

Interaction of Temperature and Humidity of Inspired Air
on Tissue Temperatures of the Tongue and Hard Palate

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ABSTRACT

Six healthy young men ($\bar{M}$ = 23.7 years $\pm$ 3.7 SD) volunteered to breathe hot, humid air while walking on a treadmill at 40% $\dot{V}O_{2\max}$. Each subject was presented nine experimental conditions with tests occurring on separate days. Tongue and hard palate temperatures were monitored via thermocouples mounted in a custom-fitted mouthpiece. Core temperature (T_{re}) and heart rate (HR) were monitored as

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secondary dependent measures. Elevated dry bulb temperature (T_{db}) caused increases of both tongue ($p < .001$) and hard palate ($p < .001$) tissue temperatures. Similarly, increases in relative humidity (RH) caused elevations in tissue temperatures of both the tongue ($p < .001$) and hard palate ($p < .001$). There were no interactions, however, in tissue temperature reactions. Core temperature and heart rate were not affected by increases of either dry bulb temperature or relative humidity ($p > .05$). Subjective feelings of discomfort in mouth tissues due to inhalation of hot, humid air were greatest for the experimental conditions with a T_{db} of 51°C and RHs of 80% and 95%. The magnitude of changes in mouth tissue temperatures when breathing hot, humid air provides useful information to consider when determining federal standards for the maximum allowable temperature limits for Self-Contained Breathing Apparatus (SCBAs).

INTRODUCTION

Man is not ordinarily subjected to conditions where the upper respiratory tract experiences heat gain while the total body heat balance remains normal. However, during the use of some types of SCBAs (Killick, 1932; Lind, 1955; Kamon et al., 1984), or during certain anesthetic procedures in hospitals (Comroe, 1974), a person may be subjected to respiratory heat gain that may cause extreme discomfort or burns in the mouth of the user. While much work has been done on the conditioning of inspired air under normal conditions (Seeley, 1940; Cole, 1954; Ingledet, 1955; McFadden et al., 1982), relatively little is known about tissue temperature responses of the upper respiratory mucosa to conditions where respiratory heat gain will occur (Gallagher, 1984). Such information is valuable in order to protect the mouths of persons required to breathe hot, humid air and for setting federal standards for maximum allowable temperatures of SCBAs.

Relatively few studies have examined the physiological response to inhalation of hot air. Haldane (1915) described the effects of breathing hot air, while

the subject remained in a hot ambient environment. Killick (1932) was the first to study the responses of subjects breathing hot air while in a comfortable ambient environment. Her study reported that subjects found breathing hot air was tolerable until the inspired wet bulb temperature reached 59-64°C (at rest), or 54.5 ~ 60.0°C (at a metabolic rate equivalent to walking 4.0-4.5 mph). A more recent study found that respiratory discomfort was first felt at a saturated temperature of 39°C (Lind, 1955). Experimental studies with animals have shown that hot, dry air at temperatures of up to 55°C is still adjusted towards body temperature in the tracheobronchial tree and produces remarkably little lung damage (Moritz et al., 1944). A study of pulmonary function with exercise under conditions of temperature-humidity stress found that measures of pulmonary function were generally not affected by inhalation of warm, humid air, with the exception of forced vital capacity (FVC), which increased (Stacy et al., 1982). McCutchan and Taylor (1951) demonstrated the mass and heat transfer process of respiratory exchange to be fully analogous to a wet bulb thermometer; inspired wet bulb temperature has also been found to reflect changes in mouth tissue temperatures (Gallagher

et al., 1985). The present study was initiated to examine the interaction of dry bulb temperature and relative humidity on tissue temperatures of the tongue and hard palate.

BACKGROUND

During inspiration under normal temperate conditions, heat and water are transferred from the respiratory tract mucosa to inspired air. Turbulent mixing of inspired air in the upper respiratory tract allows a large portion of respired air to come into contact with the mucosa of the upper respiratory tract, causing a quick dissipation of heat throughout the airstream (Proetz, 1951). As inspired air is warmed, its capacity to hold water vapor is increased. Therefore, evaporation of water from the respiratory mucosa occurs in order to establish a vapor pressure equilibrium between mucosal water and water vapor in the inspired air. The respiratory mucosa is cooled in this process both by evaporation and turbulent convective heat loss. During expiration, the warmed and saturated air of the alveolar environment comes into contact with the cooler respiratory mucosa. This

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initiates a heat and water exchange from the expired air towards the respiratory mucosa. In this manner, the mucosa is rewarmed and rehydrated for the inspiration to follow (Walker et al., 1961).

