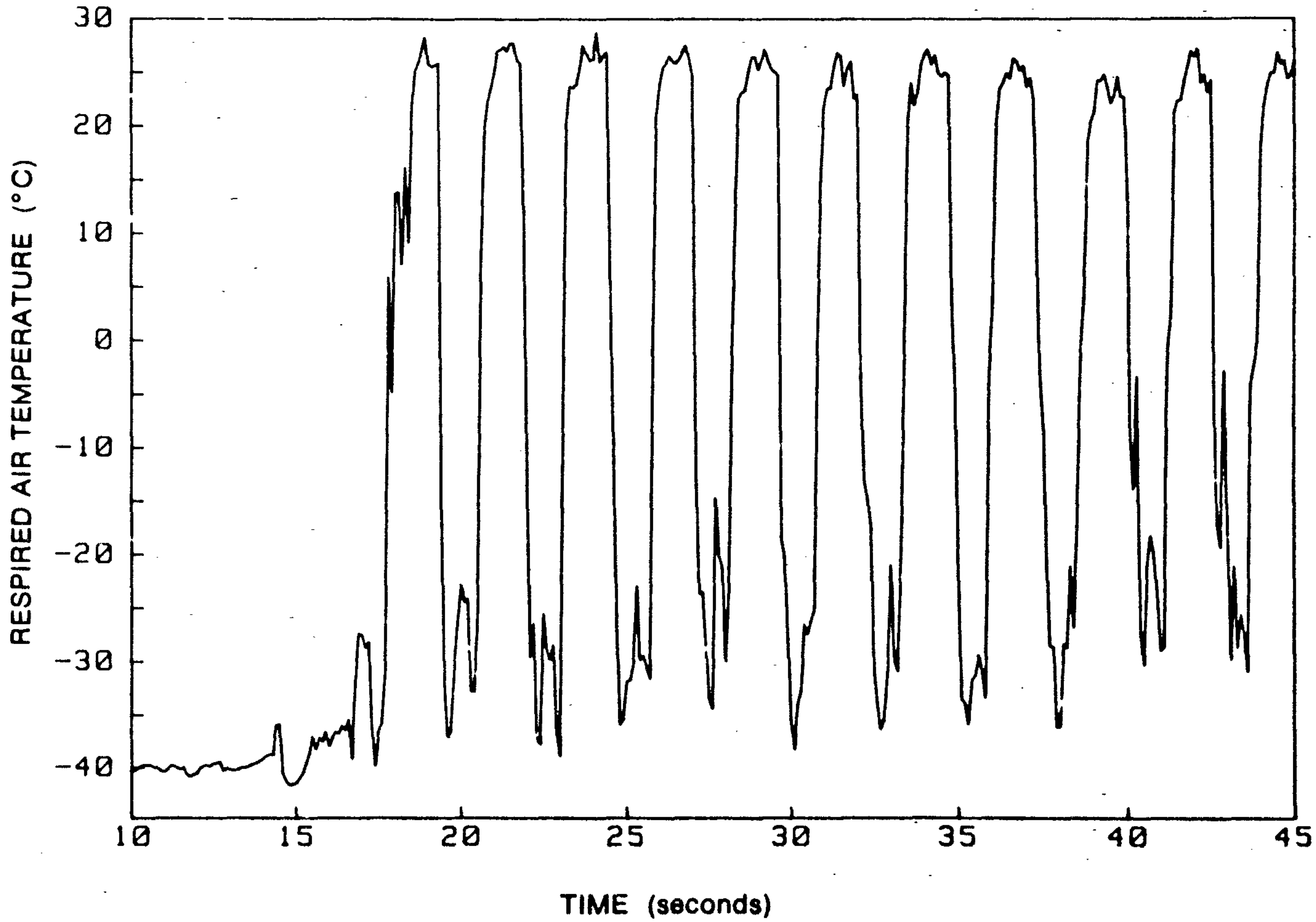

Figure 1a. Typical data from measurements of the respired air temperature.

