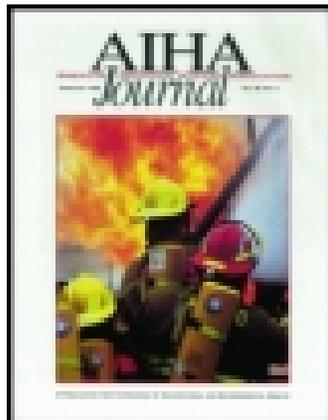


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## American Industrial Hygiene Association Journal

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/aiha20>

### THERMAL DISCOMFORT OF RESPIRATORY PROTECTIVE DEVICES

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Published online: 04 Jun 2010.

To cite this article: A.B. DuBois, Z.F. Harb & S.H. Fox (1990) THERMAL DISCOMFORT OF RESPIRATORY PROTECTIVE DEVICES, American Industrial Hygiene Association Journal, 51:10, 550-554, DOI: [10.1080/15298669091370086](https://doi.org/10.1080/15298669091370086)

To link to this article: <http://dx.doi.org/10.1080/15298669091370086>

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# THERMAL DISCOMFORT OF RESPIRATORY PROTECTIVE DEVICES\*

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*Respiratory protective devices which would protect the wearer against noxious material and gases are not worn in many of the appropriate circumstances. They have been said to feel uncomfortable and hot. In the present study, six men and six women in a 25°C room reported on facial discomfort, thermal sensation, and sweating while wearing three different types of half-facepiece respirators requiring tidal airflow. Skin temperature of the face was measured using a thermocouple taped to the nasolabial fold. The subjects reported that the face felt comfortable when the skin temperature was 34°C or below. However, at skin temperatures above 34.5°C, the face felt increasingly warm, uncomfortable, and sweaty. This finding is similar to that reported previously when subjects wore a half-facepiece respirator supplied continuously with warm, humid air. The conclusion is that thermal conditions of the face contributed to, and may possibly dominate, the discomfort of wearing respiratory protective devices.*

**W**hen properly used, respiratory protective devices protect the wearer against undesirable exposure to potentially injurious dusts and gases. However, one report<sup>(1)</sup> indicates that such devices are worn in only 20% of appropriate circumstances, increasing to 60% after a month of training in their use, and 75% after 11 more months of close supervision. White et al.<sup>(2)</sup> found hot to very hot conditions in face pieces or clothing in subjects exercising in a warm, humid room. Hodous et al.<sup>(3)</sup> indicated that the most bothersome aspect of wearing respiratory protective devices was excessive heat inside these devices. Considering that thermal discomfort of the face may be a factor discouraging use of face masks, the present authors are attempting to define the acceptable range of temperature and humidity inside such masks. Previously, a mask was modified so that a continuous flow of air could be supplied through an inlet port and allowed to leave through an expiratory opening.<sup>(4-6)†</sup> Warm, humid air supplied to the mask from a Plexiglas<sup>®</sup> chamber produced a sensation of thermal discomfort, skin wettedness, and a slight increase of breathing effort, related to increase of skin temperature of the face.

\*This work was supported in part by NIH Grant No. OH 02564.

†Antecedent literature on this subject has been reviewed in these references.

But in respirators that depend on tidal breathing, heat and water vapor delivered by expired air also affect the temperature and humidity of the face. The present study measures facial discomfort as a function of temperature of the skin of the face when using face masks that depend on tidal breathing rather than continuous airflow. The new results are compared to the results previously obtained by Gwosdow et al.<sup>(6)</sup> to ascertain whether facial discomfort is dependent on the type of airflow (tidal versus continuous) in the mask or instead on increase of skin temperature resulting from heat and humidity in the air around the face.

## EXPERIMENTAL METHODS

The subjects were healthy volunteers who were students or professionals but not experienced laborers. Subject characteristics are listed in Table I. Although the men had had some experience with SCUBA or surgical masks, 4 out of 6 women had had no previous experience with respiratory protective devices.