During the inhalation of hot air, the respiratory tract is generally able to increase its heat losses so that body thermoregulation is aided by the elimination of greater amounts of heat. When breathing hot air, the humidity of the air is of particular importance. If the inspired air is hot and dry, some evaporation of the water from the upper respiratory mucosa will occur during inspiration. This evaporation cools the mucosa enough that hot, dry air in excess of 180°C can be breathed without a great deal of discomfort (Killick, 1932). The reason for such a remarkable cooling of the upper respiratory tract is the fact that the cooling action produced by the evaporation of water is highly efficient (the latent heat of evaporation is 538 calories per gram). If, however, inspired air is both hot and humid, no significant evaporative cooling of the respiratory tract mucosa will occur during inspiration. If inspired air is saturated and above body temperature, the mucosa will gain heat both from the inspired air and the water

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vapor in the inspired air, which will release its latent heat through **condensation** on the mucosa. Under these **conditions**, the respiratory tract **is** eliminating as much heat as it possibly can, but is gaining **in** net value both heat and water (Walker et al., 1961).

METHOD

Six healthy young men between the ages of 21 and 28 ($\bar{M} = 23.7 \pm 3.8$ SD) volunteered to serve as paid subjects (U.S. \$5/hr) to breathe nine conditions of **hot**, humid air. The subjects breathed one **hot**, humid air condition per day with each test lasting 60 minutes. None of the subjects had previous experience with breathing hot air, and were unaware of the hot, humid air conditions they were **experiencing**. Experimental conditions were presented in a progressive order (n=4) and random order (n=2). Mean subject height was 179.7 cm ± 6.6 SD, and the average weight was 72.2 kg ± 4.2 SD. The subjects walked on a treadmill at 40% $\dot{V}O_{2\max}$ as determined by a previously administered graded exercise tolerance test (mean $\dot{V}O_{2\max} = 59.6 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1} \pm 9.6$ SD; range = 43.6 ~ 72.0). The mean estimated

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$\dot{V}_E$ at 40% $\dot{V}O_{2\max}$ for these subjects was 41.0
liters/min $\pm$ 6.5 SD .

The experimental conditions consisted of three elevated dry bulb conditions (41°, 46°, and 51°C). At each elevated dry bulb condition, three relative humidities were studied: 65 %, 80 %, and 95 %. The actual achieved dry bulb temperatures and relative humidities for this study are given in Table 1.

TABLE 1. - Desired versus achieved dry bulb temperature and relative humidity for the nine hot, humid air conditions

Desired air condition		Achieved air condition	
T_{db} (°C) ^{1/}	pct R.H. ^{2/}	T_{db} (°C) ^{1/}	pct R.H. ^{2/}
41	65	41.3 (± 0.1 SD)	64.5 (± 1.9 SD)
41	80	41.1 (± 0.2 SD)	81.1 (± 2.1 SD)
41	95	41.3 (± 0.2 SD)	93.3 (± 2.2 SD)
46	65	45.9 (± 0.3 SD)	65.6 (± 1.8 SD)
46	80	46.2 (± 0.2 SD)	79.2 (± 1.0 SD)
46	95	45.8 (± 0.3 SD)	94.4 (± 2.7 SD)
51	65	51.1 (± 0.5 SD)	65.0 (± 1.7 SD)
51	80	51.0 (± 0.4 SD)	79.7 (± 2.0 SD)
51	95	50.7 (± 0.2 SD)	92.6 (± 2.4 SD)

SD - Standard deviation.

^{1/}Dry bulb temperature.

^{2/}Percentage, relative humidity.