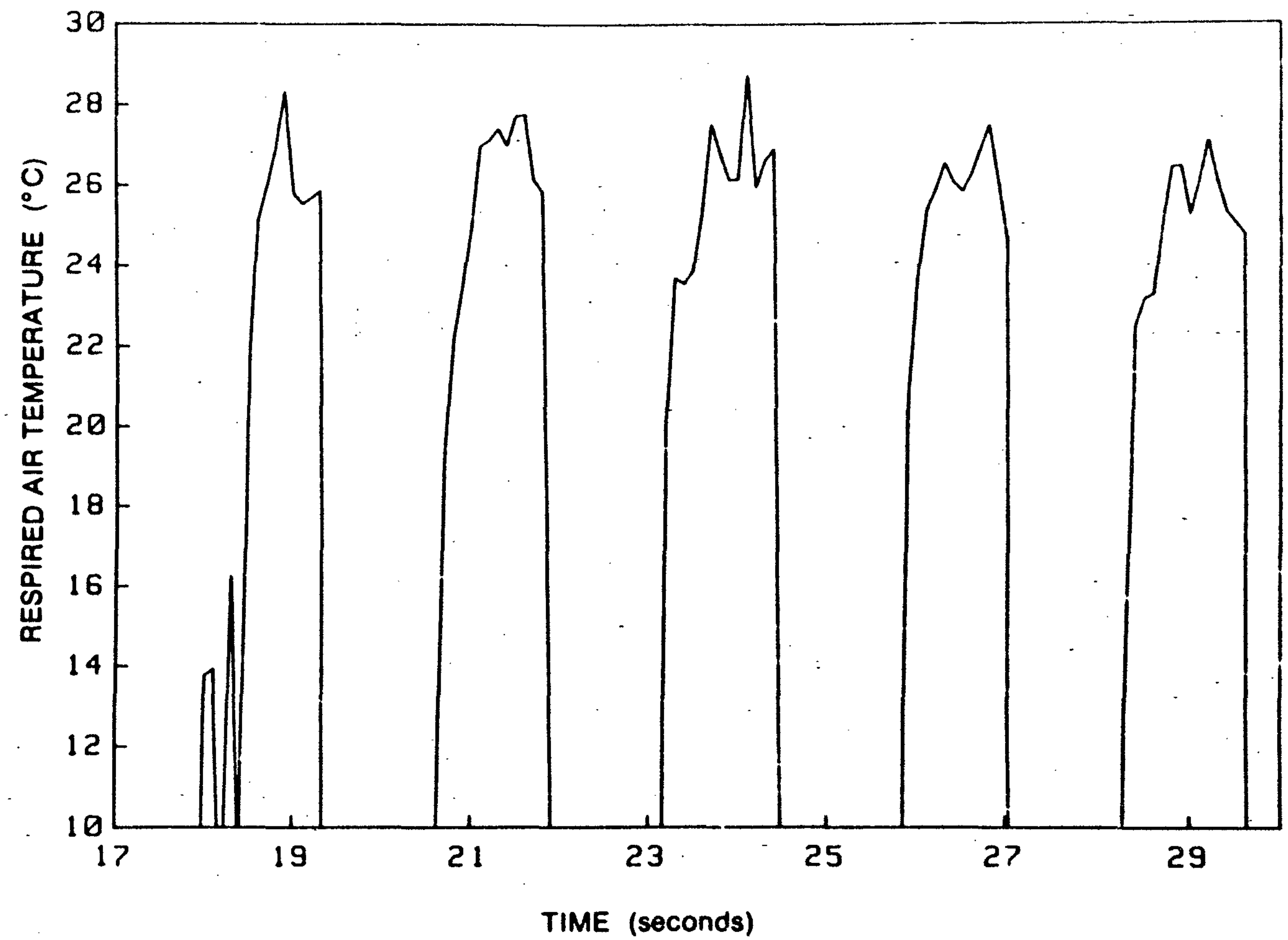

Figure 1b. Enlarged detail of the expired air temperature for the first few breaths of the data shown in Figure 1a.

