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THE EFFECT OF DRY AND HUMID HOT AIR INHALATION ON EXPIRED RELATIVE HUMIDITY DURING EXERCISE*

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It has been previously demonstrated that under certain environmental conditions, expired air is not fully water saturated because of the low relative humidity of the first part of the expirate. This finding is of interest to those involved in respirator research, particularly those who design and test robotic metabolic simulators. These simulators must accurately mimic the physiological responses of human airways to breathing air of various temperatures and relative humidities (RHs). Because these responses are not fully quantified, this study examined the mean relative humidity of expired air during four inspired air conditions: cool dry (26°C, 60% RH), cool humid (26°C, 95% RH), hot dry (45°C, 11% RH), and hot humid (45°C, 95% RH). These conditions were administered during three exercise intensities: rest, low (35% $\dot{V}_{O_2}$max*), and moderate (70%* $\dot{V}_{O_2}$max*). As compared to the cool dry (CD) condition, frequency of breathing (f) was 9.3% lower and tidal volume (*V_T*) was 9.4% greater across all exercise intensities for the hot humid (HH) condition (*$p < 0.05$*). Mean expired relative humidity (ERH) was substantially lower for the hot dry (HD) condition as compared to the other three conditions during each sampling period. These findings support the conclusion that the mean ERH of expired air depends upon several respiratory and environmental factors in addition to inspired air temperature.*

Since the early study of McCutchan and Taylor[1] demonstrated that expired air is not always fully saturated with water, respiratory heat and water exchange with various inspired air temperatures and humidities have been investigated by various authors. In 1984, Ferrus et al.[2] investigated the effects of inspired air temperature (10 to 40°C) and partial pressure of water on respiratory water loss. Both were found to be positively and significantly related to respiratory water loss. Recently, Tabka et al.[3] observed a progressive fall in mean expired relative humidity (ERH) to approximately 78% RH during 15 to 20 min of cycle ergometry when subjects breathed 28 to 30°C dry (0% RH) air. They observed no decrease in ERH when the same subjects breathed 28°C, 20% RH air.

Based on previously published multiple regression equations,[4] Varene recently published heat exchange equations in which the mass of expired water, used to calculate evaporative heat loss, is estimated from inspired air temperature and water vapor pressure.[5] These equations were derived from experiments in which the inspired air temperature (T_I) ranged from 10 to 40°C, minute ventilation ($\dot{V}_E$) was between 5 and 43 L/min, and inspired air water vapor pressure (P_{IH_2O}) was varied. Varene's equations may not apply when inspired air temperatures are outside of this range.

Of particular interest to those in the field of respirator research are the effects of breathing hot dry air, during rest and exercise, on expired air water content and respiratory heat exchange. Robotic metabolic simulators, which are being used to test closed-circuit, self-contained breathing apparatus (SCBA), must be able to reproduce accurately the physiological responses of human airways to hot, dry air inhalation. Because these responses are still being quantified, the purpose of the current study was to measure the mean ERH of subjects breathing hot air during rest and exercise and to apply the results to the equations that are currently used in predicting the physiological responses to various inspired air conditions.

EXPERIMENTAL MATERIALS AND METHODS

The subjects for this study were nine male, nonsmoking volunteers between the ages of 18 and 35 yr. Subjects were professional and volunteer fire fighters, safety personnel, and exercise physiology and occupational safety students.

Prior to inclusion in the study, all subjects signed a consent form, completed a medical history questionnare, and received a resting 12-lead electrocardiograph and spirometry. Each subject also completed a graded exercise test on a treadmill by using a modified Balke protocol.[6] Maximum aerobic capacity was determined by measuring maximum oxygen consumption

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TABLE I. Means and Standard Deviations (SD) for Inspired Air Conditions

Condition	Dry Bulb (°C)	Wet Bulb (°C)	Water Vapor Pressure (mmHg)	Enthalpy (J/g dry air)
Cool dry	25.8	20.1	15.1	59.3
SD	0.6	1.1	1.7	3.3
Cool humid	26.2	25.4	23.9	77.8
SD	0.7	0.7	1.1	3.4
Hot dry	44.7	25.5	15.1	78.2
SD	0.9	0.8	1.9	3.3
Hot humid	45.1	44.2	68.3	131.2
SD	0.8	0.7	2.7	2.7

