# Physiological Responses to the Wearing of Protective Equipment and Respirators: Effects of Hot, Humid Inspired Air on Work of Breathing

Final Report

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**16. Abstract (Limit: 200 words)** The physiological effects of breathing cool/dry, cool/humid, hot/dry, and hot/humid air were observed during rest, and during light and moderate intensity exercise on a cycle ergometer. Nine male volunteers, 18 to 35 years old, took part in four 50 minute submaximal exercise tests under the four different inspired air conditions. The results demonstrated several positive effects of hot air breathing on lung mechanics. Dynamic lung compliance was increased with both hot/dry and hot/humid air breathing during rest and exercise. These increases in compliance implied a decrease in the inspiratory work of breathing, although no statistically significant decreases were demonstrated. Frequency of breathing was decreased and tidal volume increased with hot air, allowing a more efficient breathing pattern. These results lent support to the current inspired air temperature criteria for SCBA certification, as set forth in 30 CFR, Part 11 and proposed 42 CFR, Part 84. The authors suggest that future research in this area include a study in which both inspired air and ambient air temperatures are varied. The possibility of interactions between hot inspired air and hot ambient air should be explored as closed circuit respirators used in both fire fighting and hazardous waste operations may be used under hot ambient conditions.

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ABSTRACT

The physiological effects of breathing cool/dry, cool/humid, hot/dry and hot/humid air were observed during rest, light and moderate intensity exercise on a cycle ergometer. Inspired air dry and wet bulb temperatures were 26/20°C, 26/25°C, 45/25°C and 45/44°C, respectively. Physiological variables measured include dynamic lung compliance, respiratory frequency and esophageal and rectal temperatures. No significant differences were observed among the four inspired air conditions for $O_2$ consumption, $CO_2$ production or minute ventilation. As compared to the cool/dry condition, frequency of breathing was 9.3% lower and tidal volume was 9.4% higher across exercise intensities for the hot/humid condition. Time of expiration and inspiration were 11% higher for hot/humid as compared to cool/dry. No significant differences were observed for either end-expiratory or end-inspiratory pressure. Both rectal and esophageal temperatures were significantly increased (0.21 and 0.25°C, respectively) for hot/humid as compared to cool/humid. Mean expired air relative humidity was significantly lower (10% during rest and 20% during exercise) for the hot/dry condition as compared to the other conditions. This decrease in expired relative humidity is due to the high level of evaporative respiratory heat exchange associated with the hot/dry condition. Dynamic lung compliance (Cdyn) was significantly increased for both hot/dry (16.8%) and hot/humid (19.9%) as compared to cool/dry. These observed increases in compliance are not completely consistent with the results of previous <u>in vitro</u> studies. The apparent discrepancy may be due to differences between excised and intact lung studies; the decrease in compliance seen in excised lung studies at 42 to 45°C may start to occur at a higher inspired air temperature in intact lungs. Possible mechanisms for the temperature dependence of dynamic compliance which are supported by these results include: 1) a decrease in surface tension as temperature increases and 2) a slight increase in tidal volume leading to a secondary increase in compliance.

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INTRODUCTION

The various respiratory stresses encountered during the use of closed-circuit, self-contained breathing apparatus (SCBA) include elevated inspired air temperature, humidity, $CO_2$ concentration and breathing resistance. Previous and currently proposed respirator certification regulations (30 CFR, Part 11 and 42 CFR, Part 84) permit an inspired air temperature of 46°C with 0-100% Relative Humidity (RH) for a one to two hour closed-circuit, self-contained, escape only device. Several recent studies in which human subjects breathed 33 and 36°C humid air within a facepiece at rest and during exercise reported increased sensations of difficulty breathing (1,2). In addition, several _in vitro_ animal studies have demonstrated a decrease in lung compliance when inspired air temperatures exceeded 42°C (3,4). These results have led to concern among the respirator research community that elevated inspired air temperature and humidity may cause significant increases in work of breathing. This increase in work of breathing could in turn contribute to a decrease in work tolerance or escape performance experienced by wearers of closed-circuit SCBA.

The purpose of this NIOSH study was to compare the effects of cool/dry, cool/humid, hot/dry and hot/humid inspired air on human lung mechanics, including dynamic compliance, during rest, low, and moderate intensity exercise.

## SUMMARY OF LITERATURE

### Subjective Responses

It has long been recognized that elevated dry and wet bulb temperatures of inspired air may be limiting factors for work performance. Subjective responses to breathing air at these high temperatures were recorded as early as 1915 by Haldane (5). He found that when men were exposed to hot environments at a wet bulb temperature of 45°C, they were able to breathe "pretty freely" during hard work; however, at 49.5 to 51.5°C wet bulb, ordinary quiet breathing was more or less painful. Haldane also noted that air that was even hotter, but dry, could be breathed without great discomfort.

In 1932, Killick (6) observed that when subjects at rest in a cool environment breathed hot, humid air, they did not experience discomfort until the wet bulb temperature of the inspired air reached 54.5 to 63°C. Breathing was described as "tolerable" until the wet bulb temperature of the inspired air reached 59 to 65°C. When her subjects worked on an ergometer at a rate equivalent to approximately 4 to 4.5 mph, these limits dropped to 51.1 to 54.5°C and 54.5 to 60°C wet bulb temperatures for discomfort and "tolerable" limits, respectively. Killick also confirmed Haldane's findings for hot, dry air by observing that 186°C and 104.5°C dry air could be breathed comfortably at rest and during ergometry work, respectively.