Skin temperature was measured by a thermocouple touching the skin of the left nasolabial fold inside the mask. It was fastened in place by adhesive tape on the adjacent wire. Heat flow was measured by heat flow disc 2.7 cm in diameter and 0.2 cm thick, which was fastened with adhesive tape across its edges to the right nasolabial fold of the face. Thermocouple temperature and heat flow were recorded on a direct writing recorder (Model 7, Grass Instrument Co., Quincy, Mass.) A rating scale, shown in Table II, was used by the subject to record numerical estimates of discomfort, thermal sensation, and sweating, at regular time intervals.

Experimental protocol was as follows: upon arrival, the subject sat in the room for 15 to 30 min, during which the thermocouple was applied and the rating scale was explained. Room temperature (21 to 26°C) was measured with a mercury thermometer and dew-point temperature (7 to 13°C) with an automatic dew-point sensor.<sup>(7)</sup> Control measurements consisting of ambient temperature and dew-point temperature, skin temperature, and comfort ratings were made at 1 to 4 min before application of the first face mask. Each mask was worn for 30 min with a 30-min recovery/control period between masks. The first device was a rubber mask with dust and organic mist filters on the two inlet valves and with a single outlet valve (Wilson model 122510, WGM Safety Corp., Reading, Pa.), weighing 284 g. It was worn for 30 min, during which the measurements listed above were repeated at 1, 10, 20, and 30 min. The mask

**TABLE I. Mask Subjects**

Gender	Age	Ht. (cm)	Wt. (lb)	Occupation	Clothes	Previous Experience
F	29	170	142	nurse	cotton	surgical
F	25	168	133	student	wool	none
F	25	150	111	student	cotton	none
F	24	168	128	student	cotton	SCUBA
F	27	165	128	cashier	cotton	none
F	26	163	113	student	wool	none
M	26	173	160	student	cot + wool	SCUBA
M	29	185	185	M.D.	cotton	SCUBA + surg
M	65	190	205	physiologist	cotton	SCUBA + surg
M	20	165	125	student	cotton	SCUBA + surg
M	29	187	205	M.D.	cot + wool	SCUBA + surg
M	29	187	192	student	cotton	surgical

**TABLE II. Rating Scale**

Discomfort	Thermal Sensation	Sweating Sensation
1 Comfortable	0 very cold	1 not at all
2 Slightly uncomfortable	1 cold	2 slightly
3 Uncomfortable	2 cool	3 moderately
4 Very uncomfortable	3 slightly cool	4 heavily
5 Intolerable	4 neutral	5 maximally
	5 slightly warm	
	6 warm	
	7 hot	
	8 very hot	

was removed and the subject sat for the 30-min control period. During the control period, measurements were made when skin temperature of the face was steady (10 min after removal of the mask). These readings were used as the control for the next mask. Following the first control period, a porous fiber mask without valves (3M 9913 Dust-Mist TC-21C-234), weighing 10 g, was placed on the face and held by two elastic bands. The measurements were repeated at 1, 10, 20, and 30 min. The mask was removed and a 24-min recovery period allowed, with measurements taken at the 10th min to be used as the control for the last device (which was a lightweight, loosely fitting curved aluminum shell with cotton cloth glued to its outer surface, wetted to cool the "mask"). It had no valves or filters. During breathing, air entered and left through gaps between the face and the mask and an inspiratory/expiratory port (diameter 1.2 cm) located in front of the mouth. Measurements were repeated at 1, 10, 20, and 30 min and again 10 min after removal. The dry weight was 56 g and wet weight 59 g. Drying of the cotton cloth was prevented by adding water using a dropper at 10-min intervals.

## RESULTS

Table III shows that the mean facial skin temperature of the women averaged 0.2°C less than that of the men during a control period but increased about equally for men and women wearing

respiratory protective devices. The comfort votes changed in proportion to skin temperature about equally. Since the results from the two groups, men and women, were virtually the same, they were combined to form one experimental group.