TABLE II. Minute Ventilation (Mean ± SD)

Condition	Rest	Low-Intensity Exercise	Moderate-Intensity Exercise
$\dot{V}_E$ (L/min)			
Cool dry	10.7 ± 1.3	34.0 ± 4.8	73.6 ± 14.0
Cool humid	10.2 ± 1.2	32.3 ± 2.9	71.4 ± 10.1
Hot dry	10.2 ± 1.0	33.1 ± 3.0	68.6 ± 13.2
Hot humid	10.6 ± 3.3	32.4 ± 3.3	66.6 ± 9.6

($\dot{V}_{O_2}$max) with an MMC Horizon, Advanced Exercise System 5, metabolic cart (SensorMedics, Yorba Linda, Calif.).

Following the graded exercise test, subjects were studied on four different days (at least 48 hr apart) during four 50-min submaximal exercise tests. All exercise was performed on a Lode paramagnetic cycle ergometer, Model RH 400 (Cal Med, Brea, Calif.), which displayed work load in watts and rpm. Each subject's work load was individually determined; absolute work loads that elicited similar minute ventilations for all subjects were chosen. The low-intensity exercise bout was equivalent to approximately 35% $\dot{V}_{O_2}$max and the moderate-intensity was approximately 70% $\dot{V}_{O_2}$max for all subjects. The order of the low- and moderate-intensity bouts was balanced so that in half of the tests, the low-intensity bout was performed first and in the other half, the moderate-intensity bout was first. Subjects were seated on the cycle ergometer for all rest periods.

One of the following inspired air conditions was randomly administered for each of the four 50-min submaximal exercise tests: (1) 26°C dry bulb (T_{db}), 20°C wet bulb (T_{wb}); (2) 26°C T_{db}, 25°C T_{wb}; (3) 45°C T_{db}, 25°C T_{wb}; and (4) 45°C T_{db}, 44°C T_{wb}. The inspired air characteristics are given in Table I. Inspired air conditions were chosen so that the cool dry (CD) condition would simulate an average indoor air temperature and RH. The dry-bulb temperature for the hot air conditions was selected to be in the range of the proposed maximum permissible inspired air temperature for a 1- to 2-hr closed circuit SCBA, as described in 30CFR, Part 11, of the *Code of Federal Regulations.*[7] The CD and hot dry (HD) conditions were then matched for water vapor pressure. The cool humid (CH) and HD conditions had nearly identical enthalpies. The hot humid (HH) condition had the same dry-bulb temperature as the HD condition but was nearly saturated (>95% RH) with water vapor.