In 1951, McCutchan and Taylor (7) observed that, in resting subjects in a comfortable environment, 49°C was not sensed as being different from room air, and 71°C was sensed as being "warm" or "dry." At 93°C and the highest water vapor pressure tested (30 mmHg), three of their five subjects felt that the hot, humid air "set their teeth on edge."

In 1955, Lind (8) examined inspired air temperatures in men working hard in a hot (35°C), saturated environment while wearing closed-circuit SCBA. He observed that these subjects first reported respiratory discomfort at 39°C (range = 39 to 43°C), 6°C lower than the temperature reported by Haldane as acceptable. Lind provided three possible explanations for this observation: 1) the absolute workload in his experiment was heavier than that performed by Haldane's subjects, 2) the subjects were wearing actual SCBA's in his study, and some of the discomfort may have been due to soda-lime dust reaching their throats, and 3) the individual variation in Lind's subjects was greater than that of Haldane's subjects.

Several recent studies have examined "ratings of acceptability" by subjects who breathed 22 to 36°C dry and humid air from a respirator facepiece. During rest (2) and light exercise (1) in various ambient environments, subjects rated respirator air temperatures above 33°C as less than 100% acceptable. Several subjects in each study reported that warm, humid respirator air made their breathing seem "slightly hard" (a 3 on a scale of 1 to 5). However, the investigators concluded that respirator acceptability, thermal sensation and discomfort were highly correlated with lip skin temperature and mask dew point temperature, functions of the mask microclimate which may have little relation to sensations of breathing effort.

In summary, the threshold for negative subjective responses to breathing hot/dry or hot/humid air seems to range from 33 to 54.5°C for both rest and exercise. Possible mechanisms for these negative responses, such as increased work of breathing, have been suggested but have not been systematically explored.

Lung Mechanics

The effects of hot/dry and hot/humid inspired air on lung mechanics are still being quantified. In the range of 32°C to 42°C, the effects on pressure-volume curves appear to be minimal; however, several of those studies performed on air-filled animal lungs have produced discrepant findings (9-13). This lack of agreement may have been caused by several methodological differences among the studies: temperature ranges were not always the same, different animal species were used and different techniques for comparing volumes and pressures were applied.

Inoue et al. (3) attempted to resolve some of the above discrepancies by comparing pressure-volume curves of excised rabbit lungs at the same absolute lung volumes over a wide temperature range (from 4°C to 52°C). They observed progressive increases in static compliance at moderate lung volumes as temperature was increased from 4 to 35°C but began to see decreases at temperatures above 42°C. These decreases occurred at middle to low lung volumes and may reflect a transition zone where pure dipalmitoyl phosphatidylcholine (DPPC) begins to melt and can no longer sustain near-zero surface tension (3,4).

Results similar to those above were obtained in a study performed on autopsied human lungs (14). Dynamic compliance increased 23% between 5 and 35°C, while total pulmonary resistance and airway resistance decreased 34% and 29%, respectively. Only one lung withstood further testing at 40 and 50°C, and dynamic compliance at these temperatures was no different than that at 35°C. The increases in compliance were attributed to alterations in both tissue elasticity (including surface tension) and tissue viscosity.

These limited observations, although inconsistent, are often accepted as conclusive evidence that work of breathing is increased with hot/dry or hot/humid inspired air, although there have been no systematic human studies which support this conclusion. The current study was conducted to gain a further understanding of the effects of hot, humid or dry, inspired air on human lung mechanics.

## Expired Air Relative Humidity

Since the pioneer study of McCutchan and Taylor (7) 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 several authors (15-19). Tabka et al. (18) recently observed a progressive fall in mean expired relative humidity (ERH) to approximately 78% RH during 15 to 20 minutes of cycle ergometry when subjects breathed 28 to 30°C dry air. They observed no decrease in ERH when the same subjects breathed 28°C, slightly humid air. These investigators concluded that since the upper airway mucosa was unable to saturate expired gas, the mucosa must have become dehydrated and probably hyperosmotic.

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. The recent studies cited above have provided some additional insight into the relationship between expired air water content and inspired air temperature, water content and minute ventilation. However, since these effects are still being quantified, one of the purposes of the current study was to measure the mean ERH of subjects breathing hot, relatively dry air during rest, light and moderate intensity cycle ergometry.

## METHODS

The subjects for this study were nine male, nonsmoking volunteers between the ages of 18 and 35 years from the Morgantown, West Virginia, area. Subjects were professional and volunteer fire fighters, safety personnel, and exercise physiology and occupational safety students. All subjects were remunerated for their participation. The physical characteristics of the subjects are shown in Table 1.

Prior to inclusion in the study, all subjects underwent a physical examination by a NIOSH physician which included a resting twelve-lead electrocardiograph (ECG) and a pulmonary function evaluation, signed the informed consent form, and completed a medical history questionnaire. Each subject also completed a graded exercise test on a treadmill using a modified Balke protocol (20). The test consisted of a five-minute warmup period at a workload of 3.5 mph and 5% grade, followed by two-minute stages where the grade was incremented 2.5% until the test was terminated due to attainment of maximum exertion levels. If the subject reached 20% grade, the workload was progressively incremented by increasing only the speed of the treadmill.