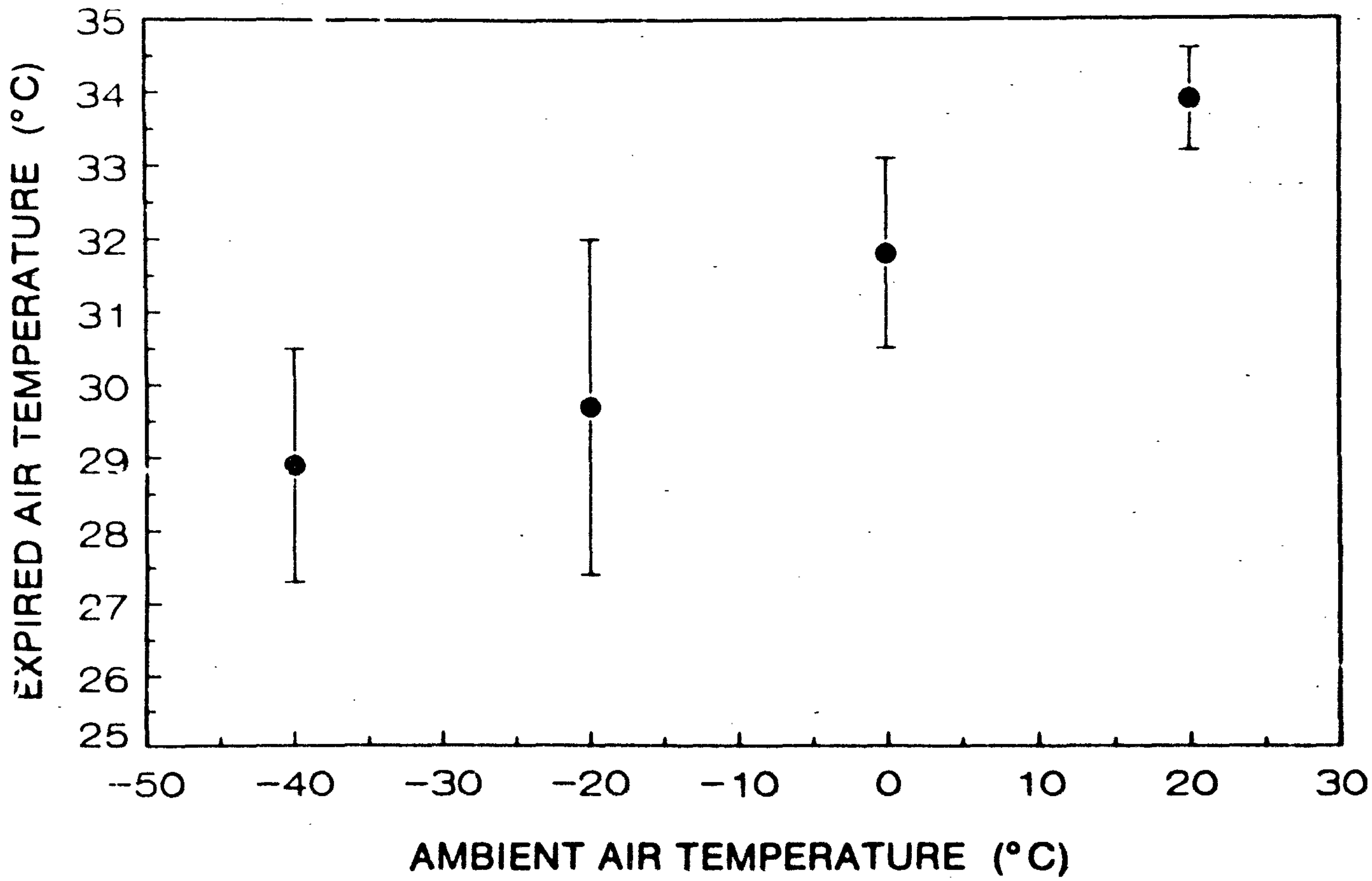

Figure 2. Expired air temperatures averaged for all subjects and work rates at various ambient air temperatures.

The expired air was found to be close to saturation at the measured expired air temperature and was greater than 90% relative humidity in most cases. The average amount of water collected varied from 0.44 ± 0.06 (mean + standard deviation) to 1.0 ± 0.27 $g \cdot min^{-1}$ for respiration rates of 8.7 ± 2.5 to 41.5 ± 8.3 $l \cdot min^{-1}$ respectively. The experimental uncertainty in these measurements was approximately 40% at the low respiration rates and approximately 15% at the high respiration rates. In several experiments, the results indicated that the expired air was supersaturated.

