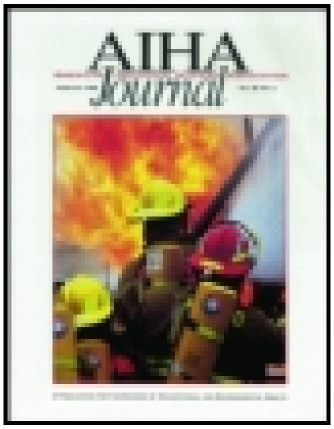

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Effect of Thermal Conditions on the Acceptability of Respiratory Protective Devices on Humans at Rest*

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The physiological and subjective responses of six sedentary subjects wearing half-facepiece respirators were observed over a wide range of room and respirator air conditions. Room air and dew-point (T_a:T_{dp}) temperatures were 25:11°, 30:13°, and 35:16° C in still air. Respirator air temperatures were maintained independently of room conditions at 27°, 30°, 33°, and 36° C with relative humidity levels of 47% and 73%. Physiological measurements included local skin and dew-point temperatures. Subjective judgments of acceptability, thermal sensation, degree of discomfort, sense of skin moisture, and difficulty of breathing were recorded separately for the thermal environment in the room and inside the respirator. Respirator temperatures cooler than 33° C were always comfortable and 100% acceptable; respirator air temperatures above 33° C or higher humidity levels decreased respirator acceptability. Acceptability of the respirator environment decreased as lip temperature increased above 34.5° C or when respirator dew-point temperature increased above 20° C. Increased respirator air temperature and humidity often made breathing seem "slightly hard." The respirator conditions influenced the subjects' judgment of the acceptability of the surrounding thermal environment.

Introduction

Respiratory protective devices are used to protect people from airborne health hazards. When such devices (*e.g.*, face respirators, hoods) are uncomfortable and the health risk is not perceived as immediate, they are sometimes removed or not worn.[1] It is estimated,[2,3] partly for this reason, that respirators are used in only 20% to 30% of the industrial situations for which they are recommended.

Discomfort resulting from wearing the respirator has been attributed by Martin and Goldman[4] and by Martin and Callaway[5] to the decrease in thermal exchange between the respirator wearer and his environment. Despite discomfort, firemen,[6] miners,[7] and rescue workers typically tolerate hot, humid air inside respirators or facepieces for the time required to complete their jobs because the health risk of doing otherwise is clear. It has been reported that surgeons wearing surgical masks for 15 min in air conditioned operating rooms experience a 5° C rise in respirator air temperature and a 16% increase in respirator air humidity.[8] Such thermal conditions have been related to subjective fatigue and an increase in the number of mental errors. Hence, it would appear that keeping the head and face cool during work with a respirator would prove beneficial both physically and psychologically.[9]

The temperature and humidity conditions necessary for thermal comfort inside respirators are not known precisely. Such information appears to be essential for the design of user-accepted facepieces for respiratory protection. Further, industrial respirators should be designed to operate with minimal decrement in the work efficiency of the user.[9] The authors hypothesize that providing appropriate respirator environments in the workplace will minimize the unpleasantness and discomfort and improve the compliance of wearers, while protecting them against airborne hazards. The present study was conducted to determine the range of temperature and humidity conditions necessary for acceptance inside respirators worn by sedentary persons in neutral, warm, and hot environments.

Materials and Methods

Six healthy volunteers with an average age of 35 yr, height of 175 cm, and weight of 71 kg participated in these experiments. Each subject was informed about the content and purpose of this investigation, and each subject's written consent was obtained. All the participants had prior experience with different types of respiratory protective devices but were not industrial workers who used them routinely on the job. The experiments reported herein were conducted during the summer months (July and August) when subjects were naturally acclimatized to hot environments. Before the onset of testing, each subject was familiarized with the laboratory and the experimental procedure.

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The ambient temperature of the environmental room[10] was maintained at one of the following room air and dew-point (T_a:T_{dp}) temperatures: 25:11°, 30:13°, 35:16°C, with an air speed of 0.05 m/sec. The ambient conditions were chosen from a parametric study with a two-compartment (skin and core) thermophysiological and subjective model of human temperature response.[11] The study predicts that sedentary subjects with a clothing insulation of 0.6 clo (long sleeved shirt and trousers [1 clo = 0.155° C m^2/ W]) will judge the thermal environment as neutral, warm, or hot at air temperatures of 25°, 30°, and 35° C, respectively. In general, thermal sensations without a respirator increase and decrease with ambient temperature at a rate of 1 thermal sensation scale division per 3° C change (*i.e.*, approximately slightly warm at 28°, warm at 31° C). Conditions were maintained constant throughout each experiment.