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The range of corresponding wet bulb temperatures for the experimental conditions was 34.7 ~ 49.3°C. The experimental hot, humid air conditions were generated using a specially designed apparatus (Gallagher, 1984; Gallagher et al., 1985). Air was delivered at approximately 125 liters/min into a vapor generator which saturated the air with water vapor. This saturated air then travelled to a heat gun which heated the air to the desired temperature and relative humidity conditions before going to the subject's mouth. Final dry bulb and relative humidity conditions were determined by means of dry and wet bulb thermocouples which sampled air at a point six inches before reaching the subject. It should be noted that while the subject was breathing hot air through this system, the ambient environment was comfortable (air-conditioned room with fans blowing on the subject during work on the treadmill).

Tissue temperatures of the tongue and hard palate were obtained by means of thermocouples mounted in a mouthpiece that was custom-fitted to the subject's mouth. This arrangement allowed temperature sampling at fixed locations on the tongue and hard palate. A rectal thermistor was utilized to monitor the

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subject's core temperature. Heart rate (beats/min) was displayed on a digital monitor (Respironics Exersentry SN), or was measured using a Hewlett-Packard Electrocardiograph. Inspired dry bulb temperature and relative humidity, tongue temperature, palate temperature, core temperature, and heart rate were recorded every 5 minutes during the one hour test.

The data collected on mouth tissue temperatures, heart rate, and core temperature were analyzed individually in a 3×3 (T_{db} x RH) analysis of variance on repeated measures design with post hoc tests performed according to a Tukey WSD procedure. The level of significance was .05 in all cases.

RESULTS

Significant increases in tongue tissue temperature resulted from increases in both the dry bulb temperature ($F_{1,5} = 124.0$, $p < .001$) and percentage relative humidity ($F_{1,5} = 195.1$, $p < .001$) of the inspired air. Hard palate tissue temperature was similarly affected by increases of both inspired dry bulb temperatures ($F_{1,5} = 390.0$, $p < .001$) and relative humidity ($F_{1,5} = 401.5$, $p < .001$). The interaction of dry bulb temperature and relative

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humidity, however, was not significant for either tongue tissue temperature ($F_{1,5} = 1.5$, $p = .254$) or hard palate tissue temperature ($F_{1,5} = 1.2$, $F = .329$). Core temperature (T_{re}) was not significantly affected by either increasing inspired dry bulb temperatures ($F_{1,5} = 0.6$, $p = .564$) or relative humidity ($F_{1,5} = 1.1$, $F = .369$). The other secondary dependent measure, heart rate, also remained unaffected by increasing inspired dry bulb temperatures ($F_{1,5} = 3.2$, $p = .084$) or increasing relative humidity ($F_{1,5} = 0.4$, $F = .669$) of the inspired air. Figures 1 and 2 show mean tongue and palate temperatures, respectively, as a function of inspired dry bulb temperature at the three relative humidities studied.