The respiratory heat loss was calculated for cold ambient temperatures using experimental values for the expired air temperature and the respired volume flow rate. The expired air was assumed fully saturated as suggested by the results of this study. The absolute humidity of the ambient air for temperatures less than 0°C was negligible. The respiratory heat loss, expressed as a percentage of the total metabolic rate, is plotted in Figure 3 versus metabolic rate for ambient temperatures of -40, -20 and 0°C The results for 20°C are not included as the ambient humidity was not controlled during these tests and may have been significant. For metabolic rates between 75 and 100 W, the respiratory heat loss was found to represent between 25 and 30% of the metabolic rate. For metabolic rates greater than 200 W, the respiratory heat loss was approximately 10% lower.

4.0 Discussion

As noted earlier, the mouthpiece was made as short as possible. This was to minimize the effect upon the respired air temperature. Preliminary air temperature measurements made in a large mouthpiece (Hans Rudolph, 2-Way Valve) indicated that the inspired air was warmer than the ambient air. This suggested that the mouthpiece and valve assembly were heated by the expired air which then in turn heated the inspired air of the following breath. Measurements of the expired air temperature in the large mouthpiece indicated changes of several degrees within a centimetre out of the mouthpiece as the expired air was cooled by the mouthpiece and tubing. This phenomenon had been noted previously (McCutchan and Taylor, 1950) and suggests that some investigations (McCutchan and Taylor, 1951; Hartung et al., 1980) may have reported expired air temperatures which were lower than those at the mouth.