The half-facepiece respirator (Model no. 1200, Willson Safety Products, Reading, Pa.) used in these experiments covered the nose, mouth, and part of the cheeks. The respirator was modified by removing the filters and valves from each side of the facepiece and the exhalation valve. Air entered the respirator from the bottom (exhalation valve) and flowed out through one of the side openings; the other was sealed. The outer surface of the respirator was insulated with 5-mm thick neoprene sponge.

A semiportable Plexiglas® climate box (1 m^3 in volume) provided a supply of separately conditioned air for the respirator (Figure 1). The climate box was capable of supplying air temperatures ranging from 0° to 50° C. In addition, the climate box could supply humid air to the respirator. A small fan mixed the air in the box. The box temperature and humidity of the fan-mixed air were measured with a thermocouple and dew-point sensor, respectively.

A small centrifugal blower moved air from the climate box through an insulated tube connected to the inlet port of the respirator. The conditioned air blew across the subject's face at a constant rate of 24 L/min. This rate of airflow through the respirator provided sufficient ventilation to prevent rebreathing, while at the same time, minimized the feeling of air rushing past the face.

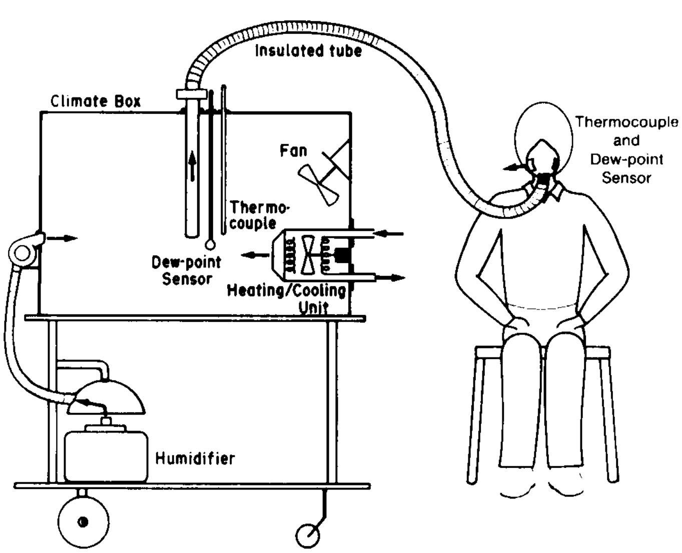

Figure 1—The semiportable climate box used to supply conditioned air to the respirator.

Inspired air temperature was measured with thermocouples placed in the insulated tube and respirator. Facepiece humidity was monitored by continuously drawing a small sample of inspired air through a resistance-type, miniature, dew-point sensor[12] directly attached to the respirator. The air temperature in the respirator was maintained at 27°, 30°, 33°, and 36° C. Respirator relative humidity (RH) was kept at dry (47%) and humid (73% RH) levels for each air temperature.

Local skin temperatures were measured with thermocouples on the forehead (he), upper lip (ul), cheek (ck), chest (ch), back (bk), upper arm (ua), forearm (fa), hand (ha), thigh (th), and calf (cf).

Mean skin temperature ($\bar{T}_{sk}$ in ° C) was calculated as the area-weighted mean of 10 local skin temperatures:

$$\bar{T}_{sk} = 0.175\ T_{ch} + 0.175\ T_{bk} + 0.046\ T_{he} + 0.012\ T_{ck} + 0.012\ T_{ul} + 0.084\ T_{ha} + 0.070\ T_{ua} + 0.070\ T_{fa} + 0.190\ T_{th} + 0.166\ T_{cf} \quad (1)$$

Local skin dew-point temperatures were measured under the clothing on the chest, upper arm, and thigh with miniature, resistance-type dew-point sensors. The sensors were placed adjacent to the skin thermocouples. The local skin wettedness, w (%) (fraction of skin covered with water), at these three body sites was calculated from the ambient room dew-point and the measured local skin and dew-point temperatures[13]:

$$w = 100\ (P_{sk} - P_{sdp})/(P_{ssk} - P_{sdp}) \quad (2)$$

where P_{sk} is the vapor pressure at the surface of the skin determined from the miniature dew-point sensor under the clothing; P_{sdp} is the saturation vapor pressure at ambient dew-point temperature; and P_{ssk} is the saturation vapor pressure at skin temperature.