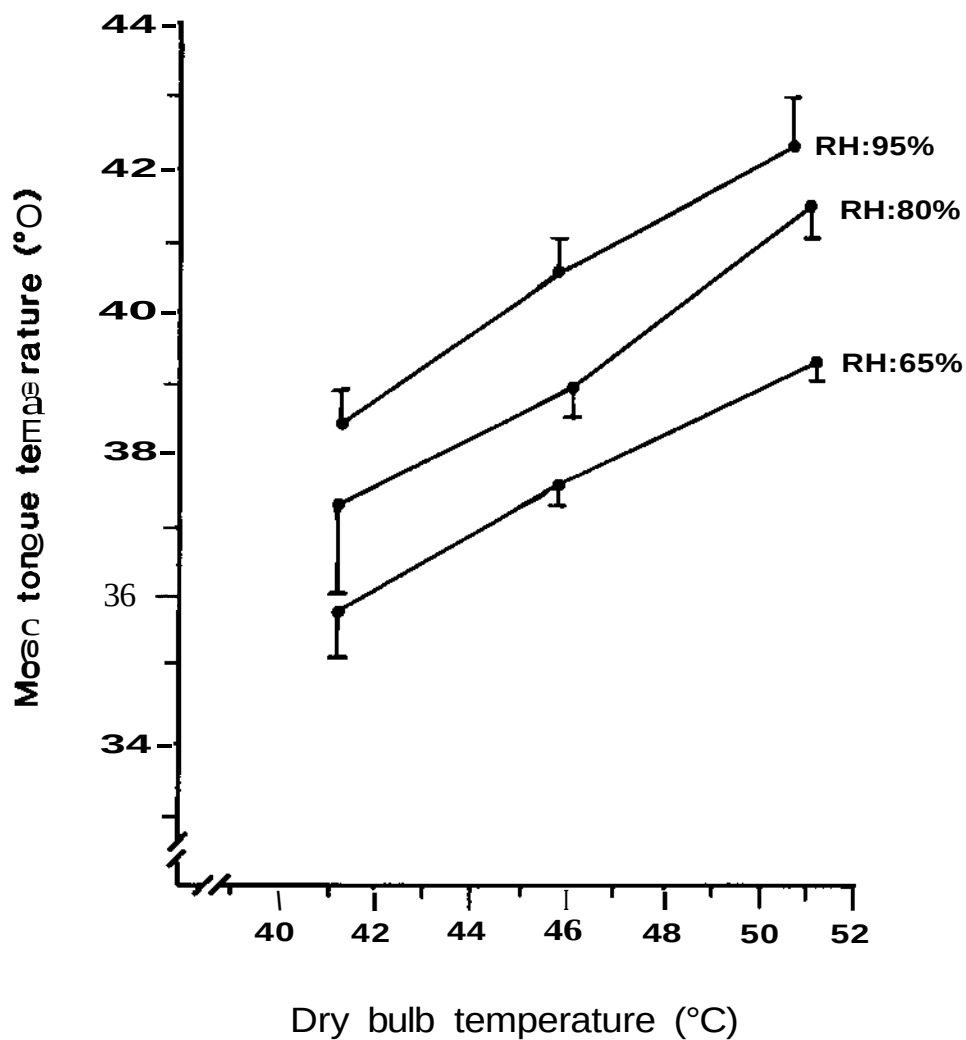


Figure 1. Mean tongue temperatures as a function of dry bulb temperature and relative humidity of inspired air.
[Note: $\bar{x} \pm s.e.$ = standard error of the mean; RH = relative humidity]