Figure 1 shows mean values and unpaired standard errors of the skin temperature of the face throughout the experiment on the 12 subjects (6 men and 6 women). The rubber mask with inlet and outlet valves increased the mean skin temperature of the face from a control of 33.4°C (SD 0.52, SE 0.15) to 34.9°C (SD

0.36, SE 0.10) after 30 min of wearing the mask. The control before putting on the porous mask for nuisance dust was 33.8°C (SD 0.42, SE 0.13). Wearing the mask for 30 min increased the skin temperature to 35.9°C (SD 0.54, SE 0.16). The control before the wet aluminum mask was 34.1°C (SD 0.59, SE 0.18). After 30 min of wearing this mask, the temperature was 34.0°C (SD 0.64, SE 0.18); 10 min after removal of this aluminum mask, the skin temperature was 33.8°C (SD 0.67, SE 0.19).

Subjective ratings of thermal sensation as a function of skin temperature of the face are shown in Figure 2 which contains data for men and women shown as open squares and a regression line with its equation ( $r = 0.83$ ). At a mean skin temperature of 34.3°C, the thermal sensation was neutral ("4"). The sensation of warmth increased by 0.92 units for an increase of 1°C over the range of skin temperature from about 33.2 to 36.1°C. The corresponding sensations ranged from slightly cool through neutral, slightly warm, and warm.

Figure 2 also shows solid black points that were replotted using the data published previously.<sup>(6)</sup> The regression line with its equation is shown ( $r = 0.94$ ). The points of the study overlap those of the old study, and the regression lines are almost identical.

**TABLE III. Skin Temperatures of Men and Women<sup>A</sup>**

	Males (n = 6)		Females (n = 6)	
	Mean	SE	Mean	SE
Control	33.5	0.26	33.3	0.17
Rubber mask	35.0	0.16	34.9	0.16
3M porous dust mask	36.3	0.21	35.7	0.16
Aluminum mask	34.0	0.16	34.0	0.37
"Comfortable"	33.7		33.4	
"Slightly uncomfortable"	35.6		35.2	

<sup>A</sup>Comparison between skin temperatures (°C) of the face in men and women during a control period, 30 min wearing a rubber mask with valves, a porous dust mask, or an aluminum shell mask. Also shown are comfort votes at skin temperatures for men and women.

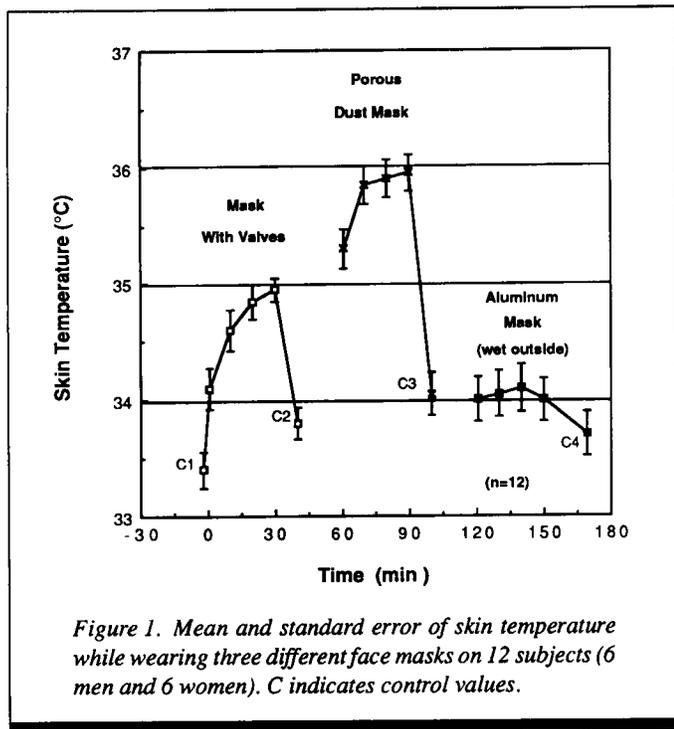


Figure 3 is a graph of the sweating sensation of the face as a function of skin temperature. All of the control ratings for sweating were 1, meaning not at all. There was a proportional increase in rating so that a rating of 2, or slight sweating, occurred when the skin temperature of the face had risen an average of 1.9°C ( $r = 0.94$ ). The points obtained 1 min after putting on the masks (solid black points) were excluded from the regression line and its equation; the skin temperature had increased 1 min after putting on the porous dust mask, but sweating did not start that early.