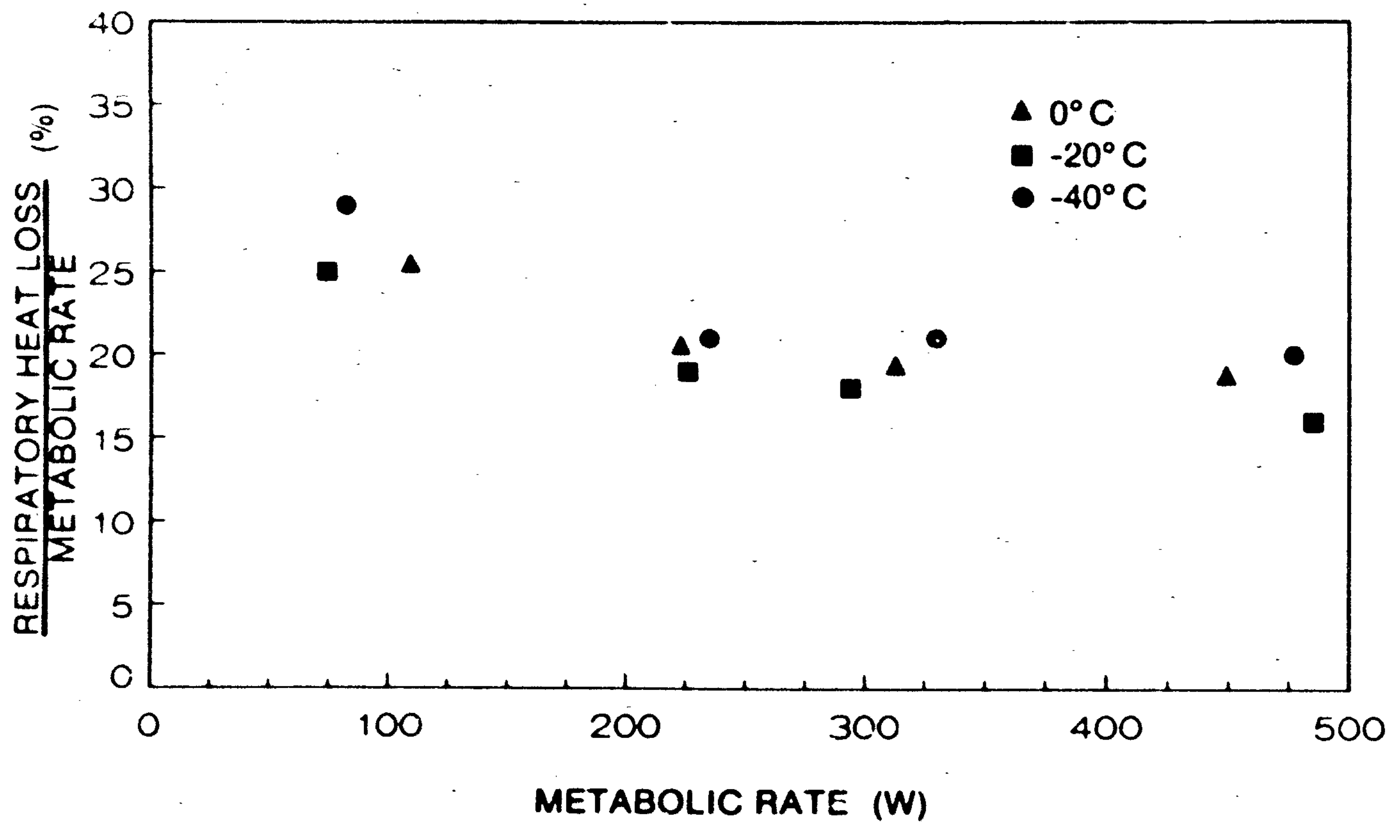

Figure 3. Respiratory heat loss expressed as a percentage of the total metabolic rate at the four work rates used in this investigation. Results are based on expired air temperatures, metabolic rates and respiratory ventilation rates averaged for all subjects at each work rate. The expired air is assumed fully saturated while the inspired air is assumed dry

The thermocouple which was used to measure the respired air temperature extended into the centre of the shortened mouthpiece and, to minimize its response time, no support other than the bare thermocouple wires was used. The temperature of the expired air was not found to vary significantly if the thermocouple junction was inside the plane of the lips, but substantially lower temperatures were observed even within one centimetre outside of the mouthpiece as ambient air mixed with expired air.

The response time of temperature sensors is a function of several variables (Dahl and Herzfeld, 1962). To select an appropriate temperature sensor to measure the respired air temperature, the response time in moving air (as opposed to water) (McFadden et al., 1982; McFadden et al., 1985) must be considered. Also, the sensor should be mounted such that its nominal response time is not significantly affected. The highest respiration frequency observed in this investigation was 40 breaths$\cdot$min^{-1}. If it can be assumed that the temperature of the respired air can be represented by a square wave with a maximum respiration frequency of 60 breaths$\cdot$min^{-1}, then the response time of a sensor must be less than 0.125 s to record 98% of the step change in temperature between inspiration and expiration. If the response time is greater than this, then the temperatures measured will lie somewhere between the inspired and expired air temperatures.

The opening in the mouthpiece was oval with an approximate area of 4 cm^2. Measurements of respiratory ventilation rates ranged from approximately 10 l$\cdot$min^{-1} at rest to 40 l$\cdot$min^{-1} at the highest work rate which correspond to average air speeds between 0.8 and 3.4 m$\cdot$s^{-1} through the mouthpiece. The copper-constantan thermocouple used in this investigation has a response time of 0.004 s in fast moving air and 0.05 s in still air (Omega, 1985). Although these air speeds were not as fast as the air speed used to determine the thermocouple response time (20 m$\cdot$s^{-1}), the response time of the thermocouple used was thought to be adequate at these air speeds for this problem. The data points shown during each expiration cycle in Figure 1b justify this assumption. Thus, the response time and the recording time of 10 readings per second provided a detailed measurement of the respired air temperature with time.

The data in Figure 1a indicate that the air temperature measured by the thermocouple upon inspiration was that of the ambient air. It was therefore assumed that the temperature recorded upon expiration was an accurate measure of the expired air temperature.

In most experiments, the recorded inspired and expired air temperatures began to change, with one or both tending to some temperature intermediate to the ambient and body temperatures (Figure 4). Examination of the mouthpiece after these events showed water or ice either on the thermocouple junction or on the thermocouple lead wires. Water on the junction or wires was thought to result from droplets of condensation in the expired air, although saliva may have been responsible in some cases. This phenomenon significantly increased the response time of the thermocouple producing obviously different and erroneous results. In Figure 4, the recorded inspired air temperature indicates that the sensor was not accurately measuring the ambient air temperature. In other experiments, the recorded expired air temperature changed abruptly in a similar fashion. This phenomenon was reported in only one other reference (Hartung et al., 1980), although, as it occurred in virtually all of the tests of this investigation at some point in the measurements, it is likely to have occurred in each of the other investigations. To avoid any problem with water on the thermocouple, the maximum expired air temperature was estimated from the first few breaths only. If the data showed a peculiar response during this time, the measurements were repeated.