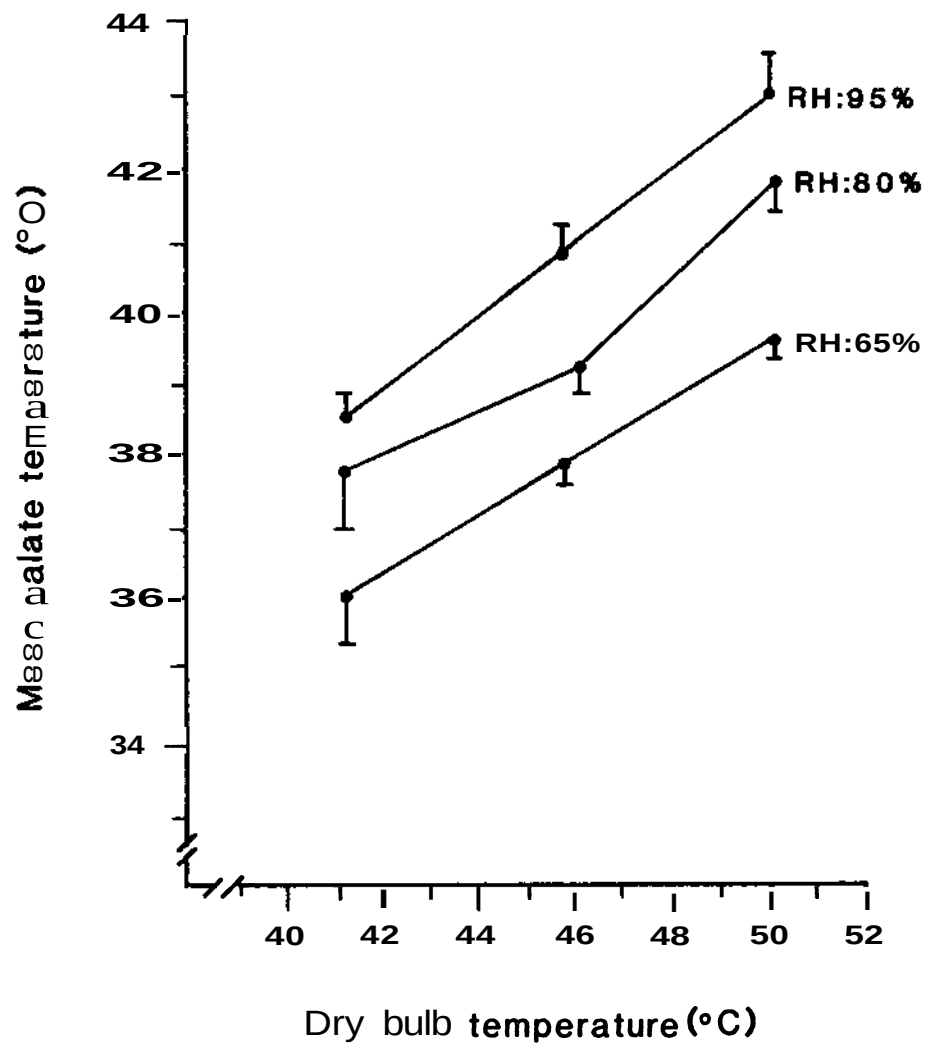


Figure 2. Mean palate temperatures as a function of dry bulb temperature and relative humidity of inspired air.
[Note: $\bar{x} \pm \text{SE}$ = standard error of the mean; RH=relative humidity]

Increases in tongue and hard palate temperatures were found to be well-described in terms of inspired wet bulb temperature by the following equations:

$$(1) T_{\text{tongue}}(^{\circ}\text{C}) = 19.7 (^{\circ}\text{C}) + 0.46 T_{\text{wb}} (^{\circ}\text{C})$$

(Standard Error of Estimate = 0.53)

$$(2) T_{\text{palate}}(^{\circ}\text{C}) = 21.0 (^{\circ}\text{C}) + 0.43 T_{\text{wb}} (^{\circ}\text{C})$$

(Standard Error of Estimate = 0.47).

The relationship between inspired wet bulb temperature and mouth tissue temperatures is dealt with in more detail elsewhere (Gallagher et al., 1985). It should be noted that these equations apply only to moderately exercising subjects ($40\% \dot{V}O_{2\text{max}}$).

DISCUSSION

Both tongue and hard palate tissue temperatures are influenced by the dry bulb temperature and relative humidity of inspired air. As illustrated in Figures 1 and 2, increases in relative humidity with a constant dry bulb temperature causes mouth tissue temperatures to increase. Conversely, increasing the dry bulb temperature of the air inhaled while maintaining a constant percentage of relative humidity will cause a **similar increase in mouth tissue temperatures**. However, while dry bulb temperature and relative humidity both increase tissue temperatures of the tongue and hard palate, these variables do not interact, i.e., both cause increases in tissue temperatures of the mouth in a similar additive fashion. Although both of these variables have measurable effects on mouth tissue **temperatures**, inspired wet bulb temperature is the preferred metric to use when describing increases in tissue temperatures of the mouth (Gallagher, 1984; Gallagher et al., 1985).

Since the experimental conditions were expected to cause respiratory heat gain, it was of interest to

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determine whether elevated dry bulb temperature or relative humidity might affect core temperature (T_{re}). Core temperature was not, however, significantly affected by increases of dry bulb temperature or relative humidity. In general, core temperature rose 0.5 - 1.0 °C during the hot, humid air inhalation sessions, at which point T_{re} reached a steady state. The rise in T_{re} is attributable to the moderate exercise performed by the subjects during the test. Previous research has suggested that there may be an increase in sweating to compensate for the respiratory heat gain incurred during hot, humid air inhalation (Killick, 1932), but no quantitative measurements were taken during this study and no subjective changes were reported. Heart rate also remained unaffected due to inhalation of hot, humid air. This finding is in agreement with Killick (1932), who found no consistent change in pulse rate due to inhalation of hot, humid air.