Figure 4 is a graph of discomfort as a function of time throughout the experiment, using the three face masks on all 12 subjects. All of the control values, without a mask, had a rating of 1 (comfortable). The subjects gave a mean rating of 2.1 (SD 0.90, SE 0.26) after 30 min of wearing the rubber mask with breathing valves. The mean was 2.4 (SD 0.65, SE 0.19) after 30 min of the porous mask. After 30 min of the aluminum mask, the mean was 1.3 (SD 0.45, SE 0.13).

A graph of discomfort as a function of skin temperature under the mask (Figure 5) shows that the value 1 (comfortable) corresponded to a skin temperature of 33.3°C. As the skin temperature increased, the discomfort increased. The rating of discomfort increased approximately 1 unit (a change from comfortable to slightly uncomfortable) for a rise in skin temperature of the face of 2.0°C. A simple regression line (labeled with an  $r$  value of 0.90) is drawn through the open squares which are values obtained in the present experiment using the three different masks.

Figure 5 also shows the values obtained previously using a single mask with continuous air supply in which the temperature of the air was altered so as to produce the change in the values of skin temperature.<sup>(6)</sup> Those values are presented as solid black points, with an exponential regression line and equation. The new values overlap the old ones, and their regression lines are close.

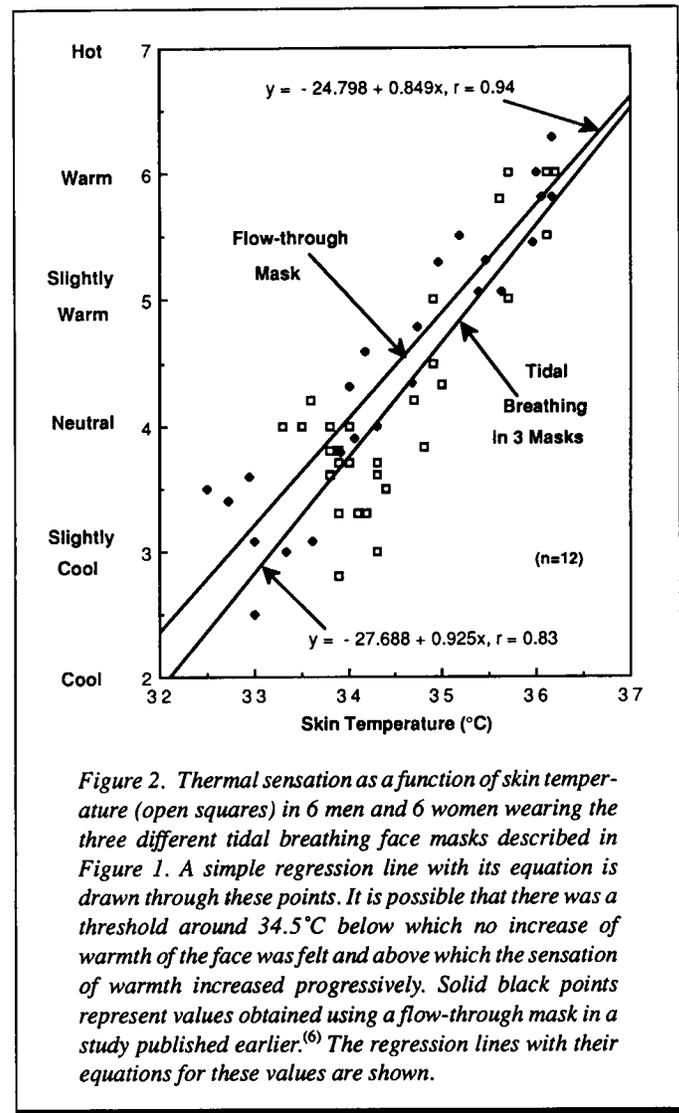
Figure 6 is a graph of comfort as a function of sweating sensation of the skin under the mask. Comfort voting changed from