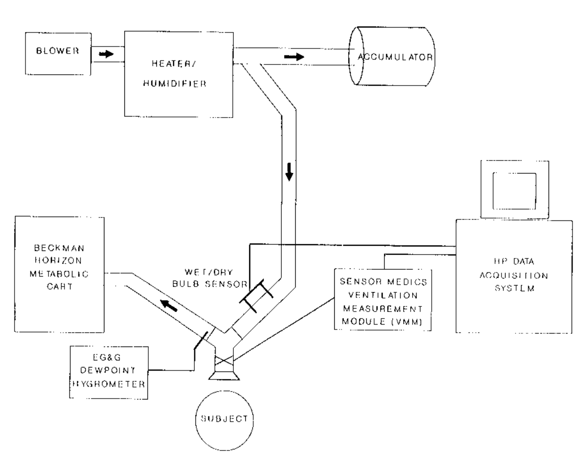

FIGURE 1. Schematic of experimental setup

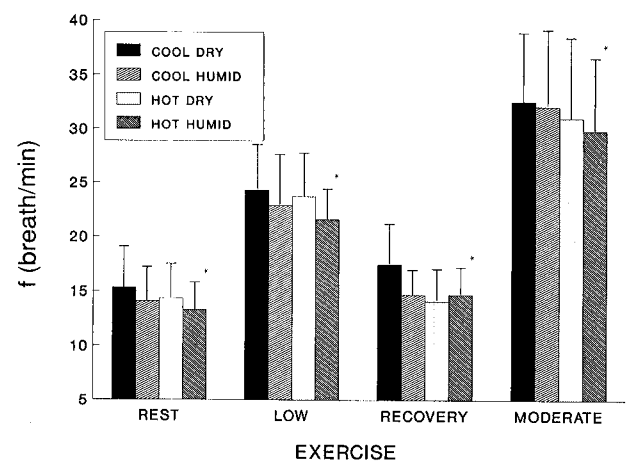

FIGURE 2. Frequency of breathing (f) for the four inspired air conditions (p < 0.05 for HH as compared to CD)

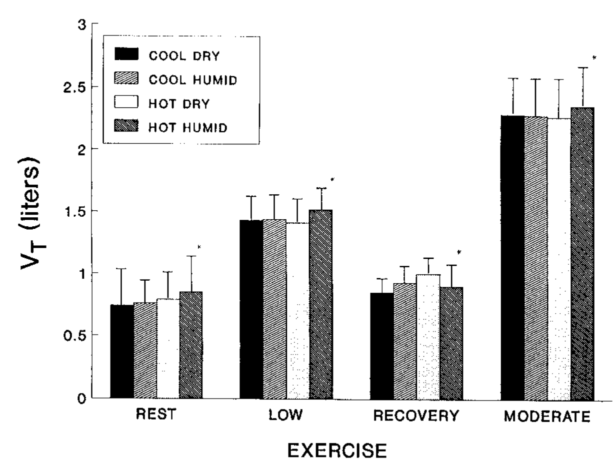

FIGURE 3. Tidal volume (V_T) for the four inspired air conditions (p < 0.05 for HH as compared to CD)

TABLE III. Time of Expiration (t_E) and Inspiration (t_I) (Mean ± SD)

Condition	Rest	Low-Intensity Exercise	Moderate-Intensity Exercise
t_E (sec)			
Cool dry	2.1 ± 0.5	1.3 ± 0.2	0.9 ± 0.2
Cool humid	2.2 ± 0.5	1.3 ± 0.3	1.0 ± 0.2
Hot dry	2.4 ± 0.7	1.3 ± 0.2	1.0 ± 0.3
Hot humid	2.4 ± 0.5^A	1.4 ± 0.2^A	1.1 ± 0.2^A
t_I (sec)			
Cool dry	2.0 ± 0.5	1.3 ± 0.2	0.9 ± 0.2
Cool humid	2.2 ± 0.5	1.3 ± 0.3	0.9 ± 0.2
Hot dry	2.1 ± 0.7	1.3 ± 0.2	1.0 ± 0.2
Hot humid	2.3 ± 0.5^A	1.4 ± 0.2^A	1.0 ± 0.2^A

$^A p < 0.05$ for hot humid as compared to cool dry.

TABLE IV. Temperature (°C) of Expired Air (Mean ± SD)

Condition	Rest	Low-Intensity Exercise	Recovery	Moderate-Intensity Exercise
Cool dry	31.3 ± 1.5	30.6 ± 1.4	31.4 ± 2.1	30.2 ± 1.5
Cool humid	30.9 ± 3.0	30.7 ± 3.0	30.9 ± 3.0	30.8 ± 3.1
Hot dry	36.3 ± 1.3^A	38.3 ± 1.5^A	36.8 ± 1.6^A	39.2 ± 2.2^A
Hot humid	38.6 ± 1.9^A	39.3 ± 1.9^A	37.9 ± 1.7^A	39.8 ± 1.6^A

$^A p < 0.05$ for hot dry and hot humid as compared to cool dry and cool humid.

Inspired air for the CH and HH conditions was supplied by a heater/humidifier capable of saturating air up to a flow rate of 250 L/min (Precision Biomedical Systems, State College, Pa.). Room air was supplied to the heater/humidifier by an Ambi-Air Blower (3M, St. Paul, Minn.) at a flow rate of approximately 200 L/min. The heater/humidifier was bypassed during the two dry air conditions.