Skin wettedness is a term used by thermophysiologists to define the percentage of skin area functionally covered with water.[14] The three local skin wettedness levels were averaged, by area, to obtain a representative mean skin wettedness under clothing, $\bar{w}_{uc}$ (%):

$$\bar{w}_{uc} = 0.470\ w_{ch} + 0.090\ w_{ua} + 0.430\ w_{th} \quad (3)$$

Subjective reports of acceptability, thermal sensation, degree of discomfort, perceptions of sweating, and skin wettedness were obtained using standard scales.[15] The subjective rating scales were displayed on a written chart. The subject's oral reports were recorded first for the respirator (Table I) and then for the remainder of the body (Table II). These scales were explained to the subjects prior to the first experiment. During the experiments the subjects responded orally to the charts (Tables I and II), and no other verbal questions were given by the operator. The environment or conditions inside the respirator were judged to be either acceptable or unacceptable. An unacceptable state was defined as one the subject would like to change. These answers were averaged for the six subjects, and the mean was rounded to one significant figure and plotted to the nearest decade on a scale of 0% to 100% (*i.e.*, 10%, 20%, . . . 100%). All other rating scales were recorded as continuous scales and calculated to two significant digits. Subjective reports about breathing (Table I) were not introduced into the protocol until after several experiments had been completed, when it was observed that many subjects complained of breathing difficulty. For this reason the data on breathing difficulty are not complete. The results, however, though incomplete are interesting and merit reporting.

Each experimental session began by having the subject sit on a webbed lawn chair in the environmental room at test conditions for at least 30 min. During this time, the subject was instrumented for the measurement of local skin and dew-point temperatures. After this initial period, the subject remained sedentary and wore the respirator for a 15-min exposure to one of the experimental respirator conditions. Subjective responses were recorded at the end of this exposure period.

TABLE I
Subjective Rating Chart for the Thermal Environment Inside the Respirator

Each subject was asked to evaluate the thermal environment inside the facepiece in terms of the following:

A: Is the respirator environment	B: Discomfort	C: Thermal Sensation
	1 comfortable	
1 acceptable	2 slightly uncomfortable	0 very cold
2 unacceptable	3 uncomfortable	1 cold
	4 very uncomfortable	2 cool
	5 intolerable	3 slightly cool
		4 neutral
		5 slightly warm
		6 warm
		7 hot
		8 very hot

D: Is your face inside the respirator sweating?

1 not at all
2 slightly
3 moderately
4 heavily
5 maximally

E: Rate the wettedness of your skin inside the respirator:

0 dry
1 neutral
2 slightly wet
3 wet
4 very wet
5 soaking wet

F: Rate your perception of breathing:

1 very easy
2 easy ("normal")
3 slightly hard
4 hard
5 very hard

TABLE II
Subjective Rating Chart for the Ambient (Whole Body) Thermal Environment

Each subject judged how the thermal environment in the room felt in terms of his or her general body feeling.

A: Is the room environment	B: Discomfort	C: Thermal Sensation
	1 comfortable	
1 acceptable	2 slightly uncomfortable	0 very cold
2 unacceptable	3 uncomfortable	1 cold
	4 very uncomfortable	2 cool
	5 intolerable	3 slightly cool
		4 neutral
		5 slightly warm
		6 warm
		7 hot
		8 very hot

D: Is your body sweating?

1 not at all
2 slightly
3 moderately
4 heavily
5 maximally

E: Rate the wettedness of your skin over your entire body:

0 dry
1 neutral
2 slightly wet
3 wet
4 very wet
5 soaking wet

Simultaneous measurements of room, skin, and dew-point temperatures were obtained each minute (minutes 1 through 15) with a computerized data acquisition system. Data on the room and respirator conditions were averaged over the 15-min period (minutes 1 to 15). Physiological data (skin and dew-point temperatures) collected from minutes 10 to 15 were averaged. The subjective responses were recorded at the end of this data collection period (*i.e.*, minute 15).

All subjects participated in each experimental condition. Each subject was exposed to each room and respirator condition randomly. The subjects did not know the condition to which they were exposed. Three respirator environments usually were completed in each experimental session.

Differences between treatments were determined by analysis of variance using a 4 x 3 x 2 factorial design, with 4 respirator air temperatures, 3 ambient air temperatures, and 2 humidity levels. Duncan's multiple range test was used to compare the means between factors. Linear and nonlinear regressions[16] were used to fit the best curve functions by the least squares method. Significance was selected as $P < 0.05$.

Results

Acceptability of the respirator environment was dependent on respirator air temperature ($P < 0.01$) and respirator humidity ($P < 0.01$). Respirator air temperatures of 27° and 30° C, with either the 47% or 73% RH, were always 100% acceptable