comfortable to slightly uncomfortable when the sweating sensation changed from no sweating to slight sweating and became uncomfortable when the subjects reported moderate sweating. One minute after applying the porous dust mask, subjects felt slightly uncomfortable without reporting any sweating. This is presented on the graph as a circle. Figure 1 shows the temperature during this first minute to rise from 33.8 (Point C2) to 35.3°C.

Heat flow measurements are listed below, except for the rubber mask, in which they were not considered valid since the rubber flap sealing the edge against the face covered most of the heat flow disc. Heat flux of the bare face before putting on the porous mask averaged 104 W/m<sup>2</sup> (SD 16, SE 6.6). Wearing the porous face mask decreased the heat flux to 41 W/m<sup>2</sup> (SD 13, SE 5.4). The heat flux was 102 W/m<sup>2</sup> (SD 15, SE 6.2) 10 min after removal of the mask. Wearing the wet aluminum mask for 30 min only slightly altered the heat flux to 102 W/m<sup>2</sup> (SD 12, SE 4.9); 10 min after removal of the mask, the heat flux was 89 W/m<sup>2</sup> (SD 12, SE 4.9).

### DISCUSSION

Skin temperature of the face under the mask increased within a few minutes of putting on the mask. The skin temperature



increased more under the porous dust mask than under the rubber mask with valves but did not increase significantly under the aluminum shell "mask" cooled by evaporation. The facial sensations of skin temperature, sweating, and discomfort increased in direct proportion to the increase in facial skin temperature as measured with a thermocouple.

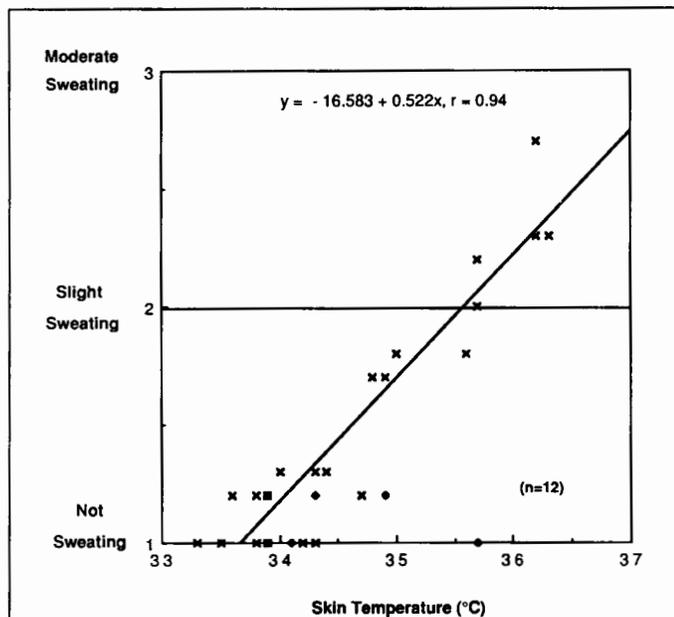


Figure 3. Sweating sensation as a function of skin temperature in 12 subjects (6 men and 6 women) wearing the three different face masks described in Figure 1. A simple regression line is drawn through the points, with  $r = 0.94$ . Solid black points represent values obtained 1 min after wearing each of the three masks. These values were not included in calculating the regression line and its equation for the reason mentioned in the text.