Table 1. Mean and S.D. of Subject Characteristics

| | Age (yrs) | Ht (cm) | Wt (kg) | $\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$) | FVC (l) | FEV1 (l) |
|---|---|---|---|---|---|---|
| Mean | 25.0 | 182.6 | 85.2 | 43.5 | 5.8 | 4.4 |
| S.D. | 4.8 | 5.8 | 18.7 | 6.6 | 0.6 | 0.6 |

Maximum aerobic capacity was determined by measuring maximum oxygen consumption ($\dot{V}O_2max$) using a Beckman Horizon Metabolic cart.

Following the graded exercise test, subjects came to the lab on 4 different days (at least 48 hours apart) to complete a series of four 50-minute submaximal exercise tests. All exercise was performed on a Lode paramagnetic cycle ergometer which displayed workload in watts and rpm. Each subject's workload was individually determined; absolute workloads which elicited similar minute ventilations for all subjects were chosen. The low-intensity workload was equivalent to approximately 35% $\dot{V}O_{2max}$ and the moderate-intensity was approximately 70% $\dot{V}O_{2max}$ for all subjects. The order of the low- and moderate-intensity workloads was balanced so that in half of the tests, the low workload was performed first and in the other half, the moderate workload was first. Subjects were seated on the cycle ergometer for all rest periods.

For each of the four 50-minute submaximal exercise tests, one of the following inspired air conditions was randomly administered: (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 2. 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 one- to two-hour closed circuit SCBA, as described in proposed 42CFR, Part 84, of the Federal Register. The CD and Hot/Dry (HD) conditions were then matched for water vapor pressure. The Cool/Humid (CH) and HD conditions had 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.

Table 2. Mean Inspired Air Conditions

| | Dry Bulb (°C) | Wet Bulb (°C) | Vapor Pressure (mmHg) | Enthalpy ($j \cdot g^{-1}$) |
|---|---|---|---|---|
| Cool Dry (CD) | 26.3 | 20.4 | 15.2 | 77.8 |
| Cool Humid (CH) | 26.6 | 25.7 | 24.1 | 96.4 |
| Hot Dry (HD) | 44.3 | 25.5 | 15.0 | 96.4 |
| Hot Humid (HH) | 44.8 | 43.6 | 64.5 | 210.3 |

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 $l \cdot min^{-1}$ (Precision Biomedical Systems, Inc.). Room air was supplied to the heater/humidifier by an Ambi-Air Blower (3M) at a flow rate of approximately 200 $l \cdot min^{-1}$. The heater/humidifier was bypassed during the two dry air conditions. Inspired air was then directed toward the subject as shown in Figure 1. Heat tape was applied to the inspired tubing for the two hot air conditions.

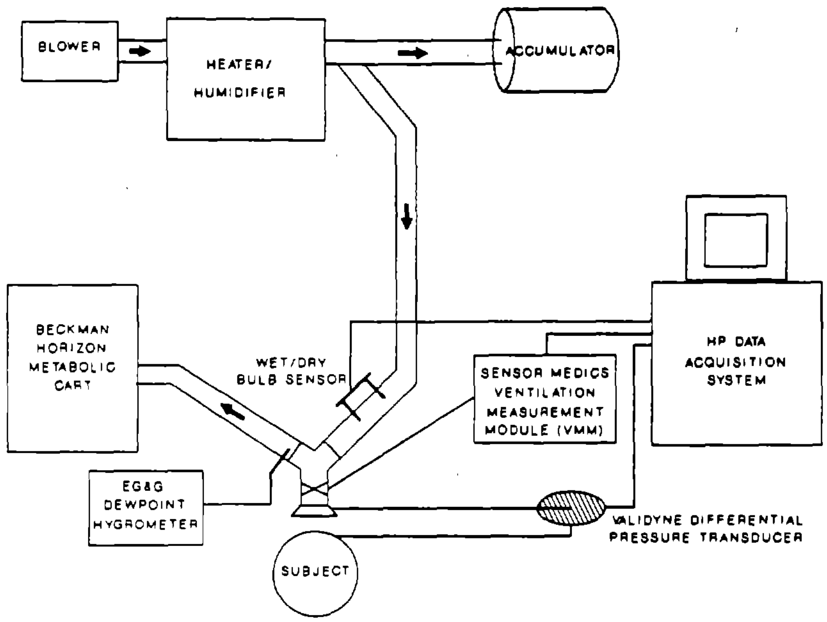


Figure 1. Experimental setup.

Dynamic lung compliance was measured according to the technique described by Milic-Emili et al. (21). Tidal volumes (VT) were measured using a SensorMedics Ventilation Measurement Module. Esophageal catheters were constructed by attaching a small latex esophageal balloon to an adult naso-gastric feeding tube with surgical silk. The difference between mouth and esophageal pressures was measured with a Validyne differential pressure transducer and carrier-demodulator. Rectal temperature ($T_{re}$) was measured using a flexible thermistor probe (Yellow Springs Instruments, Type 401) inserted 10 cm into the rectum. Esophageal ($T_{es}$) and expired temperatures ($T_{exp}$) were measured using fast-response Type T thermocouples. The above data were logged by a Hewlett-Packard Series 9000 Model 216 scientific computer interfaced to a Hewlett-Packard 3497A data acquisition and control unit.

Inspired dry and wet bulb temperatures were measured and logged using a Metrosonics Heat Stress Monitor. A Beckman Horizon Metabolic Measurement System was used to measure minute ventilation ($\dot{V}E$), breathing frequency (f), oxygen consumption ($\dot{V}O_2$), and carbon dioxide production ($\dot{V}CO_2$). Heart rate (HR) was monitored using a Physio-Control Life-Pak 6 interfaced to the Beckman metabolic cart.