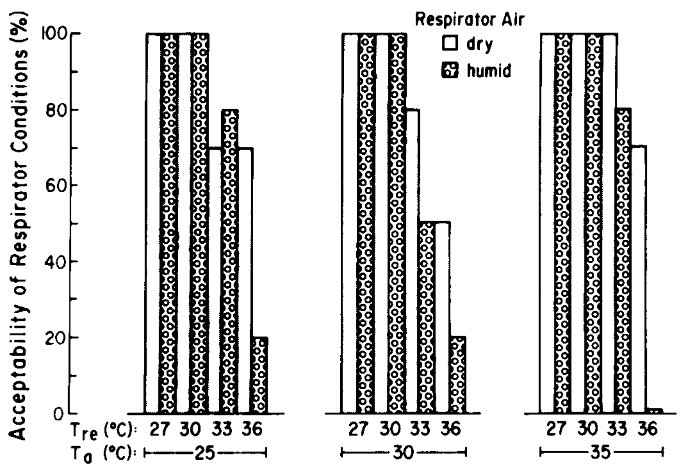

Figure 2—The influence of respirator (T_{re}) and ambient (T_a) air temperatures on thermal acceptability of the respirator environment. Each bar represents the mean of six subjects, rounded to the nearest decade of percent of group reporting "acceptable." Dry respirator air represents 47% relative humidity (RH) while humid respirator air refers to the 73% RH condition.

(Figure 2) regardless of room conditions. At room air temperatures of 25° and 30°C, acceptability of the respirator conditions decreased ($P < 0.05$) when respirator air temperature was 33°C or above. In a hotter room environment (35°C), respirator conditions of 33°C and 47% RH were 100% acceptable, while respirator conditions of 33°C or more and 73% RH had lower ($P < 0.05$) levels of respirator acceptability. In general, respirator humidity of 73% had a lower acceptability level than the 47% RH respirator conditions.

When the thermal conditions under the respirator were acceptable to all six subjects (*i.e.*, 100% acceptable), thermal sensation ranged from "neutral" to "cool," the respirator was "comfortable," perceptions of skin wettedness ranged from "dry" to "slightly wet," perception of sweating was "not at all" (Figure 3), and perception of breathing was rated as "normal." Respirator acceptability typically decreased (*i.e.*, some of the subjects rated the respirator condition unacceptable) when these subjective responses changed from their respective neutral ratings.

Subjective responses of respirator thermal sensation, degree of discomfort, and acceptability of the respirator environment correlated ($P < 0.05$) to lip skin temperature. When lip temperature increased above 34.5°C, the respirator began to feel warmer, became uncomfortable, and the acceptability of the respirator thermal environment decreased (Figure 4).

Perceptions of skin wettedness, sweating under the respirator, and breathing were influenced ($P < 0.01$) by respirator dew-point temperature. As respirator dew-point temperature increased above 20°C, the sense of skin wettedness and sweating inside the respirator increased (Figure 5), and the perception of breathing of some subjects changed from "easy" to "slightly hard." In addition, perception of breathing was related to the thermal properties (*i.e.*, heat content) of the inspired air and increased above a heat energy content (enthalpy) of 88 kJ/kg.

The thermal conditions under the respirator significantly ($P < 0.05$) influenced the subjects' judgment of the surrounding thermal environment. A room air temperature of 25°C was acceptable to at least 80% of the subjects, regardless of respirator conditions (Figure 6). In ambient conditions of 30°C, increasing respirator air temperature above 30°C decreased ($P < 0.05$) acceptability of the surrounding room environment to below 80%. At a room air temperature of 35°C, subjects breathing cool respirator air (27°C) reported greater acceptance (70%) of the surrounding thermal environment than those breathing warm (36°C) respirator air (20%); respirator air temperatures of 30° and 33°C resulted in acceptability ratings between these two extremes.

The room environment was acceptable to most (90%) subjects when the subjective responses evaluated for the whole body with respect to thermal sensation, comfort, sweating, and skin wettedness were (1) neutral, (2) comfortable, (3) not at all, and (4) neutral (Figure 7). These subjective ratings were reported when mean skin temperature was 33.2°C and mean skin wettedness was about 20%. Accepta-