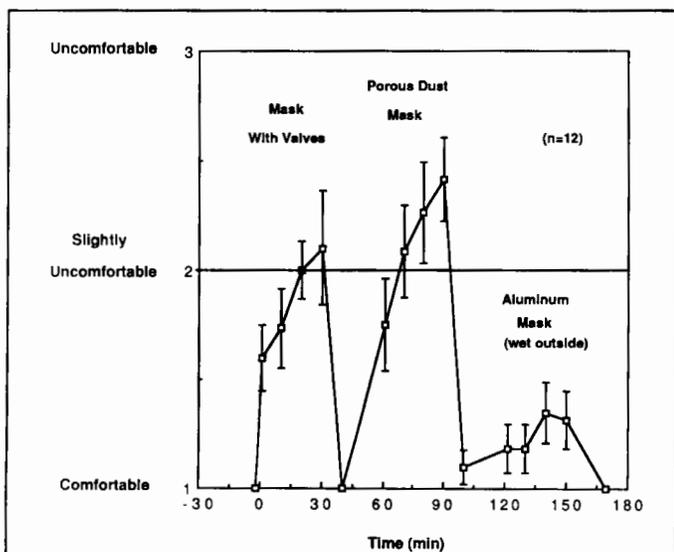


Figure 4. Discomfort as a function of time in the 12 subjects wearing the three different face masks described.

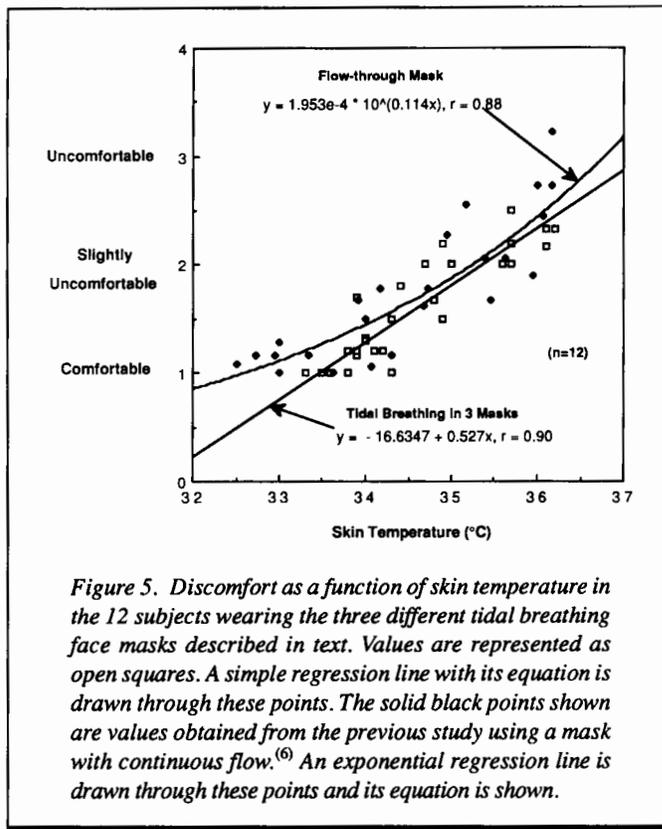


Figure 5. Discomfort as a function of skin temperature in the 12 subjects wearing the three different tidal breathing face masks described in text. Values are represented as open squares. A simple regression line with its equation is drawn through these points. The solid black points shown are values obtained from the previous study using a mask with continuous flow.<sup>(6)</sup> An exponential regression line is drawn through these points and its equation is shown.