All of the experimental conditions were generally well-tolerated by the subjects. However, two of the hot, humid air conditions tended to be perceived as uncomfortable (though not intolerable) by the subjects. These conditions were 51°C, 80% RH and 51°C, 95% RH

(T_{wb} = 46.9 and 49.3 °C, respectively). During and after these tests there were often complaints of discomfort in the subject's gums, tongue, hard palate, and posterior pharynx due to the inhalation of the hot, humid air. Redness of the subject's gums, hard palate, tongue, and posterior pharynx were often noted after the two most stressful test, however, this phenomenon was transient in nature. One subject elected not to finish the 51 °C, 95% RH condition (in accordance with the informed consent procedure used) after 44 minutes of inhaling this air. The subject's gums were often the first area of concern with regard to tissue sensitivity to inhaling hot, humid air. This may be due to the fact that almost no conditioning of the inspired air could have been achieved at this point in the respiratory tract; a point where both vapor pressure and temperature gradients between the inspired air and the respiratory mucosa would be greatest. However, Killick (1932) reported that subjects most often first felt the effects of the heat on the roof of the mouth. The reason for this discrepancy is unclear. Respiration was observed to be more rapid and shallow during tests at 51°C, 80% RH and 51°C, 95% RH. This may indicate that there is a mechanism in action which attempts to limit the amount

of heat delivered to the respiratory tract per breath under **these conditions**. Deep inhalation of this air often elicited a coughing **response**. It **should** be noted that **persons** undergoing anesthetic procedures in **hospitals** (at a relatively low $\dot{V}_E$) may be able to breathe this air with less difficulty than exercising **subjects**.

The data **presented** in this study indicates that breathing hot, humid air is **well-tolerated** by moderately **exercising** subjects for all except the 51°C, 80% RH ($T_{wb} = 46.9^\circ\text{C}$) and 51°C, 95% RH ($T_{wb}^* = 49.3^\circ\text{C}$) **conditions**. During these tests mouth **tissue** temperatures **rose** to higher than 41.0°C. It should be **noted, however**, that all but one of the subjects were able to finish the most stressful condition with only relatively minor complaints of discomfort in tissues of the mouth. These findings suggest that moderately exercising subjects are able to tolerate inhalation of hot, humid air up to inspired wet bulb temperatures of 45°C with relative ease. However, before any definitive **recommendations** for maximum allowable temperature limits are recommended, more work needs to be done to ascertain the effects of higher ventilation rates, and studies need to describe how the stress of breathing hot air interacts with other

stressors inherent in SCBA design (i.e., breathing against resistance and positive pressure, and breathing elevated concentrations of CO_2). This research would allow us to gain a better understanding of how SCBA units may be made safer to use (Vercruyssen et al., 1984).

One additional word of caution is appropriate when interpreting these results. Although a somewhat homogeneous sample group of subjects was used in this study, the subjects may not have been representative of the population of individuals who might need to use an SCBA. Kamon et al. (1983) collected physiologic data on six coal miners simulating an escape from an underground mine following an explosion. Compared with the physical characteristics of subjects used in this study, the coal miners were older (45.2 vs. 23.7 years), shorter (172.0 vs. 179.6 cm), heavier (78.6 vs. 72.2 kg), and had a lower aerobic capacity ($34.1 \text{ vs. } 59.6 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$). The lower aerobic capacity of miners at comparable exercise intensities may result in higher minute ventilation rates, and would thus cause a greater amount of heat to be presented to the mouth tissues.

Based on the findings of this study, it is somewhat surprising to note that the current guidelines for the

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amount of heat that may be generated by a one-hour **rescue respirator** certified by the National Institute of Occupational Safety and Health (**NIOSH**) is 45°C for a relative humidity range of 0~50% and 41°C for a relative humidity range of 50~100%. If a device **is** designated to be used for escape only, these temperature limits may be increased by 5°C each. Given the effects of relative humidity on tissue temperatures in the mouth as described in **this paper**, it can be **seen** that a broad range of relative humidities at a **constant** dry bulb temperature will cause a variety of responses in mouth tissue **temperatures**. In practical **terms**, it can be **seen** that a person breathing 46°C, 100% RH air **is** much more at risk of experiencing mouth discomfort than a person breathing 50°C, 50% RH air. Therefore, it may be advisable to define maximum allowable temperature limits for SCBAs in terms of smaller ranges of relative humidities at various dry bulb **temperatures**, or preferably in terms of the **inspired** wet bulb temperature of the air (Gallagher, 1984; Gallagher et al., 1985). If such changes were made, **manufacturers** of SCBA units may be allowed to use CO₂ absorbants that create very hot, but dry air which may actually decrease the amount of heat presented to the mouth tissues (due to a lower

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inspired wet bulb **t**emperature) compared to that which **i**s currently allowed with **s**aturated air. In **f**act, very dry air at up to 100°C may actually be **l**ess physiologically **s**tressful to mouth **t**issues than fully saturated air at 41°C.