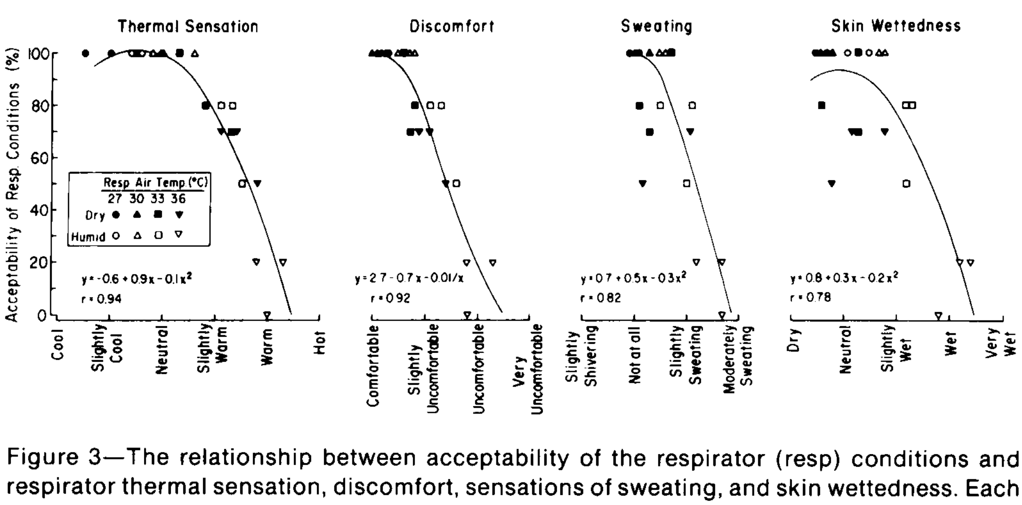

Figure 3—The relationship between acceptability of the respirator (resp) conditions and respirator thermal sensation, discomfort, sensations of sweating, and skin wettedness. Each point represents the mean of 6 subjects (n = 24). Dry and humid respirator air refers to the 47% and 73% relative humidity conditions, respectively.

bility decreased ($P < 0.05$) when mean skin temperature rose above 34.2° C and mean skin wettedness was greater than 25% (Figure 8). Increases in mean skin temperature and mean skin wettedness significantly ($P < 0.05$) correlated with changes in subjective ratings, indicating that the whole body felt warmer, more uncomfortable, and wet with sweat.

Discussion

The present study quantified the thermal conditions for acceptability when respiratory protective devices were worn by sedentary subjects naturally acclimatized to summer

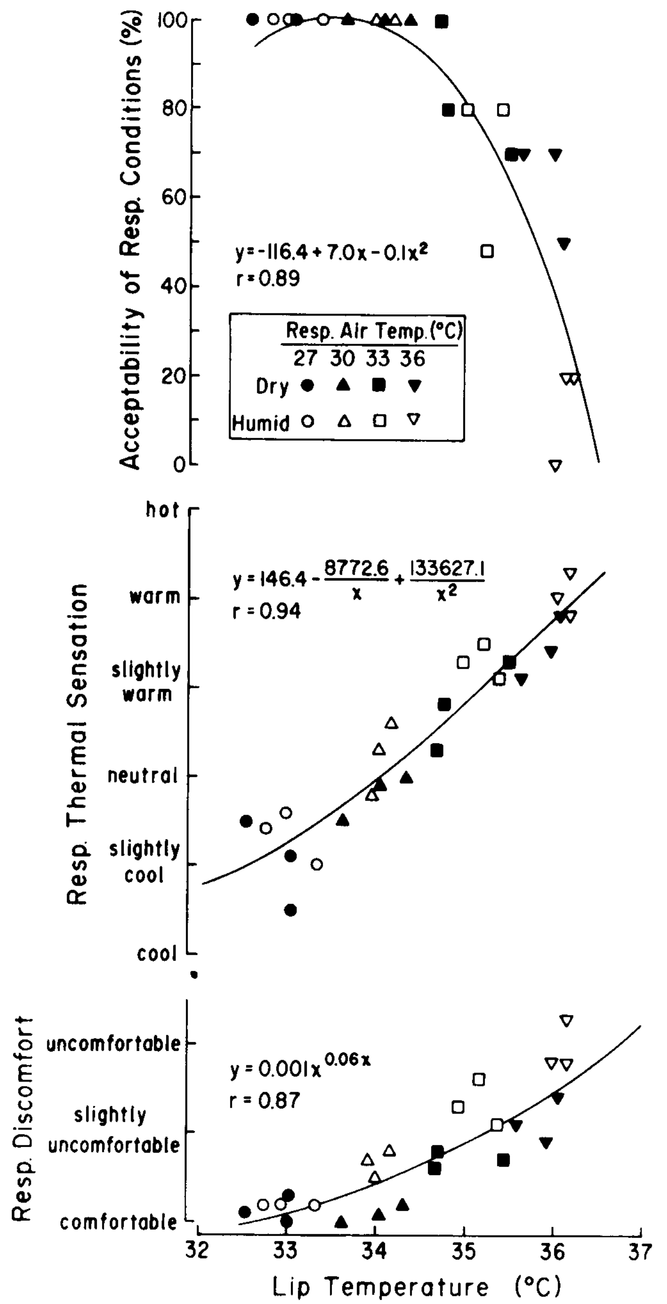

Figure 4—The relationship between subjective responses of respirator (resp) acceptability, thermal sensation, discomfort, and lip skin temperature. Each point represents the mean of 6 subjects (n = 24). Dry and humid respirator air refers to the 47% and 73% relative humidity conditions, respectively.