Mean expired relative humidity (ERH) was measured using an EG&G 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 8 inches from the mouth. A constant flow rate of 2 $l \cdot min^{-1}$ was pumped through the dew point sensor and then returned to the expired tubing upstream from the metabolic cart.

## EXPERIMENTAL PROTOCOL

Preparation for each experimental test consisted of having the subject insert the rectal thermistor, placing ECG electrodes on the subject's chest, and inserting the esophageal catheter. Subjects were then apprised of the order of their low- and moderate-intensity exercise bouts. Subjects were not informed of the inspired air condition they were to receive.

The 50-minute submaximal tests consisted of the following work and rest periods: (1) 15 minutes of rest, (2) 10 minutes of exercise, (3) 15 minutes of recovery and (4) 10 minutes of exercise. Metabolic data were collected continuously throughout the test and were analyzed 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 workload. Dynamic lung compliance was calculated as a mean of five or six breaths which were sampled at minutes 4, 9 and 13 for rest, 19 and 23 for the first exercise period and 44 and 48 for the second exercise period. At minute 36, 11 minutes into the recovery period between the exercise bouts, subjects were asked to perform a slow maximal inspiration, followed by a slow maximal expiration. This maneuver was used to approximate a static pressure-volume loop from which static compliance was calculated. Data from this quasi-static pressure-volume loop were analyzed separately. No measurements of dynamic lung compliance were made during the recovery period.

Following the 50-minute test, subjects were allowed to rest while one additional minute of metabolic data was collected. 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.

Data Analysis

Raw data were stored in Hewlett Packard format and later converted to IBM format for export into a spreadsheet package. Pressure and volume data were separated into individual breaths, dynamic compliances were calculated and pressure-volume loops were plotted by macros created within the spreadsheet.

All data were analyzed using a 2-way repeated measures analysis of variance in SAS. The two factors in the analysis were:

| | |
|---|---|
| Factor 1 (4 levels): | Inspired Air Temperature and Relative Humidity: Cool/Dry, Cool/Humid, Hot/Dry, Hot/Humid |
| Factor 2 (4 levels): | Workload: Rest, Light Exercise, Recovery, Moderate Exercise |

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 3. However, as compared to the CD condition, f was 9.3% lower (Figure 2), and VT was 9.4% higher (Figure 3) across exercise intensities for the HH condition ($p < .05$). Time of expiration (TE) and inspiration (TI) were both significantly increased ($p<.05$) for the HH condition as compared to CD (Table 4).

Dynamic lung compliance (Cdyn) was significantly increased in both the HD and HH conditions ($p<.05$) as compared to the CD condition (Figure 4). The magnitudes of the

Table 3. Minute Ventilation (Mean ± S.D.)

| | Rest | Low Intensity Exercise | Moderate Intensity Exercise |
|---|---|---|---|
| $\dot{V}E$ ($l \cdot min^{-1}$) | | | |
| CD | 10.7 ± 1.3 | 34.0 ± 4.8 | 73.6 ± 14.0 |
| CH | 10.2 ± 1.2 | 32.3 ± 2.9 | 71.4 ± 10.1 |
| HD | 10.2 ± 1.0 | 33.1 ± 3.0 | 68.6 ± 13.2 |
| HH | 10.6 ± 3.3 | 32.4 ± 3.3 | 66.6 ± 9.6 |

Table 4. Time of Expiration and Inspiration (Mean ± S.D.)

| | Rest | Low Intensity Exercise | Moderate Intensity Exercise |
|---|---|---|---|
| TE (sec) | | | |
| CD | 4.2 ± 1.0 | 2.6 ± 0.5 | 1.9 ± 0.4 |
| CH | 4.5 ± 1.1 | 2.7 ± 0.5 | 2.0 ± 0.4 |
| HD | 4.7 ± 1.5 | 2.6 ± 0.4 | 2.0 ± 0.5 |
| HH | 4.8 ± 1.0* | 2.8 ± 0.5* | 2.2 ± 0.5* |
| TI (sec) | | | |
| CD | 4.1 ± 0.9 | 2.5 ± 0.5 | 1.9 ± 0.4 |
| CH | 4.4 ± 1.1 | 2.6 ± 0.5 | 1.9 ± 0.4 |
| HD | 4.2 ± 1.4 | 2.6 ± 0.4 | 2.0 ± 0.5 |
| HH | 4.6 ± 1.0* | 2.8 ± 0.4* | 2.1 ± 0.5* |

* $p < .05$ for HH as compared to CD.

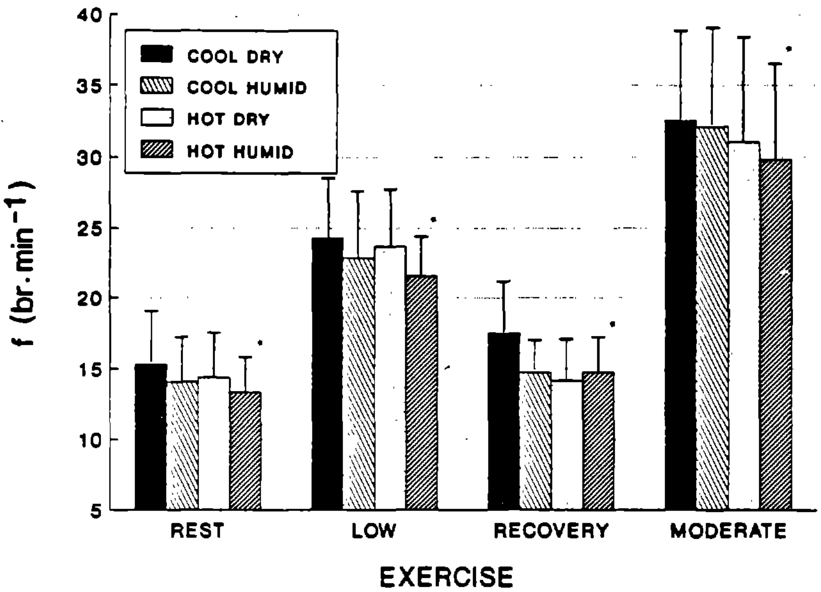


Figure 2. Frequency of breathing (f) for the four inspired air conditions (mean ± S.D., * p<.05).