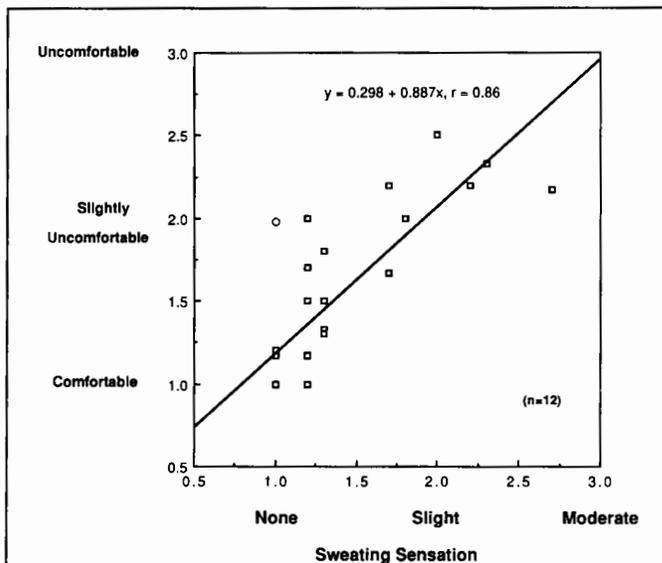


Figure 6. Discomfort as a function of sensation of sweating in the 12 subjects wearing the three different face masks described. Values are represented as open squares. A simple regression line is drawn through these points and its equation shown. (o) represents a point 1 min after the application of the porous dust mask. At this point the skin temperature has already increased to a value of 35.3°C, yet the sensation of sweating did not start that early. This point was not included in the calculation of the regression line. Discomfort at this point is probably related to the increase in skin temperature rather than sweating.

The heat flux per unit area of the bare face,  $104 \text{ W/m}^2$ , is double that of the rest of the body, which is around  $50 \text{ W/m}^2$ . The heat flux diminished when the face was covered by a porous mask. This caused an increase in the temperature of the skin under the mask. Under the aluminum mask, heat flux from the skin did not diminish, and the mask felt comfortable and slightly cool. The skin temperature did not increase. The explanation for these findings may be that aluminum was a good heat conductor and the mask was cooled by evaporation from a wet cloth, whereas the porous mask was a poor heat conductor and surrounded the face with warm, moist air.

These findings on face masks with spontaneous breathing are comparable to previous data obtained using masks which had a continuous air supply.<sup>(6)</sup> In both studies, the masks were comfortable when the skin temperature of the face was  $33^\circ\text{C}$  and became slightly uncomfortable at a skin temperature of  $35^\circ\text{C}$ . In both studies, the thermal sensation of the face was slightly cool to neutral at a skin temperature of  $33^\circ$  to  $34^\circ\text{C}$  and became warm at  $36^\circ\text{C}$ . In the previous study, temperature of the skin above the upper lip was measured within a single mask supplied with air of different temperatures and humidity levels. By contrast, the present study used different masks in which room air of approximately constant temperature and humidity was breathed in tidal fashion while skin temperature was measured at the nasolabial fold. The recording equipment, observers, and most of the subjects were different. Despite the differences, the points plotted as discomfort versus skin temperature are superimposable and so are the points plotted as thermal sensation versus skin temperature. The implication is that whatever the mechanism may be, discomfort is a function of skin temperature. The mechanism of discomfort may be related to thermal sensation, sweating and hydration, condensation of expired alveolar water vapor, cutaneous bloodflow, or vascular congestion, or all of the above.

In the study using a continuous air supply, the deadspace of the mask was flushed continuously, and the weight of the mask was constant. Therefore, these were not factors that might have changed the level of discomfort. In the present study, deadspace of the mask was rebreathed by the wearer. However, this did not alter the relationship between comfort rating and skin tempera-

ture or thermal sensation and skin temperature from those of the previous study. It was concluded that deadspace of the mask (at least within that range of volume in the three tested masks) was not a factor in discomfort of these masks.

Another factor that could have influenced the rating of discomfort of the three masks tested was their weight. The rubber mask with canisters and valves was heaviest, 284 g, the porous dust mask lightest, 10 g, and the aluminum mask with a wet cloth surface heavier than the porous dust mask, 59 g. Yet the lightest mask, which was hottest, was the least comfortable. The heaviest mask was cooler and generally more comfortable than the lightest mask, although 3 females and 1 male said it felt heavy. The mask intermediate in weight was the coolest and was not uncomfortable. This suggests that although some of the discomfort was brought about by the weight of the mask, most of the discomfort was related to the temperature of the face under it.

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