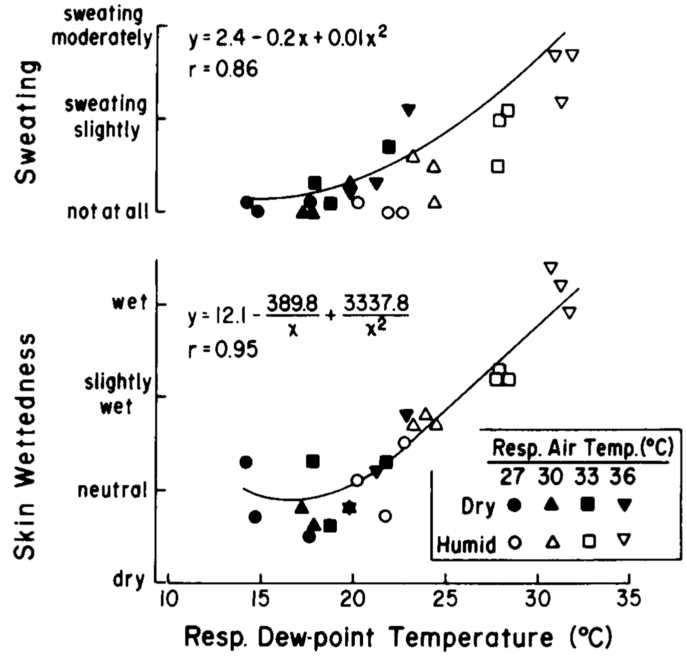

Figure 5—The relationship between sensations of sweating and skin wettedness inside the respirator (resp) and respirator dew-point temperature. Each point represents the mean of 6 subjects (n = 24). Dry and humid respirator air refers to the 47% and 73% relative humidity conditions, respectively.

conditions. The respirator conditions served as local temperature stimuli for the skin inside the facepiece. The room and respirator conditions were chosen to represent typical routine, nonemergency work environments requiring respirators.

The respirator used in this experiment covered the nose, mouth, and part of the cheeks. The face—in particular, the cheeks and forehead—are the body regions most sensitive to warm stimuli.[17] At the beginning of the investigation, it was hypothesized that the sensitivity of the face to thermal stimuli might be a major cause of discomfort when wearing respirators.

This study provides evidence that respirator comfort is primarily affected by the temperature and humidity conditions inside the respirator. In general, respirator temperatures cooler than 33° C were always 100% acceptable; higher respirator air temperature or humidity levels were acceptable to fewer people. A lower range of acceptable respirator conditions was reported for exercising subjects.[18] In addition, Lind's [19] studies on tolerance to work in the heat (45°-50° C wet-bulb temperature [WB]) reported discomfort when breathing through a respirator at inspired air temperatures above body temperature (39° C). Killick,[20] whose subjects were in a cool environment and breathed hot, moist air through a tube, found that for men at rest, the lowest temperature which caused discomfort was 54.5° C.

It was found in this study that respirator discomfort and thermal sensation were perceived in accord with lip skin temperature and/or moisture on the skin surface inside the facepiece. At lip skin temperatures between 32.5° and 34.5° C, the respirator was acceptable to all six subjects (*i.e.*,

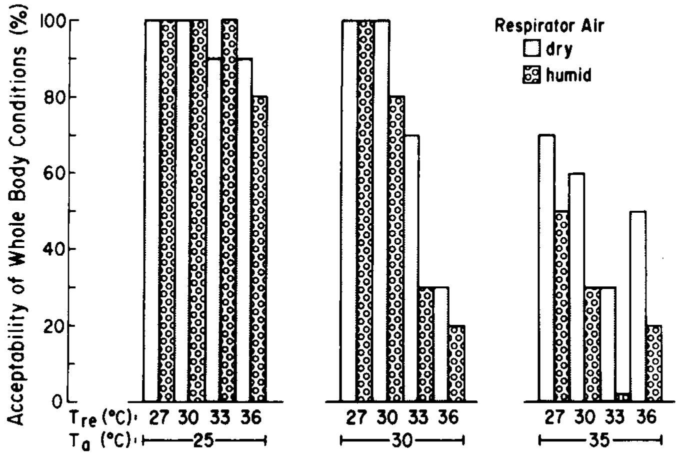

Figure 6—The effect of ambient (T_a) and respirator (T_{re}) air temperatures on acceptability of the surrounding (whole body) thermal environment. Each bar represents the mean of six subjects, rounded to the nearest decade of percent of group reporting "acceptable." Dry and humid respirator (resp) air refers to the 47% and 73% relative humidity conditions, respectively.

100% acceptable). When the respirator was 100% acceptable, the thermal conditions inside the facepiece were rated as comfortable, with a neutral thermal sensation, minimal sweating, and little sense of skin wettedness. In addition, most subjects rated breathing as "normal."