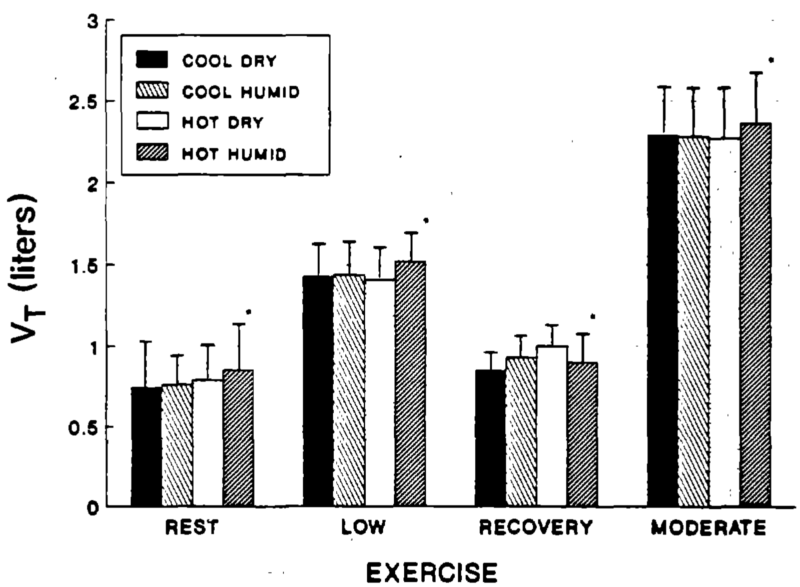


Figure 3. Tidal volume (VT) for the four inspired air conditions (mean ± S.D., * p<.05).

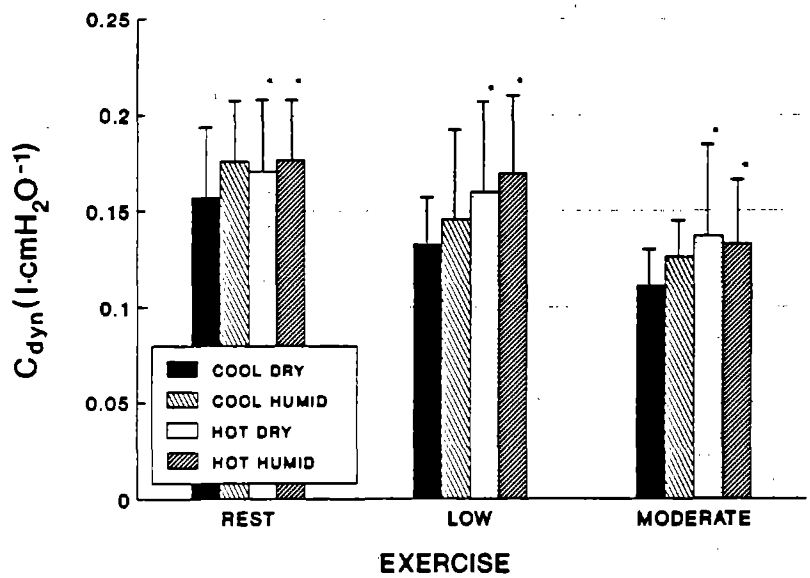


Figure 4. Dynamic lung compliance (Cdyn) for the four inspired air conditions (mean ± S.D., * $p<.05$).

increases were 16.8% and 19.9% for HD and HH, respectively. No significant differences were observed in either end-expiratory pressure (EEP) or end-inspiratory pressure (EIP) (Table 5). However, the increase in compliance seen during the HD condition was the result of a slight increase in tidal volume accompanied by a slight decrease in inspiratory-expiratory pressure change ($\Delta p$). The increase in compliance seen during HH was the result of a significant increase in tidal volume with no accompanying change in $\Delta p$. Figure 5. shows sample pressure-volume loops from one

Table 5. End Expiratory (EEP) and End Inspiratory (EIP) Pressures (Mean ± S.D.)

| | Rest | Low Intensity Exercise | Moderate Intensity Exercise |
|---|---|---|---|
| EEP ($cmH_2O$) | | | |
| CD | -7.0 ± 2.8 | -3.0 ± 3.0 | 0.9 ± 2.5 |
| CH | -6.5 ± 2.2 | -3.2 ± 2.0 | 0.6 ± 3.0 |
| HD | -6.7 ± 2.7 | -4.2 ± 2.4 | 0.3 ± 2.6 |
| HH | -6.0 ± 2.7 | -4.0 ± 2.3 | -0.4 ± 2.8 |
| EIP ($cmH_2O$) | | | |
| CD | -12.9 ± 3.2 | -14.1 ± 2.7 | -20.5 ± 2.3 |
| CH | -11.6 ± 3.2 | -14.2 ± 3.3 | -19.6 ± 4.3 |
| HD | -11.8 ± 2.9 | -13.8 ± 3.7 | -18.8 ± 4.2 |
| HH | -11.6 ± 3.4 | -14.7 ± 2.5 | -19.7 ± 3.6 |

subject during the moderate exercise period. These loops demonstrate the observed increases in tidal volume for similar pressure changes during HD and HH. No significant differences in compliance, $\Delta p$ or percent vital capacity attained were noted for the quasi-static pressure-volume loop obtained during the recovery period. In addition, no significant differences in compliance work done on the lung