The variation of the expired air temperature with ambient air temperature was found to be somewhat different from that reported in some other investigations (Belding et al., 1945; McFadden et al., 1985; Hartung et al., 1980) but is in reasonable agreement with others (Hoppe, 1981). There is insufficient data from this investigation to determine the exact form of the relationship between the expired and ambient air temperatures, however, the data shown in Figure 2 suggests that the peak expired air temperature approaches a minimum value between 27 and 30°C for ambient temperatures below -30°C under otherwise normal working conditions. It would also appear that the expired air temperature approaches the body core temperature as the ambient temperature approaches 37°C, although the value actually attained will be dependent on the inspired air humidity.

Humidity sensors typically have time constants which are much greater than the response time required for measurements in respired air and are therefore not suitable for these experiments. It was therefore decided to calculate the humidity by condensing and weighing the quantity of water collected in ten minutes from the respired air. This procedure would have required additional refrigeration during tests at and above 0°C, so the water content of the expired air was measured at the two coldest ambient temperatures only. A difficulty with this technique is the low accuracy of the measurement of the mass of condensed water. The condensing tubes and face mask weighed approximately 2.2 kg while average quantities of water collected varied from 4 to 10 g for the low to high respiration rates respectively.

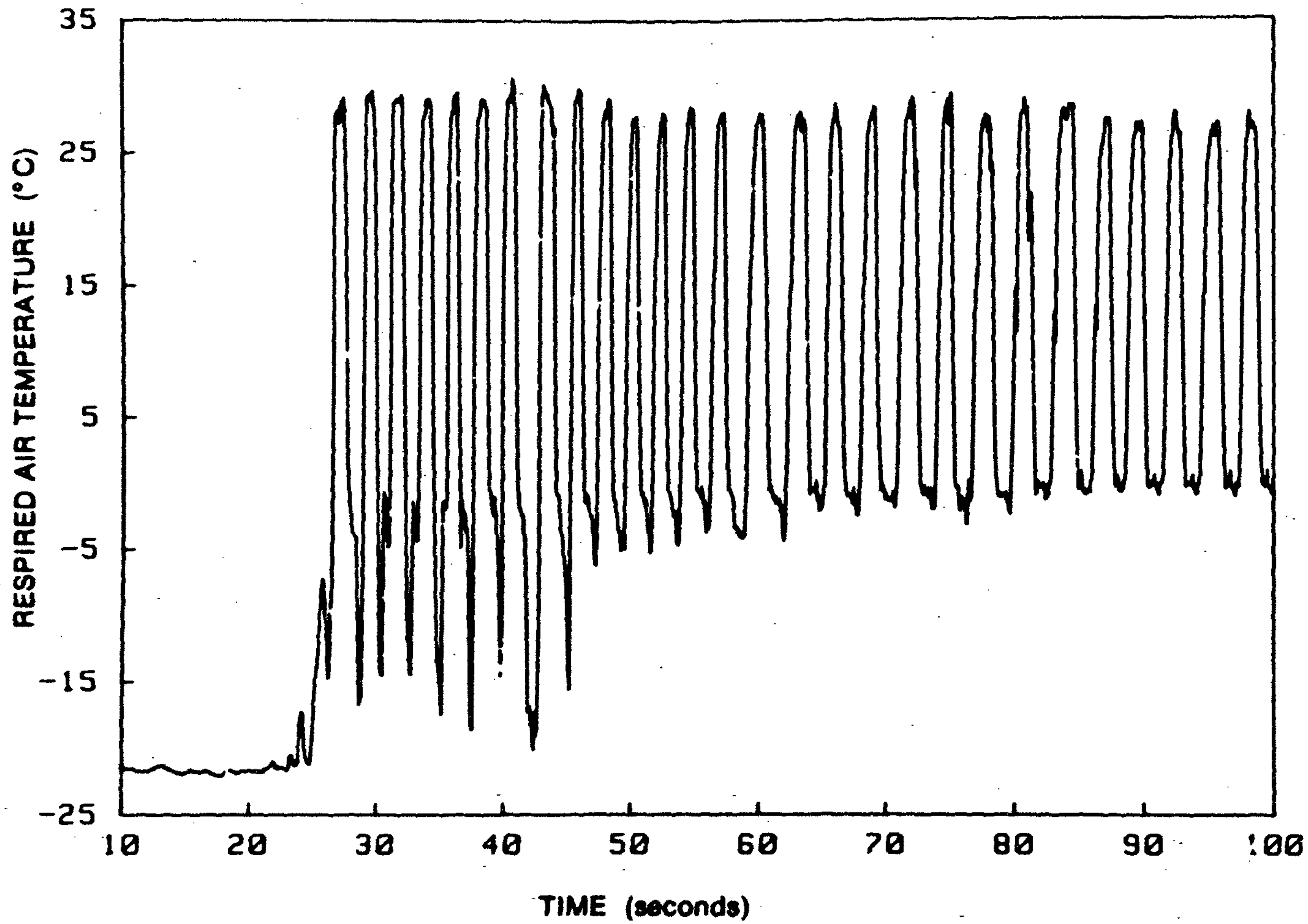

Figure 4. Typical data recorded during respired air temperature measurements. At about 45 secs the thermocouple has become wetted with condensed water-vapour or saliva.

The results indicated that the expired air was close to saturation and in many of the experiments, the expired air appeared to be supersaturated, even after the experimental error was considered. Although saliva may have been responsible for some error in the measurement, the expired air may actually supersaturate briefly at some point during expiration. It has been suggested that the air in the lungs is very close to saturation at the body core temperature (McCutchan and Taylor, 1950) and that as the expired air cools, the water vapour condenses onto the mucous membranes of the bronchial tree or in the mouth and throat. If, instead, a substantial portion of this condensate remained as an aerosol in the expired air, it would be collected along with the remaining water vapour. This aerosol would not represent a significant energy loss, however, the energy released during condensation would tend to warm the expired air. This would buffer the cooling that occurred at the walls of the breathing passages and would be reflected in the expired air temperature.