As lip skin temperature rose above 34.5°C, respirator acceptability decreased. The reduced respirator acceptability was reflected by changes in subjective responses. For example, as respirator acceptability decreased, the respirator environment felt warmer, and subjective ratings of respirator discomfort increased. Respirator discomfort has been shown to relate to decreased job performance.[4,8]

The acceptability of the respirator also decreased when the respirator dew-point temperature rose above 25°C. Unfortunately, the corresponding skin wettedness inside the facepiece could not be measured in the present experiment. The skin dew-point temperature inside the respirator, however, was assumed equivalent to that of the inspired respirator air. This was confirmed by the subjective responses. In particular when high respirator humidity was combined with high respirator air temperature, the respirator environment felt warmer, respirator discomfort increased, and respirator acceptability decreased. This is in agreement with Killick[20] who observed that, compared to the saturated environment, very hot but dry environments can be breathed without great discomfort. Killick reports that, for subjects at rest, dry air temperatures of up to 186°C could be breathed in comfort. Breathing hot humid air may have been unacceptable partly because respiratory evaporative heat loss was reduced.[19,21] The Lind experiments[19] indicated that, if the inspired air temperature became greater than body temperature, heat loss via the lungs was eliminated and, in fact, heat gain occurred. When evaporative cooling from the trunk was decreased, the normally unimportant role of cooling by respiratory evaporation assumed greater significance.

In the present study, when the respirator air humidity was high (73%) some subjects rated breathing as "slightly hard." These subjects may have perceived breathing as being more difficult because humid inspired air may have increased breathing resistance, a reflex reaction,[9] or induced changes in the breathing pattern.[22] It has been reported[22] that humans accurately judge changes in the breathing pattern. If sensory breathing judgments are linked closely to the function of the respiratory system,[23] then any change in respiration may signal discomfort.[1,9]

The respirator thermal conditions reported herein influenced subjective judgments of whole-body thermal acceptability of the surrounding room environment. Similar results were observed by Nielsen et al.[18] for exercising subjects. In the sedentary study reported herein, whole-body perceptions changed when mean skin temperature increased above 34.2°C or mean skin wettedness above 25%. The converse

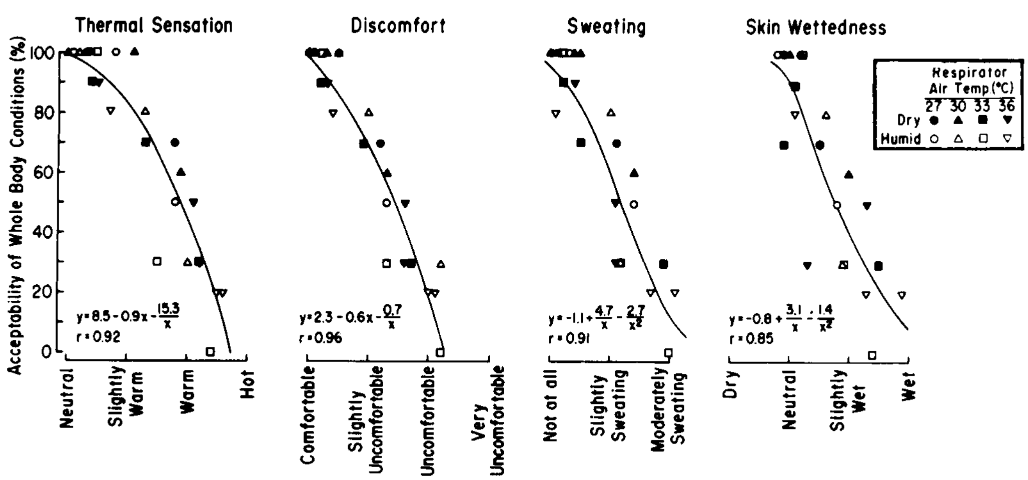

Figure 7—Acceptability of the ambient thermal environment as a function of whole body thermal sensation, discomfort, sensations of sweating, and skin wettedness. Each point represents the mean of 6 subjects (n = 24). Dry and humid respirator (resp) air refers to the 47% and 73% relative humidity conditions, respectively.