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REFERENCES

- Cole, P. (1954), "Recordings of Respiratory Air Temperatures," Journal of Laryngology and Otology , 68 : 295-307.
- Comroe, J. H. (1974), Physiology of Respiration, 2nd Edition (Year Book Medical Publishers, Chicago), 220-221.
- Gallagher, S. (1984), The Effects of Inspired Wet Bulb Temperature on Tissue Temperatures of the Tongue and Hard Palate , The Pennsylvania State University, University Park, PA, Master's Thesis.
- Gallagher, S., Vercruyssen, M., and Deno, N.S. (1985), "Hot Air Breathing: Effects of Elevated Wet Bulb Temperature on Tissue Temperatures of the Mouth," American Industrial Hygiene Association Journal , 46 : 332-335.
- Haldane, J.S. (1915), "Self-Contained Rescue Apparatus and Smoke Helmets: Second Report to the Doncaster Coal-Owners' (Gob-Fire Research) Committee," Transactions of the Institute of Mining Engineers , 48 : 550-595.
- Inglestedt, S. (1955), "Studies on the Conditioning of Respired Air in the Respiratory Tract," Acta Oto-laryngologica (Supplement) , 131 : 7-11*
- Kamon, E., Doyle, D., and Kovac, J. (1983), "The Oxygen Cost of Escaping from an Underground Mine," American Industrial Hygiene Association Journal , 44 : 552-555.

Hot Air Breathing

- Kamon, E., Deno, N.S., and Vercruyssen, M. (1984), Physiological Responses of Miners to Emergency (Volumes I and II); A Mining Research Report, U.S. Department of the Interior, Bureau of Mines, Pittsburgh, PA, Contract No. JO-100092.
- Killick, E.M. (1932), "Physiological Response to Breathing Hot Air," Journal of Hygiene, 32 : 332-339.
- Lind, A.R. (1955), "The Influence of Inspired Air Temperature on Tolerance of Work in the Heat," British Journal of Industrial Medicine, 12 : 126-130.
- McCutchan, J.W., and Taylor, C.F. (1951), "Respiratory Heat Exchange with Varying Temperature and Humidity of Expired Air," Journal of Applied Physiology, 4 : 121-135.
- McFadden, E.R., Denison, D.M., Waller, J.F., Asoufi, B., Peacock, A., and Sopwith, T. (1982), "Direct Recordings of the Temperatures in the Tracheobronchial Tree in Man," Journal of Clinical Investigation, 69 : 700-705.
- Moritz, A.R., Henriques, F.C., Jr., and McLean, R. (1944), "The Effects of Inhaled Heat on the Air Passages and Lungs: An Experimental Investigation," American Journal of Pathology, 21 : 311-331.
- Proetz, A.W. (1951), "Air Currents in the Upper Respiratory Tract and Their Clinical Significance," Annals of Otology, Rhinology, and Laryngology, 60 : 439-467.
- Seeley, L.E. (1940), "Study of Changes in the Temperature and Water Content of Respired Air in the Nasal Cavity," Transactions of the American Society of Heating and Ventilation Engineers, 46 : 259-289.

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- Stacy, R.W., Seal, E., Jr., Green, J., and House, D. (1982), "Pulmonary Function in Normal Humans with Exercise and Temperature-Humidity Stress," Journal of Applied Physiology: Respiratory, Environmental, and Exercise Physiology , 53 (4): 1015-1018.
- Vercruyssen, M., Christina, R.W., Noble, M.F., and Kamon, E. (1984b), "Proposed Method for Simultaneous Measurement of Physiological, Psychological, and Subjective Reactions to Stressors," Unpublished data presented at the Olympic Scientific Congress , Eugene, OR, July, 1984. Abstract in the Proceedings (pp. 25-26), Manuscript in preparation.
- Walker, J.E.C., Wells, R.E., Jr., and Merrill, E.W. (1961), "Heat and Water Exchange in the Respiratory Tract," American Journal of Medicine , 30 : 259-267.