Only the ambient air temperature and the work rate were controlled during the experiments. The subjects were allowed to breathe normally while they worked so metabolic rate, respiration rate and breathing frequency, while measured, were not controlled. There was insufficient data to determine the individual influence of these variables on the temperature and humidity of the expired air, but they did not collectively seem to have a significant effect for the conditions in this investigation.

The first two terms in the equation for the respiratory heat loss (equation 1) are of comparable magnitude in a cold environment; the third term is negligible in the cold and small even in warmer, humid environments. The results of the heat transfer calculations (Figure 3) indicate that respiratory heat loss is a larger fraction of the metabolic rate at low work rates than at higher work rates, although the data suggest that respiratory heat loss approaches a limiting value as the work rate increases. The respiratory heat loss may also represent a slightly larger fraction of the metabolic rate at lower temperatures although this may be only a statistical fluctuation in the data.

The assumption that the expired air is either at 80% or at 100% relative humidity results in only a marginal difference (approximately 10%) in the calculated value of the respiratory heat loss since the amount of energy required to heat the inspired air is approximately equal to that required to humidify the inspired air. For ambient air temperatures greater than 0°C, the absolute humidity of the inspired air can become significant and will decrease the amount of water evaporated in the respiratory tract. This will reduce the evaporative heat loss as indicated by the second term in equation 1.

5.0 Conclusion,

It was found that the temperature of expired air of individuals working normally depends mainly on the ambient air temperature but that even at very cold ambient temperatures, the expired air temperature is approximately 28°C. The expired air was found to be saturated, or very close to saturation, for all conditions studied. The respiratory heat loss was found to be between 25 and 30% of the resting metabolic rate but was between 15 and 20% of the working metabolic rate.

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The purpose of this investigation was to establish the temperature and humidity of the expired air of subjects working at various metabolic rates at ambient temperatures between -40°C and 20°C in order to calculate the heat loss from the body due to respiration. Measurements of the respired air temperature and water vapour content were made for five subjects while they either stood or walked on a treadmill. The results indicated that the maximum respired air temperature varied slightly with the ambient air temperature but changes in metabolic rate, respiration rate and breathing frequency had no apparent effect on the expired air temperature under the conditions studied. The relative humidity of the respired air was found to be close to saturation in the extreme-cold environments. Heat loss due to respiration was calculated and the influence of various physiological and environmental variables on the respiratory heat loss is discussed.

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Work
Temperature
Humidity
Metabolic Rate