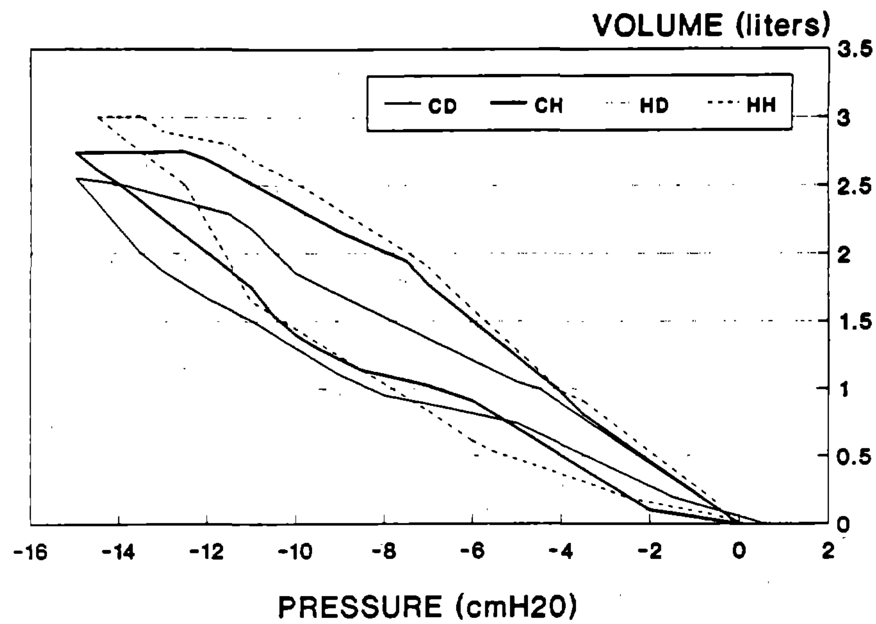


Figure 5. Representative pressure-volume loops from one subject during moderate intensity exercise.

during inspiration, expressed as either Joules per minute or Joules per liter were observed.

Significant differences in rectal and esophageal temperatures among the inspired air conditions were observed (Figures 6 and 7). Both rectal and esophageal temperatures were increased (0.21°C and 0.25°C, respectively) for HH as compared to CH ($p<.05$). However, there were no significant differences between either hot air condition and CD.

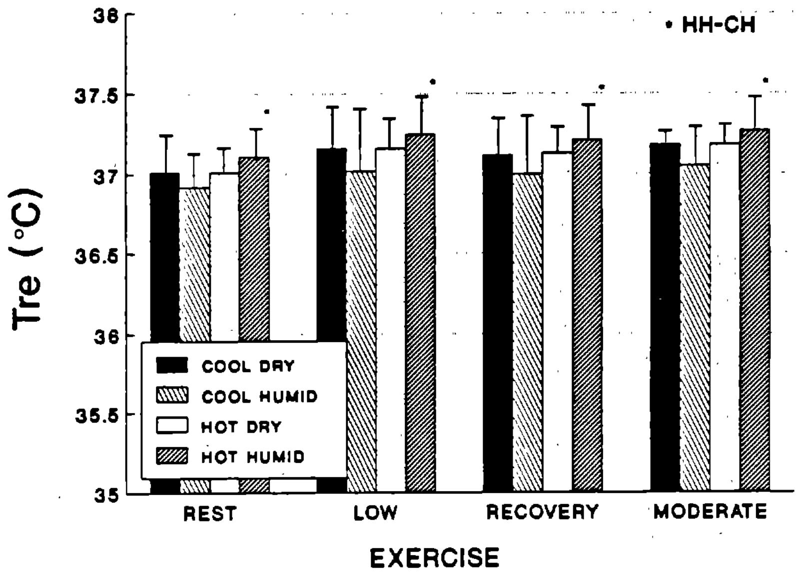


Figure 6. Rectal temperatures for the four inspired air conditions (mean ± S.D., * p<.05).

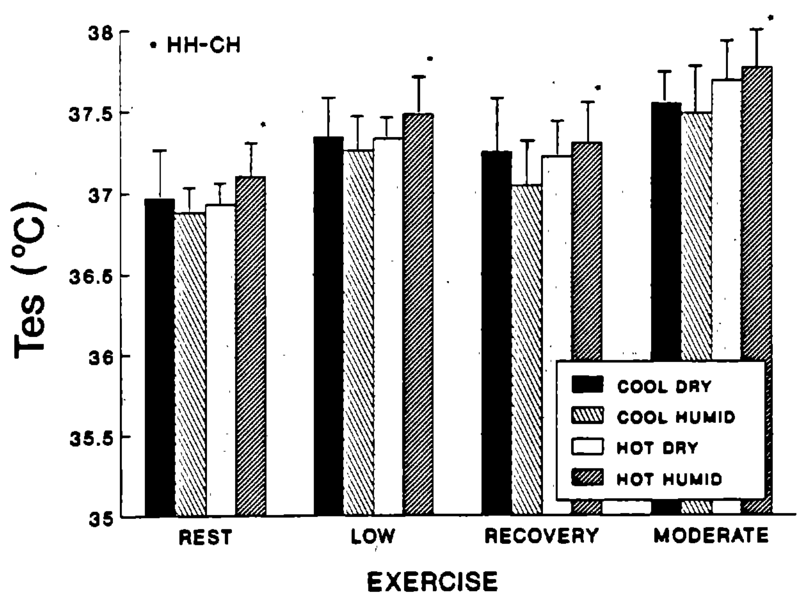


Figure 7. Esophageal temperatures for the four inspired air conditions (mean ± S.D., * p<.05).