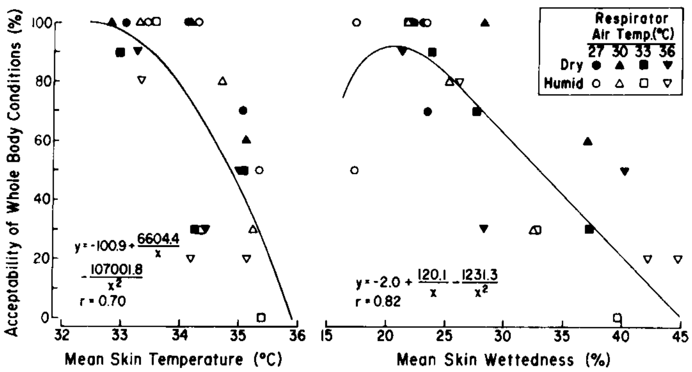

Figure 8—The relationship between acceptability of the surrounding thermal environment, mean skin temperature, and mean skin wettedness. Each point represents the mean of 6 subjects (n = 24). Dry and humid respirator (resp) air refers to the 47% and 73% relative humidity conditions, respectively.

also was true. When the whole-body conditions were warm and the mean skin wettedness and lip skin temperatures were high, respirator acceptability decreased.

On the other hand, cool (27° C) respirator air increased the acceptability of a hot ambient environment (35° C). This is supplementary to and in agreement with others[24,25] who used a water-cooled cap on the scalp of the head to reduce physiological heat strain and thermal discomfort and to improve performance in hot environments. Other investigators[26,27] also have reduced thermal strain by cooling the head and/or neck region of the body.

The amount of heat removed from the body with head cooling was quantified by Nunnely et al.[25] as about 30% of resting metabolic heat and 19% of the available heat during work in ambient environments of 20°, 30°, and 40° C. Head cooling in hot environments reduces the physiological strain on the body as indicated by a decreased rectal temperature, sweat rate, heart rate, and cardiac output.[28,29] This decrease in heat strain contributes to the decreased thermal discomfort,[28] increased productivity,[24] and increased performance[29] observed in hot environments.

But the reduction in heat strain may be limited either by the environmental conditions or by the inefficiency of airway cooling in hot conditions. Other investigators[30] reported that breathing cool (27°C) air in extremely hot, humid environments (T_a 54° C: T_{dp} 40° C) did not improve physiological indexes of heat stress, respiratory tract heat loss, or subjective responses.

Perceptions of the whole-body thermal environment generally are considered to be determined by the combined input of internal body and local skin temperatures.[31] By integrating this information in the central nervous system, the body is able to assess thermal sensation, discomfort, and other subjective responses. In this experiment, mean skin temperature and mean skin wettedness were indicators of whole-body thermal perceptions. For the respirator environment, the local skin temperature under study was assumed to be indicated by the skin temperature of the upper lip. The cutaneous thermoreceptors on the face and upper lip relay thermal information to thermosensitive structures in the brain and, as a result of altering neural transmission, may change the perceptions of the respirator environment.

Alternatively, it has been postulated[32] that a countercurrent heat exchange occurs between venous blood draining the head and arterial blood ascending to the brain. Support for this theory was provided by Cabanac and Caputa,[33] who observed that fanning the face decreased forehead and tympanic temperatures and changed subjective ratings of hyperthermia to normothermia. This was interpreted as evidence for cerebral cooling, caused by local heat exchange between venous blood returning from facial veins to the cavernous sinus, and arterial blood ascending to the brain. This local heat exchange, therefore, would change the temperature of blood perfusing the thermoregulatory centers of the brain, which, in turn, would change the perception of the respirator thermal environment. It also has been suggested[34] that venous blood returning from the nasal cavities to the thermosensitive structures in the brain may affect the perception of the thermal environment. It is possible that the respirator conditions studied herein influenced perceptions through one or more of these means.

It should be noted that the subjects chosen for this study were not routine respirator wearers. But all subjects experienced the experimental procedure before any data were collected. It is possible that slightly different results would be obtained from workers who routinely wear respirators. Such follow-up studies would serve to validate the current findings.

Conclusions

In summary, respirator acceptability was dependent on the thermal conditions inside the respirator. Maximal acceptability for the respirator environment was observed when the thermal conditions were comfortable, with a neutral thermal sensation, minimal sweating, little sense of skin wettedness, and normal breathing. This occurred when lip skin temperature was less than 34.5° C and respirator dew-point temperature was less than 25° C. Respirator acceptability decreased when increases in these temperatures were observed.

Though it generally is accepted that whole-body thermal sensations are proportional to the area-weighted mean skin temperature, the present findings indicate that this relationship changes when thermal conditions inside the respirator differ. In the current experiment, the respirator thermal conditions influenced the thermal acceptability of the surrounding environment. For example, at a room air temperature of 25° C, increasing the respirator conditions (temperature and humidity) changed the whole body thermal sensation from neutral to warm. Maximal acceptability of the surrounding thermal environment was rated in the same manner as the corresponding respirator perceptions. The surrounding thermal environment was most acceptable when the mean skin temperature was less than 34.2° C and/or mean skin wettedness on the body's surface was below 25%. In general, the acceptability of both the ambient and respirator conditions decreased when the respirator air temperature rose above 30° C (Figures 2 and 8).

Acknowledgments

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