Expired and esophageal temperatures were measured by using fast-response Type T copper-constantan thermocouples and were logged by a Hewlett-Packard Series 9000 Model 216 scientific computer connected to a Hewlett-Packard 3497A data acquisition and control unit. Inspired dry- and wet-bulb temperatures were measured and logged by using a Metrosonics (Rochester, N.Y.) heat stress monitor. An MMC Horizon metabolic cart (SensorMedics) was used to measure minute ventilation ($\dot{V}_E$), tidal volume (V_T), breathing frequency (f), oxygen consumption ($\dot{V}_{O_2}$), and carbon dioxide production ($\dot{V}_{CO_2}$). A Vacumed (Ventura, Calif.) No. 1003 mouthpiece was used; subjects wore noseclips to ensure mouth-breathing. Heart rate (HR) was monitored by using a Physio-Control (Redwood, Wash.) Life-Pak 6 cardiac monitor connected to the Beckman metabolic cart.

Mean expired relative humidity (ERH) was measured by using an EG&G (Burlington, Mass.) Model 911 Dew-All chilled-mirror, dew point hygrometer. The heated sample line and temperature sensor for the hygrometer were placed midstream in the expired tubing 20 cm (8 in.) from the mouth (Figure 1). A constant flow rate of 2 L/min was pumped through the dew point sensor cell and then returned to the expired tubing upstream from the metabolic cart.

The 50-min submaximal tests consisted of the following work and rest periods: (1) 15 min of rest, (2) 10 min of exercise, (3) 15 min of recovery, and (4) 10 min of exercise. Metabolic data were collected continuously throughout the test and were analyzed by using the mean of Minutes 5 to 14 for rest, 19 to 24 for the first exercise period, 35 to 38 for recovery, and 44 to 49 for the second exercise period. These sampling periods were chosen so that the means would represent steady-state conditions at each work load.

Inspired wet-bulb and dry-bulb temperatures were checked at a constant flow rate immediately before the test, between Minutes 30 and 35, and immediately following the test.

RESULTS

No significant differences were noted among the four inspired air conditions for $\dot{V}_{O_2}$, $\dot{V}_{CO_2}$, or $\dot{V}_E$. Means and standard deviations for $\dot{V}_E$ are presented in Table II. However, as compared to the CD condition, f was 9.3% lower (Figure 2), and V_T was 9.4% higher (Figure 3) across exercise intensities for the HH condition ($p < 0.05$). Time of expiration (t_E) and inspiration (t_I) were both significantly increased ($p < 0.05$) for the HH condition as compared to CD (Table III).

Mean expired air temperatures (Table IV) were significantly higher for the two hot air conditions as compared to either cool air condition. Expired temperatures (T_E) were an average of 3.6% higher for HH than HD.

Mean expired air relative humidity (ERH) was substantially lower for the HD condition as compared to the other three conditions at each sampling period, including rest (Figure 4). ERH decreased during exercise but returned to resting levels during the recovery period for all four conditions.

In order to compare results from the current study to those obtained in previous studies, the mass of expired water (M_{EH_2O}, in mg/L body temperature pressure saturated [BTPS]) was calculated from ERH, T_E and equations of thermodynamics.[8] The calculated values of M_{EH_2O} for each condition are presented in Table V. Assuming that the effects of each variable are additive,

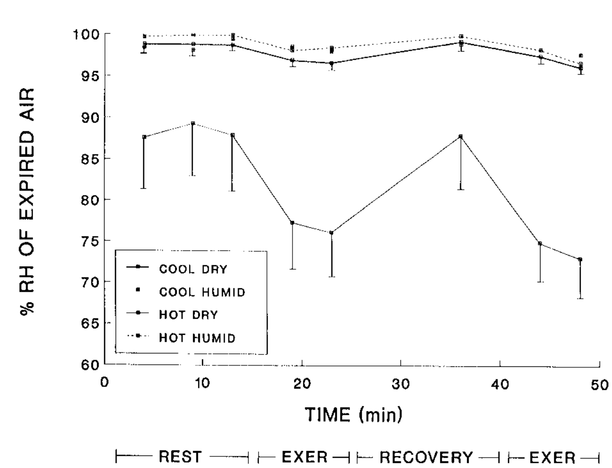

FIGURE 4. Expired relative humidity during rest and exercise for the four inspired air conditions