Expired air temperatures (Table 6) were significantly higher for the two hot air conditions as compared to either cool air condition. Expired air relative humidity (ERH) was significantly lower for the HD condition as compared to the other three conditions at each sampling period (Table 7, Figure 8). ERH decreased during exercise but returned to resting levels during the recovery period for all four conditions.

Table 6. Temperature (°C) of Expired Air (Mean ± S.D.)

| | Rest | Low Intensity Exercise | Recovery | Moderate Intensity Exercise |
|---|---|---|---|---|
| CD | 31.3 ± 1.5 | 30.6 ± 1.4 | 31.4 ± 2.1 | 30.2 ± 1.5 |
| CH | 30.9 ± 3.0 | 30.7 ± 3.0 | 30.9 ± 3.0 | 30.8 ± 3.1 |
| HD | 36.3 ± 1.3 | 38.3 ± 1.5 | 36.8 ± 1.6 | 39.2 ± 2.2 |
| HH | 38.6 ± 1.9 | 39.3 ± 1.9 | 37.9 ± 1.7 | 39.8 ± 1.6 |

Table 7. % Relative Humidity of Expired Air (Mean ± S.D.)

| | Rest | Low Intensity Exercise | Recovery | Moderate Intensity Exercise |
|---|---|---|---|---|
| CD | 98.7 ± 1.0 | 96.7 ± 2.4 | 99.9 ± 1.5 | 96.9 ± 1.5 |
| CH | 98.8 ± 1.1 | 98.3 ± 0.9 | 98.9 ± 1.4 | 97.6 ± 0.6 |
| HD | 88.2 ± 7.3* | 76.7 ± 5.9* | 87.9 ± 8.6* | 73.9 ± 4.4* |
| HH | 99.9 ± 0.1 | 98.2 ± 1.6 | 99.9 ± 0.0 | 97.8 ± 2.3 |

* $p < .05$

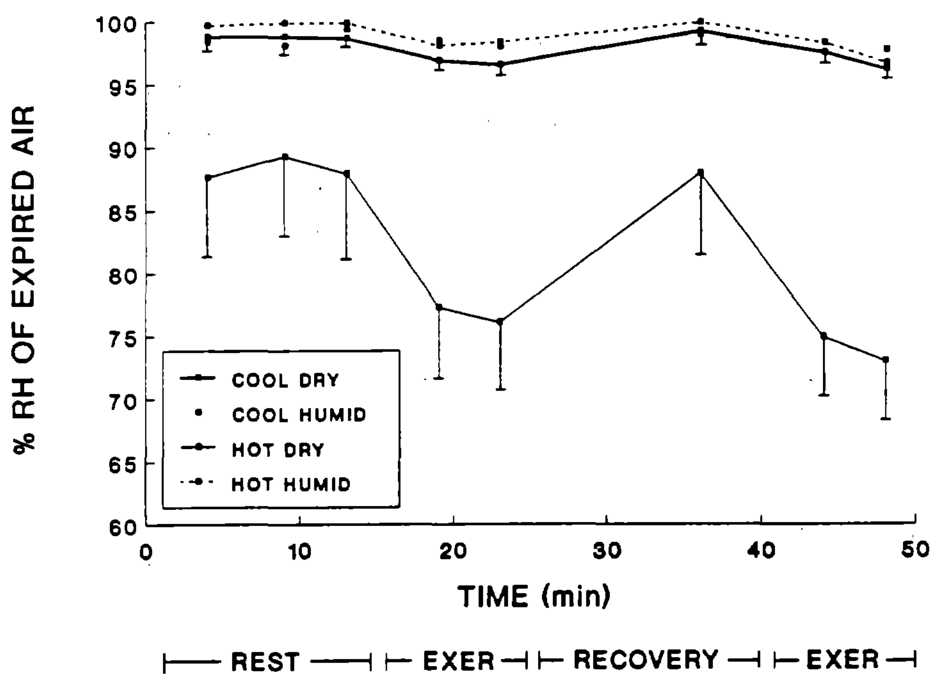


Figure 8. Expired relative humidity during rest and exercise for the four inspired air conditions.

## DISCUSSION

The purpose of this study was to quantify the effects of 44 to 45°C dry and humid inspired air on human lung mechanics during rest, low and moderate intensity exercise. This dry bulb temperature approximates the maximum allowable inspired air temperature for a one to two hour closed-circuit SCBA (46°C with 0 to 50% RH, with 50 to 100% RH for escape-only devices; 30 CFR, Part 11 and proposed 42 CFR, Part 84). There has been some concern among the respirator research community that this temperature limit should be lowered. This concern stems partly from reports of adverse subjective responses from subjects breathing hot, humid air. Although subjective responses were not systematically measured in the current study, subjects who gave anecdotal reports did not prefer any one condition over the others. Each subject completed all four tests, regardless of inspired air condition. This lack of a negative effect on performance from breathing hot air agrees with the results of a study by Babb et al. (22). Breathing 45°C saturated air did not increase the time it took for subjects to run two miles on a treadmill. However, breathing hot air in combination with 10 $cmH_2O$ external breathing resistance and/or 3% inspired $CO_2$ led to significant increases in time taken to complete the run.