TABLE V. Mass of Expired Water (M_{EH_2O}, mg/L BTPS) (Mean ± SD)

Condition	Rest	Low-Intensity Exercise	Moderate-Intensity Exercise
Cool dry	36.4 ± 2.2	34.7 ± 1.9	33.9 ± 2.1
Cool humid	36.6 ± 5.6	36.1 ± 5.8	36.3 ± 6.0
Hot dry	41.0 ± 3.1[A]	39.6 ± 2.8[A]	40.3 ± 3.7[A]
Hot humid	55.3 ± 4.9[B]	56.4 ± 4.1[B]	56.4 ± 4.9[B]

[A] $p < 0.05$ for hot dry as compared to cool dry.

[B] $p < 0.05$ for hot humid as compared to cool dry and cool humid.

TABLE VI. Regression Coefficients (Mean ± SE) for the Relationship between M_{EH_2O} and ERH and the Variables T_I, P_{IH_2O} and $\dot{V}_E$

Variable	Est. of Regression Coefficient ± SE	Statistical Significance (t-test)
M_{EH_2O} ($R^2 = 0.85$)		
Intercept (mg/L)	19.59 ± 1.84	$p < 0.0001$
T_I (°C)	0.40 ± 0.05	$p < 0.0001$
P_{IH_2O} (mmHg)	0.28 ± 0.02	$p < 0.0001$
$\dot{V}_E$ (L/min)	–0.02 ± 0.01	$p > 0.2219$
ERH ($R^2 = 0.84$)		
Intercept (mg/L)	121.44 ± 2.20	$p < 0.0001$
T_I (°C)	–1.01 ± 0.06	$p < 0.0001$
P_{IH_2O} (mmHg)	0.36 ± 0.02	$p < 0.0001$
$\dot{V}_E$ (L/min)	–0.08 ± 0.02	$p < 0.0001$

multiple linear regression relationships were computed for M_{EH_2O} and ERH with the variables T_I, P_{IH_2O}, enthalpy, and $\dot{V}_E$. The resulting regression coefficients are given in Table VI. Enthalpy was not a statistically significant factor for either M_{EH_2O} or ERH. The results of the regression analysis support the previously observed independence of M_{EH_2O} with respect to $\dot{V}_E$.[5] However, a small but significant dependence on $\dot{V}_E$ was found for mean ERH. This dependence appears to become more important during inhalation of hot, relatively dry air (Figure 4).

DISCUSSION

The effects of hot, humid air inhalation on V_T, f, and $\dot{V}_E$ have been previously reported by Babb et al.[9] When human subjects breathed 45°C saturated air while running on a treadmill, V_T was slightly increased, f was significantly decreased (10.5%) and $\dot{V}_E$ was significantly decreased (10%) as compared to a room air control condition. The same trends were seen for both hot air conditions in the present study. The mechanism for these temperature effects on ventilation is still unknown; the effects may be exerted by temperature-sensitive vagal receptors that have been demonstrated in the larynx[10] and have been hypothesized to exist in the lungs.[11]

The decrease in mean ERH seen during the HD condition can probably be attributed to alterations in the secretion of water by the mouth, pharynx, and upper airway epithelium. When breathing hot or frigid dry air, dehydration and a concomitant increase in osmolarity are likely.[3,12] However, the exact mechanisms underlying the changes in respiratory water loss during hot, dry air inhalation are still unclear.