In addition to reports of negative subjective sensations to breathing hot air, concern has been raised over several _in vitro_ animal studies which have demonstrated negative effects of hot air on lung mechanics (3,4). Inoue et al. (3) observed decreases in lung compliance above 42°C but saw progressive increases in compliance at moderate lung volumes as temperature was increased from 4 to 35°C. The current study demonstrated significant increases in Cdyn with both dry and humid 45°C inspired air. This apparent discrepancy could be explained by the differences between excised lungs exposed to a hot ambient temperature and intact lungs exposed only to hot inspired air. A temperature gradient from inspired air temperature to body temperature (37°C) exists for intact lungs but not for excised lung preparations. Intact lungs, with their intact pulmonary circulation, are better able to condition and cool hot inspired air. For these reasons, the decreases in compliance observed in _in vitro_ studies at 42 to 45°C may not occur in intact lungs until a much higher inspired air temperature. Further research is needed to determine at what temperature (above 45°C) the trend of an increasing compliance begins to reverse itself in intact lungs.

The mechanism for increases in compliance as inspired air temperature increases is still unknown. Possible mechanisms for these increases include: 1) decreases in surfactant surface tension as temperature increases (23,24), 2) small increases in tidal volume which lead to secondary increases in compliance (25), 3) decreases in airway resistance as air temperature increases (26,27) and 4) an actual temperature effect on the elastic components of lung tissue. Several of the above mechanisms probably contributed to the results observed in the current study; however, this study was not designed to isolate any individual mechanisms.

The practical consequence of an increase in dynamic compliance is a decrease in inspiratory compliance work done on the lung. Although no significant differences in compliance work were observed, the trend paralleled that seen in the compliance data: compliance work was slightly decreased for the CH, HD and HH conditions as compared to CD (Figure 9). These observations provide further evidence that negative sensations reported while breathing warm air from respirator facemasks are related more to lip and facial skin temperatures than to perceived effort of breathing (1,2).

The differences in mean expired air relative humidity observed during the HD condition have practical implications for the design of metabolic simulators. Most current

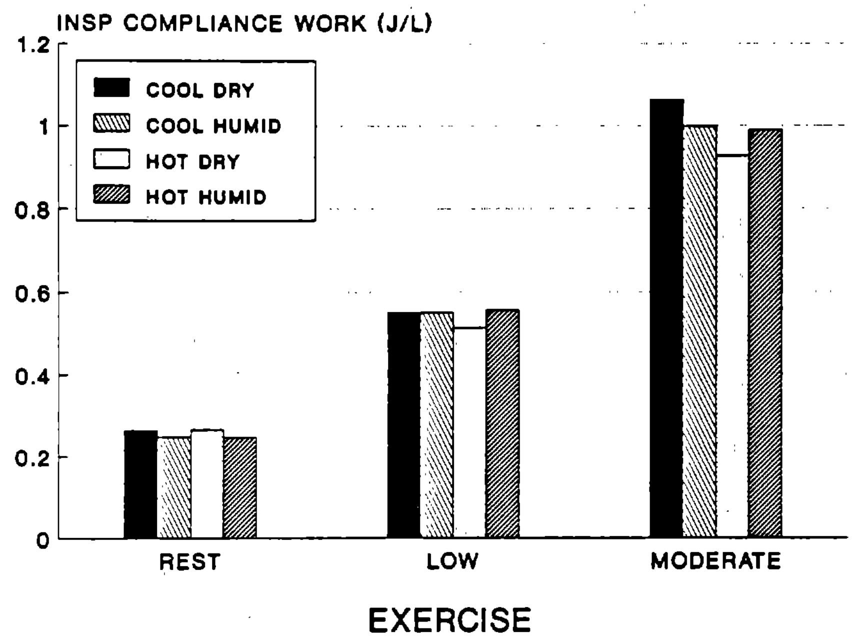


Figure 9. Inspiratory compliance work (Joules·liter$^{-1}$) for the four inspired air conditions.

simulators deliver a constant expired RH, regardless of inspired air conditions and minute ventilation. The results of this study indicate that inspired air wet and dry bulb temperatures, as well as minute ventilation, should be considered in the calculation of the approximate expired RH to be delivered by these simulators.

## CONCLUSION

The results of this study demonstrated several positive effects of hot air breathing on lung mechanics. Dynamic lung compliance was increased with both hot/dry and hot/humid air breathing during rest and exercise. These increases in compliance imply a decrease in the inspiratory work of breathing, although no statistically significant decreases were demonstrated. Frequency of breathing was decreased and tidal volume increased with hot air, allowing a more efficient breathing pattern. These results lend support to the current inspired air temperature criteria for SCBA certification, as set forth in 30 CFR, Part 11 and proposed 42 CFR, Part 84. Further research in this area should include a study in which both inspired air and ambient air temperatures are varied. Closed circuit respirators are used in both fire fighting and hazardous waste operations, activities which may involve hot ambient conditions. Therefore, the possibility of interactions between hot inspired air and hot ambient air should be explored.

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