Respiratory heat exchange consists of both convective ($\dot{W}_{CV}$) and evaporative ($\dot{W}_{EV}$) heat exchanges. In 1986, Varene[5] published the following equations, in which T_I and P_{IH_2O} are taken into account for both $\dot{W}_{CV}$ and $\dot{W}_{EV}$.

$$\dot{W}_{CV}/\dot{V}_E \text{ (J/L)} = \rho c_p[a + T_I(b - 1)] \quad (1)$$

$$\dot{W}_{EV}/\dot{V}_E \text{ (J/L)} = 59.34 + 0.53T_I - 1.55P_{IH_2O} \quad (2)$$

In these equations, ρ and c_p represent the volumetric mass and specific heat of the inspired gas, respectively. The values of a and b are functions of the relative humidity of the inspired gas. The equation for $\dot{W}_{EV}/\dot{V}_E$ was derived from a series of experiments in which $10°C \le T_I \le 40°C$ and $5 \text{ L/min} \le \dot{V}_E \le 43 \text{ L/min}$. By using Varene's equation, the calculated values of $\dot{W}_{EV}$ do not reflect the differences in ERH observed between the CD and HD conditions in the present study (Table VII). On the basis of the regression coefficients for M_{EH_2O} obtained in the present study, $\dot{W}_{EV}/\dot{V}_E$ can be calculated according to the following equation.

$$\dot{W}_{EV}/\dot{V}_E \text{ (J/L)} = 47.5 + 0.97T_I - 1.53P_{IH_2O} \quad (3)$$

A comparison of evaporative heat exchange calculations based on the equation of Varene[5] and on the above equation is shown in Table VII. The differences in $\dot{W}_{EV}$ between CD and HD are greater when using Equation 3 and are influenced more by T_I than those based on Varene's equation.

The differences in mean expired air relative humidity observed during the HD condition have practical implications for the design of metabolic simulators. On the basis of the assumption that expired gas is always fully saturated, most current simulators deliver a constant ERH, regardless of inspired air conditions and minute ventilation. However, if human airways do not always fully saturate expired gas, respirator performance during human testing may differ greatly from performance during simulator testing. The results of this study indicate that inspired air wet- and dry-bulb temperatures, as well as minute

TABLE VII. Evaporative Respiratory Heat Exchange ($\dot{W}_{EV}$) Calculations Based on the Equations of Varene[4] and the Present Study

	Evaporative Respiratory Heat Exchange (kcal/hr)					
	Rest		Low-Intensity Exercise		Moderate-Intensity Exercise	
Condition	Varene	Present Study	Varene	Present Study	Varene	Present Study
Cool dry	7.5	7.4	23.6	23.5	51.2	50.8
Cool humid	5.2	5.1	16.3	16.3	35.9	35.9
Hot dry	8.5	9.6	27.6	31.4	57.2	65.0
Hot humid	–2.5	–1.9	–7.6	–5.8	–15.7	–11.9

ventilation, should be considered in the calculation of the approximate ERH to be delivered by these simulators.

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Frank Griffith Memorial Scholarship Fund Established

A scholarship fund has been established as a memorial to Frank Griffith at his alma mater, Scott High School, in Madison, West Virginia. The scholarship is considered a very fitting memorial to Frank.

One of Frank's high school teachers, on hearing of his death, called the family and shared with them the following story. Frank was awarded a college scholarship for being one of the top students in his class. A handicapped woman was next in line for the scholarship. When Frank learned of this, he asked that the scholarship be given to her—because he was able to work for his education and she was not.

The scholarship fund will be administered by the Madison Rotary Club of Madison, West Virginia. The criteria for eligibility will be based on the following.

1. Need
2. Graduation from Scott High School
3. Attendance at the University of West Virginia

The scholarship amount (to be awarded yearly) will come from the interest earned from the fund. It is hoped that this scholarship will continue for many years.

Checks should be made payable to the Frank Griffith Memorial Scholarship Fund. Please mail your contribution to the following address.

Frank Griffith Memorial Scholarship Fund
c/o Dr. Ron Stollings/Madison Rotary Club
P.O. Box 365
Madison, West Virginia 25130

This is a tax-deductible contribution. If you would like a receipt, please make a notation when sending your contribution and remember to include your address.